RELIABLE: Wear **Re**sistant **Li**ghtweight **A**luminium **B**rakes for Vehic**le**s

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ABSTRACT: A significant amount of vehicle weight resides in the conventional cast iron brake discs. This "unsprung mass" further compounds the effects of rotational inertia and impacts fuel consumption and subsequent CO_2 emissions. In addition, non-exhaust air pollution from brake dust (disc and pad wear comprising nano-particles, PM2.5 and PM10) is of high concern due to public health issues, and the possibility of premature deaths and reduction in life-expectancy. Thus, there is a strong impetus to develop alternative approaches that reduce both CO_2 and PM emissions in future vehicles.

Light materials such as aluminium alloys present attractive options as potential solutions to help reduce vehicle weight, and consequently improve fuel economy, reduce emissions and the overall sustainability of vehicles. The main challenge for using aluminium alloys is thier relatively low maximum operating temperatures (MoT) as well as poor surface properties which lead to excessive corrosion and wear. Keronite plasma electrolytic oxidation (PEO) is an environmentally safe coating process which offers aluminium alloys multifunctional characteristics such as high hardness, strong adhesion, low stiffness and a continuous barrier which is capable of offering protection against corrosion, wear and extreme heat likely to be experienced by brake discs.

Brake discs for the rear axle of a high performance sports car have been manufactured in AA6082-T6 aluminium alloy, with and without vents. These were subsequently coated with a Keronite PEO ceramic layer. Full-scale dynamometer tests have been conducted against a standard LowMet brake pad using a modified AK Master test at increasing levels of initial braking temperature (IBT) until a physical limit is reached. Microstructural characterisation of coating and brake pad wear and tribolayer have been studied extensively using SEM and EDX. In addition, post-dyno test discs have been exposed to salt fog testing, and their corrosion behaviour and relative interactions with the tribolayer have been investigated. The overall relative performance and the degradation mechanisms have been discussed and the potential to use PEO coated light alloy discs have been proposed.

KEY WORDS: light alloy, plasma electrolytic oxidation, corrosion, friction and wear, particulate matters

1. Introduction

Grey cast-iron (GCI) remains the number one choice of material for brake discs in passenger vehicles despite significant environmental shortcomings. Heavy cast-iron discs are part of what is known as the "unsprung-mass", which amplifies the effect weight has on fuel efficiency, or battery efficiency and range in the case of electric vehicles (EVs). Furthermore, cast-iron brake wear particulate matter (PM) in urban air pollution has been linked to a range of acute health conditions, including effects on the respiratory and cardiovascular systems, asthma [1], and even Alzheimer's disease[2-4]. Cast iron brakes are a barrier to making better inroads into the wider challenges of PM and GHG (Green-House-Gas) emissions. Attempts have been made in relation to the introduction of lighter, lower wear solutions:

- Aluminium metal-matrix-composite (MMC) brake discs have previously been used on lightweight cars (Lotus-Elise <650kg). These discs were expensive to produce and were not considered viable for mass produced market and are no longer in production.

- Lightweight high-performance carbon fibre reinforced ceramic (CFRC) disc brakes are available. However, their extremely expensive nature (>£1,000) restricts their use to high-end vehicles.

- The use of aluminium brake disc combined with brazed Al_2O_3 plates had been investigated but reported the requirement of maintaining low working temperatures due to low melting point of filler materials as well as challenges achieving flatness after brazing and cracking of the ceramic plates [5].

The growth in EVs is adding another dimension to this problem and relates to their regenerative-braking systems (RBS). The RBS generator resistance acts to slow the vehicle, thereby reducing the demands on the friction brake system. Reduced demand means cast-iron discs are colder and damper for longer, significantly increasing corrosion susceptibility. As a result: 1) the corroded discs produce even higher levels of PM; and 2) they are prone to seizure following such periods of inactivity. The reduced braking demands and the pronounced issues of cast-iron discs in EVs creates an even greater need/opportunity for a lighter, wear resistant alternative.

The innovation in this research is based on the application of a unique, proprietary Keronite Plasma Electrolytic Oxidation (PEO) process to a specially designed aluminium alloy disc brake. The PEO converts the disc brake's light alloy surface layer into an extremely dense and super-hard crystalline coating of Al_2O_3 capable of surviving temperature extremes, corrosion, extreme wear and thermal stresses. Because it is a conversion layer (rather than a deposited ceramic coating or brazed ceramic layer), it offers excellent adhesion to the substrate metal, which makes the ceramic coating extremely robust and able to withstand relatively high coefficient of thermal expansion (CTE) mismatch. Keronite PEO is an environmentally safe surface treatment for light alloys including (Al, Mg, Ti) that is free of heavy metal such as Cr, V and toxic substances, unlike competing coatings technologies.

Previous researches [6] with tests undertaken either as pin-on-disc (PoD) specimens or small (∅125mm) PEO coated discs for small-scale dynamometer tests using standard low-met brake pad materials at Leeds University facilities showed promising initial results with stable coefficient of friction (CoF) and ability to withstand rubbing surface temperature around 500°C [7]. Subsequent full-scale dynamometer tests on PEO coated AA6082 vented brake disc against a standard low-met brake pad was reported to have withstood 500°C [8]. Specific properties of the PEO ceramic coating in relation to the brake disc application have derived from the following: a) Excellent adhesion to substrate [9]; high-wear resistance; environmentally-friendly [8,10]; CoF similar to cast-iron; excellent corrosion-resistance [5,6]; low-noise; integrated vented channels for heat-dissipation and cooling.

More recently, Gulden et. al [11] reported that a PEO coating on a vented AA6082 brake disc exhibits a good wear resistance in every-day braking situations as well as in emergency stops. However, a series of braking events at temperatures (IBT 200°C) resulted in a growth of the production-related cracks, the development of new cracks and the formation of a continuous crack network. Depending on the disc temperature and the brake pressure, some of these cracks penetrate the PEO coating, open partially under repeated braking and are filled with wear debris of the pad material. Moreover, the aluminium base alloy seems to be too soft at high temperatures and undergoes plastic deformation in the region around a crack, arising the need for a more temperature resistant substrate material. On the other hand, the present and the previous studies do not show extensive delamination or severe material damage, and thus prove the fundamental suitability of the material system for braking applications.

The present study focuses also on a Keronite PEO ceramic coated AA6082 brake disc of a high performance car of gross vehicle weight of 2120 kg using a modified AK master dynamometer test protocol. Moreover, this work also has attempted to look into a solid disc vs vented disc to see if convective cooling offers further benefits. Attempts are made to discuss failure mechanisms caused by the thermo-mechanical loading in relation to the coating/substrate performance.

2. Experimental Approach

2.1. Materials and Testing

An extruded aluminium alloy AA6082-T6 (nominal composition Bal Al., 0.7-1.3Si, 0.5Fe, 0.1Cu, 0.4-1Mn, 0.6-1.2Mg, 0.25Cr, 0.2Zn, 0.1Ti) was selected due to its more acceptable properties for the intended braking application as well as availability in sizes to enable manufacture in large disc diameters and relatively low manufacturing cost.

For the current research, the disc design was based on an adaption of an existing design of GCI rotors for the same vehicle. Subsequently, brake discs were CNC machined from solid without and with vents to a typical surface finish of Ra 0.2-0.3µm. The physical size and design of the brake disc was selected such that the current full-scale dynamometer housed at Alcon could be used as a test bed. Vented slots have been created by drilling straight-through 'radial' holes across the brake surface. And as such, optimisation for material strength, thickness to match up with the cast iron steel was not considered in this phase of the research but purely to understand the integrity of the coated brake discs as in current standard shape and size of a standard cast iron disc without also having to modify dynamometer/vehicle-fitting setup.

A standard LowMet brake pad, primarily comprising Al, Fe, Si, Cu, Zn, Ba, Ca, Cr, Mg containing wires and various particle aggregates of varying coarse sizes was used for a modified AK Master full-scale dynamometer test at increasing levels of initial brake temperature (IBT) until a physical limit is reached. Details of the AK Master test are described further below.

2.2. PEO coating

Prior to coating, brake discs were cleaned for 5 mins using a standard degreaser. This was done to avoid use of solvent based cleaning fluids. Subsequently, non-rubbing surfaces of discs including the hub areas were masked using a special masking paint for this research, though hard tooling masking has been envisaged for production purposes. Masking was done in order to: a) improve production efficiency by just focusing on critical braking surfaces; b) improve heat transfer via conduction through uncoated areas of the hub, perimeter and in the case of vented discs by additional convection via cooling channels; and c) minimise manufacturing costs by processing time, chemicals consumption and electrical energy. The brake discs were subsequently coated at Keronite to a nominal thickness of 50-60µm, using a 160kW PLC-controlled commercial equipment with voltage and frequency modulation capability. The electrolyte used was a low concentration (<2%) alkaline solution of proprietary composition of pH 10-12 and conductivity 6-7mS. During the coating process, the electrolyte temperature was maintained below 20°C using an external chiller. A high performance GCI (referred herein as 'iron disc') brake disc (∅295×28mm) was used as a benchmark disc.

2.3. Materials Characterisation

Coating thickness and its uniformity across the braking surface was measured using an induction thickness gauge, MiniTest 650N, manufactured by ElektroPhysik, Germany. Coating surface roughness was measured using a Surfcom 130A profilometer supplied by Advanced Metrology Systems Ltd., UK using 0.25 cut-off and 4mm evaluation length. Coating hardness was measured using a Struers Duramin 5 hardness tester with Knoop load of 50g. Coating cross-sections were prepared to 1µm diamond finish using standard metallographic techniques, ready for microscopic examination. Light optical (Nikon L150) and scanning electron microscope (SEM) Cambridge Stereoscan 240 equipped with the energy dispersive X-ray facility were used for coating and brake pad characterization.

2.4. Modified AK Master Test

First set of Al discs in solid and vented options with the Keronite PEO ceramic coating were tested according to a modified SAE J2522 Dynamometer Global Brake Effectiveness and Evaluation test procedure at Alcon [12]. In the tests, conducted in this study, each set comprised 10 test blocks as shown in Table 1 up to 400°C IBT except for the cast iron disc where block 2 and 3 were missed.

Table 1 Modified AK master test protocol

Block	Description	Inertia	Pressure	IBT
1	50pc	50%	50%	100°C
2	50pc	100%	50%	100°C
3	75pc	100%	75%	100°C
4	High drag	100%	100%	100°C
5	150 IBT	100%	100%	150°C
6	200 IBT	100%	100%	200°C
7	250 IBT	100%	100%	250°C
8	300 IBT	100%	100%	300°C
9	350 IBT	100%	100%	350°C
10	400 IBT	100%	100%	400°C

Table 2 SAE J2522 AK master test in each block

Step	Section	No of snubs	Brake-release speed (kph)	Pressure (bar)
1	µ Green	30	80-30	30
2	Bedding	62	80-30	30
3	Char value 1	6	80-30	30
4.1	Speed/pressure	8	40-5	10-80
4.2	Speed/pressure	8	80-40	10-80
4.3	Speed/pressure	8	120-80	10-80
4.4	Speed/pressure	8	160-130	10-80
4.5	Speed/pressure	8	200-170	10-80
5	Char value 2	6	80-30	30
6	Cold application	1	40-5@40°C	30
7	Motorway snubs	2	100 & 180	40
8	Char value 3	18	80-30	30

Each test block included the following steps as shown in Table 2. Each test block included 180 braking events with tests conducted totalling up to 1800 stops with IBT varying from 100-400°C. Test with IBT 400°C recorded peak Tmax. of 450°C. Second set of tests were conducted for IBT up to 300°C max. only i.e. only for test blocks 1-8 (see Table 2) to see whether a lower IBT could offer more attractive outcomes for the light alloy brake disc concept for such high performance vehicle tests.

Surface temperature of the discs was measured using a rubbing (contact) thermocouple on both faces of the discs. In addition, the dynamometer test set up included on board sensors for measurements of friction coefficient, applied brake pressure and disc speed.

The amount of wear on the discs and brake pads as well as disc runout was identified through measurements of thickness and mass. The measurements were made before and after the tests. The dimensional wear was done on the four different points with 90-degree angles on the disc and on eight points on the brake pad using a Mitutoyo digital micrometer of 0.3µm flatness and 0.001mm sensitivity.

2.5. Salt spray testing

150mm arc segments of brake discs in as-coated and after subjecting to 1800 stops at 300°C and 400°C IBT tests were exposed to a salt fog. The test was carried out following the guidelines of the ASTM standard B117-11 “Standard practice for operating salt spray (fog) apparatus” using a Corrosion-Box cabinet manufactured by COFOMEGRA, Italy. The testing comprised of exposing the surface to an atomized fog created from a 5wt% NaCl solution. Al brake disc segments were supported at 15° from the vertical and were examined mostly at 68 hours of exposures.

3. Results and Discussion

3.1. As coated brake discs

Al brake discs coated using the Keronite PEO process are shown in Fig.1 which shows the ability of the technology to be able to coat such large discs. The processing duration was typically less than 1 hr when coated individually but the number in a batch can be increased further to make the process viability for industrial manufacturing at volume. Only the braking surfaces of the aluminium disc were coated and this was done for several reasons: a) maximise coating efficiency by focusing on specific working surfaces while minimise the surface area to be coated and subsequently processing time and manufacturing costs; b) helping efficient heat transfer via conduction through disc hub/shaft and also by convection of the larger uncoated area and/or via specially drilled vent holes in the case of vented disc.

The coating is of greyish white colour, typical of this type of coating on the 6xxx series alloy and is highly uniform across the braking surface and ranged between nominally 50-60µm in thickness on both outboard and inboard faces. Usually the central and inner regions of the disc measured circa 50µm thickness while the outer edges had circa 60µm in thickness. Such a small variation is not unexpected due to higher electrical field on the outer edges.

Typical surface roughness of Ra circa 2-2.5µm in as-coated condition was measured. Coatings on solid and vented discs were rather similar and their thickness distributions across the braking surfaces are shown in Fig.1.

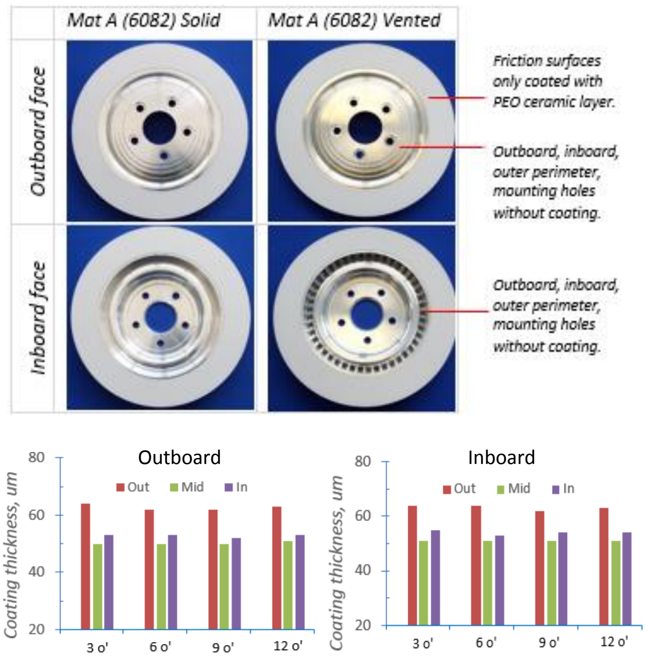

Figure 1 PEO coated discs prior to dynamometer testing (top) and coating thickness distributions across the rubbing outboard and inboard surfaces (bottom).

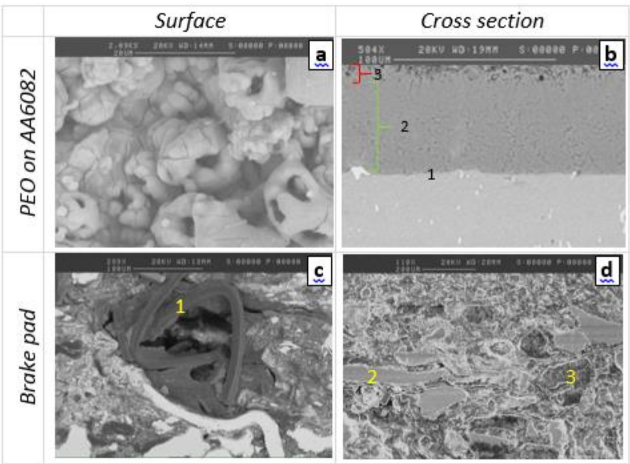

Figure 2 SEM images of the PEO coating on Al disc: a) as coated free surface, b) cross section showing '3' top porous layer, '2' main technological layer and '1' interfacial layer; and c) brake pad free surface, d) brake pad cross section. 1- Fe; 2 – Cu Zn; 3 – Al Si

3.2 Microstructure

SEM secondary electron microstructure of the as-coated PEO layer on the 6082 alloy is shown in Fig.2a. The free surface of the disc coating shows presence of micro-globular eruptions typical 5-10µm in sizes and within this discharge cannels in the form of pores or craters typically 2-5µm in diameter. In addition, presence of extensive micro-cracks due to shrinkage of molten droplets from the plasma events are visible. These features create both micro- and nano-scale fissures in the coating that are typical for the process and are often considered useful coating features. Discharge porosities are considered useful for impregnation and bonding of secondary materials e.g. in the current case, these porosities act as reservoirs for embedment of pad materials and giving the tribolayer a good mechanical keying surface. A back-scattered coating in cross-section in Fig.2b shows these shrinkage cracks as well as micro-pores follow their path all the way down to the substrate.

These shrinkage cracks reduce the global coating stiffness typically < 30GPa [13] as well as enables the coating to withstand both mechanical and thermomechanical stresses while still offering an excellent bond between the coating and the substrate. Another, typical features of the PEO coating is its multilayer structure: *a)* top highly porous and rough layer typically 15-20% of the thickness that allows easy removal during abrasive/sliding wear operations while also at the same time giving an opportunity for secondary materials to mix and impregnate into its surface thus creating a composite layer often considered useful as a tribological surface; *b)* a working or technological crystalline ceramic layer which is denser that offers durable and extremely hard surface and load bearing capacity for high contact pressures as well as resistance to environmental exposures including corrosion; and finally *c)* an interfacial layer not clearly seen on the SEM image but does exist typically as a sub-micron amorphous layer that offers an intimate bond between the main coating layer and the substrate alloy giving an extreme adhesion to the ceramic layer that typically exceeds 80MPa [14]. Hardness measurements confirmed the coatings to be extremely hard and Knoop indentations values of 1200-1600$HK_{0.05}$ was typical across all the coating cross-section often reported to be due to conversion of the aluminium surface into its ceramic form of α-Al_2O_3 [8] increasing the hardness of the substrate alloy of circa 120HK by almost 10 times.

Back-scattered SEM image of the brake pad surface in Fig. 2c and the cross-sectional view of the same in Fig.2d show the pad material to comprise different materials in the form of wires and particle aggregates of Fe, Al, Si, Cu, Zn, Ca, Mg, Ba and various other elements. EDX spectra taken from a larger 500µm x 500µm area analysis confirm darker '1' and brighter '2' regions to be rich in Fe and Cu.

3.3 Friction and wear

Generally both coated Al discs performed well and remained largely intact during the entire AK Master tests. For all discs, CoF started circa 0.29-0.30 and was seen to increase as the tests progressed through the testing protocol (from "bedding-in") and peaked to max. 0.5-0.60 at 400°C IBT. However, average CoF values at a typical 100°C IBT for most common use of a vehicle were relatively stable circa ~0.34-0.38 except for the speed/pressure cycles and motorway snubs where CoF scattered in between 0.25-0.45. Similar CoF values for the PEO coated Al discs have been reported elsewhere also using the small scale 2kW bench dynamometer tests [5].

While the behaviour of all of the discs was broadly similar some differences between the design (solid vs vented) were observed. In the standard AK Master test (100°C IBT), solid Al disc showed a rather stable CoF around 0.35 through most of the test and was quite similar to the iron disc. However, the vented Al disc showed a slightly fluctuating and somewhat higher CoF as shown in Fig.3.

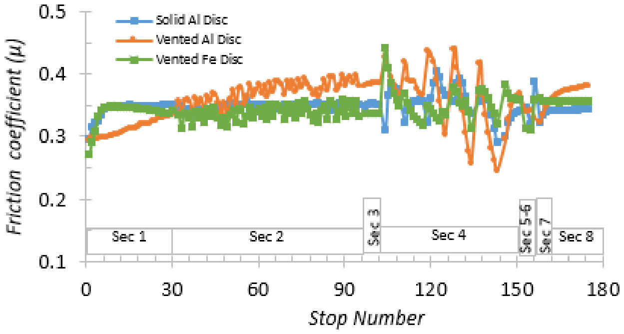

Figure 3 Average friction coefficient values of coated discs compared to cast iron disc at 100°C IBT

Pad wear for the coated solid and vented Al discs was broadly similar after 200°C IBT tests. However, after 300°C IBT tests, the pad wear against the vented Al disc was almost half to that against the solid Al brake disc. It is possible that improved heat dissipation of the vented Al brake disc both via conduction (hub) and convection (slotted vents and adjacent areas) could have minimised the pad wear or tribolayer disintegration and not requiring it to form/replenish more frequently. The data clearly shows that between the 300°C and the 400°C IBT tests, pad wear accelerated greatly in all three cases indicating to progress from friction/mild wear to damage/wear-out regime. Pad wear with the vented iron disc was highest of the tests (Fig.4) and was significantly higher than those for the Al discs probably due to lower thermal conductivity of the iron disc thus raising the iron disc/pad interface temperature significantly. In these tests conducted, interim pad wear measurement data were not available for the iron disc.

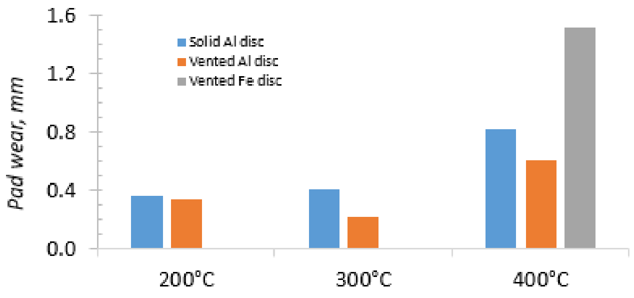

Figure 4 Pad wear values against various Al and iron discs

Disc wear data are presented in Fig.5 and shows wear rates for the three discs tested following the 400°C IBT tests (interim data is not available). Once again, the vented Al brake disc showed almost 2.5 times less wear than the solid Al brake disc. The iron disc shows the lowest disc wear of the three discs tested.

There are a number of factors that influence this result. Firstly, PEO coatings often have a top ‘porous’ layer which is 15-20% of the total thickness and this layer is often relatively easily friable/removed during initial operation of braking events such as initial ‘bedding-in’ cycles. Taking this into account, the difference between the vented Al disc wear (8μm) and the iron disc wear (5μm) was only marginal. Secondly, the pad was primarily designed for the iron disc application and no attempt to optimise the pad for a PEO coating has yet been attempted. Thirdly, under these conditions loss of disc thickness due the combined effect of corrosion and wear for the iron disc is not simulated, and it is likely that a relatively high corrosion rate of the iron disc compared to the ceramic coated Al discs would, in fact, could lead to higher total wear rate of the iron disc in practise. Some of the corrosion aspects of the coated Al discs will be discussed further sections. Finally, it may be possible the high temperature and the lack of heat dissipation in this test results in both excessive pad wear (as discussed above) and excessive stress in the coating due to the large differences in CTE between the Al disc substrate and the ceramic coating. Further, while the iron disc has shown marginally less disc wear compared to, for example, a vented Al disc, the post 400°C IBT test showed the iron disc had significantly higher disc runout that could potentially result in excessive vibration and noise.

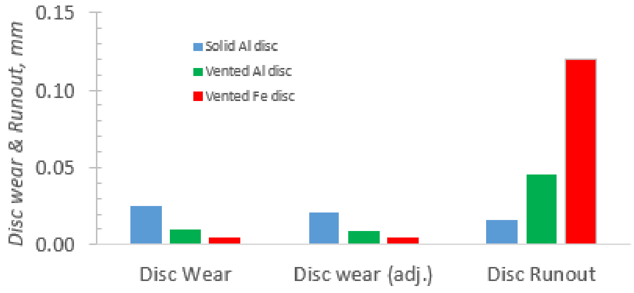

Figure 5 Disc wear and Runout measurements of various discs tested up to 400°C.

All these results indicate that 400°C IBT may be too much for Al brake discs due to possible warping at higher temperature range. Report [15] suggested that for a given brake disc, a warping temperature at which the surface deformation begins to be circa 70% of the melting temperature of the alloy. If it is to be considered then, the warping temperature of circa 385°C (70% of 555°C) may be likely at which the Al brake disc begins to deform thus limiting the use of the Al brake disc to max. 350°C. However, FEA analysis by Alnaqi et al [7] suggests that for the PEO coated Al disc, a maximum operating temperature (MoT) circa 450°C may be feasible. The latter is based upon the FEA models and as such may be too optimistic and hence, 300°C IBT with max. 350°C may be a viable option for the ceramic PEO coated Al brake discs.

Subsequent to above, AK master tests at 300°C max tests were repeated over 320 stops. CoF values remained again rather similar (not presented here) but some significant differences in the way the ceramic PEO coating on a soft Al alloy appears to offer a significantly improved coating durability.

3.4 Wear characteristics

Following the AK master tests, cut sections of the PEO coated Al brake discs (both solid and vented) were examined and the surface of the rubbing faces are presented in Fig.6. Solid Al disc after 400°C IBT tested surface had signs of some thermal crazing and the thickness survey recorded at least 50% of the initial coating thickness of 50µm has still remained. No loss of coating adhesion was noticed after such severe thermo-mechanical tests. While after the 300°C IBT test, no visible signs of thermal crazing was noticed with over 75% coating thickness still remaining.

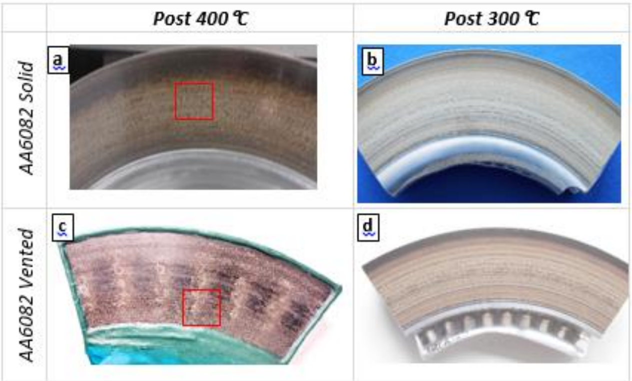

Figure 6 Photographs showing surfaces of coated discs after 400°C and 300°C brake test

For the vented Al discs after 400°C IBT tests, there was a pronounced pattern of thermal crazing along the machined slots where disc thickness was minimum (Fig.6c). However, no such thermal crazing effect on the disc after the 300°C IBT tests was observed. At least 75% of the coating thickness was recorded again on this case too with no loss of the PEO coating adhesion. Closer examination of these thermal crazing (cracking) at 400°C IBT tests revealed that in fact the cracking was primarily associated with the cracking of the brake pad-introduced tribolayer rather than the PEO ceramic coating. However at discrete locations, micro cracks in the PEO coatings were also apparent with microscopic leap formation on a few areas where Al emanating from the underlying disc substrate was observed. This is believed to have been introduced by substrate softening, melt flow and thermo-mechanical transfer of the Al materials from the coating/substrate interface. Closer examination of the disc rubbing surfaces after the 300°C IBT tests for both solid and vented Al discs, though, did not reveal visible cracks in the coating or any potential substrate exposure via these cracks. Thermal crazing was once again noticeable albeit to lesser extent and these cracks networks were again were actually the cracks in the tribolayer introduced by repetitive thermo-mechanical loading as well as poor cohesive strength within the tribolayer. There were some areas, tribolayer has been detached and spalled off from the PEO coating as such is not unexpected. However, the vast majority of the tribolayer was effectively adhered to the underlying PEO layer with adhesion provided by microscopic porosity in the coating via mechanical keying.

SEM images in Fig. 7 show the top surface view of the rubbing surface. As discussed above, these images confirm that the 400°C IBT tests were probably too excessive for both the solid and the vented Al discs. Fig.7a confirming an extensive crack of the tribolayer followed by loss of the PEO coating's microscopic fragments at discrete locations and subsequently exposing the underlying substrate. Such immediate exposure was less pronounced globally on the vented Al disc surface even after 400°C IBT tests suggesting the effectiveness of convective cooling. However, reduced material thickness (strength) just above the drilled slot had shown to result in regular cracking patterns not due to the weakness in the coating but rather the weakness in the substrate compounded by large CTE mismatches between the PEO ceramic layer and the Al substrate alloy thus resulting in repetitive stresses in the coating interface.

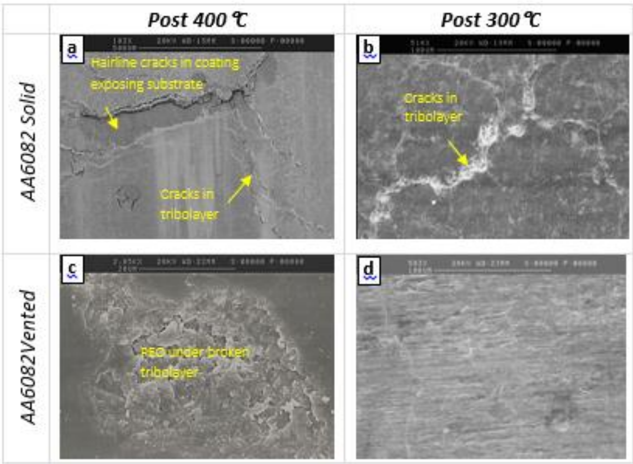

Figure 7 SEM micrographs of disc surfaces after the AK master test of 1800 stops.

Rubbing surfaces of the solid Al disc once again appears to show less of an issue in the PEO coating but cracks networks and expansion of these cracks of the tribolayer were clearly noticeable as discussed before with some occasional path leading to the substrate material. Moving onto the vented Al disc, the hairline cracks in the tribolayer appear to have left rather as grain boundary i.e. without crack propagation and the tribolayer appears to be more uniform and well covered on the rubbing faces.

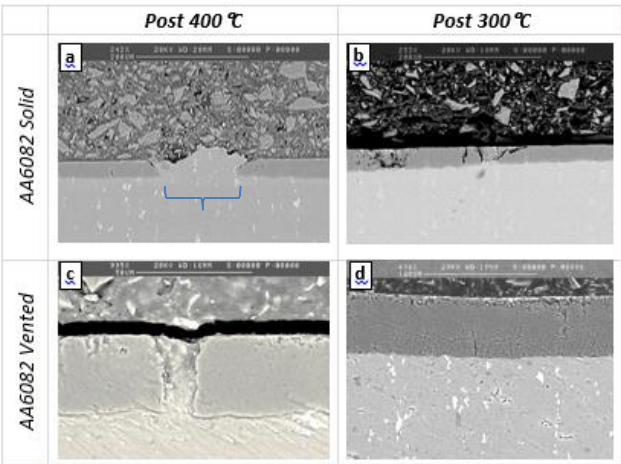

Figure 8 SEM micrographs of Al disc cross sections after the AK master test of 1800 stops.

Figure 8 shows SEM back-scattered images of the cross sections taken along these crack networks on the solids and equivalent regions on the vented Al discs. As mentioned above, some discrete locations, where the PEO coating had completely been lost and the substrate Al appears to be protruding outwards on both the solid and vented Al discs after the 400°C IBT tests. Post 300°C IBT tests, the issue was less discernible on the solid Al disc but micro cracks in the coating induced by thermal stresses are apparent. On the other hand, such micro cracks were not easily noticeable on the vented Al disc after the 300°C IBT tests. Also, the SEM images shows that the majority of the coating (80-85%) is still present after the 300°C IBT tests on the vented Al disc and also a uniform tribolayer was well adherent on the PEO coating surface.

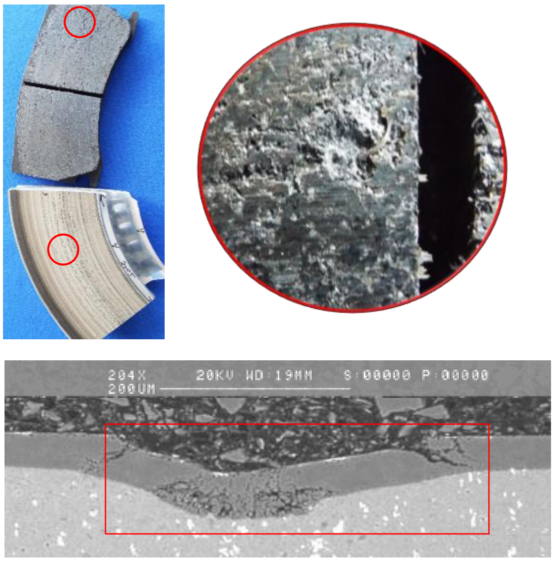

Figure 9 Micrographs vented Al disc after brake test at 300°C showing: a) gouging on the coated Al disc surface caused by hard steel wire on the brake pad; b) brake pad showing above hard steel wire used as a reinforcing material; c) BSE cross sectional image of the gouge showing the substrate plastically deformed together with the PEO coating and still maintaining strong coating adhesion.

A very interesting observation was noticed on the PEO coated Al discs, that the coating seems to possess an extremely high adhesion [8] to the substrate and likely very low stiffness as reported elsewhere [12]. And even on situations where the high local contact pressures e.g. by the pad material constituents such as hard steel wires had led to plastic deformation of the underlying substrate, the coating appears to have followed the substrate primary profile and still well adhering to the plastically deformed substrate layer as shown in Fig.9. Coatings, especially ceramic or cermet types would certainly spall-off during local plastic deformations and this is even more true if the CTE mismatch is very large during the thermo-mechanical loads over extended braking events. In this aspect, ability of the PEO coating on the Al disc to withstand severe thermo-mechanical loading and high tensile and compressive stresses is quite remarkable.

3.5 Corrosion characteristics

Surfaces of the Al discs (both solid and vented) before and after 68h of exposure to the salt fog test are presented in Fig.10. One thing is obvious that the test pieces after the corrosion tests show white corrosion product (usually known as 'white rust') on the surface indicative of the corrosion of the substrate Al disc.

This also confirms once again that micro-cracks are present creating micro paths for the salt solution to penetrate while tribolayer present on the surface usually protected by sacrificial actions of the corrosion of the Al substrate.

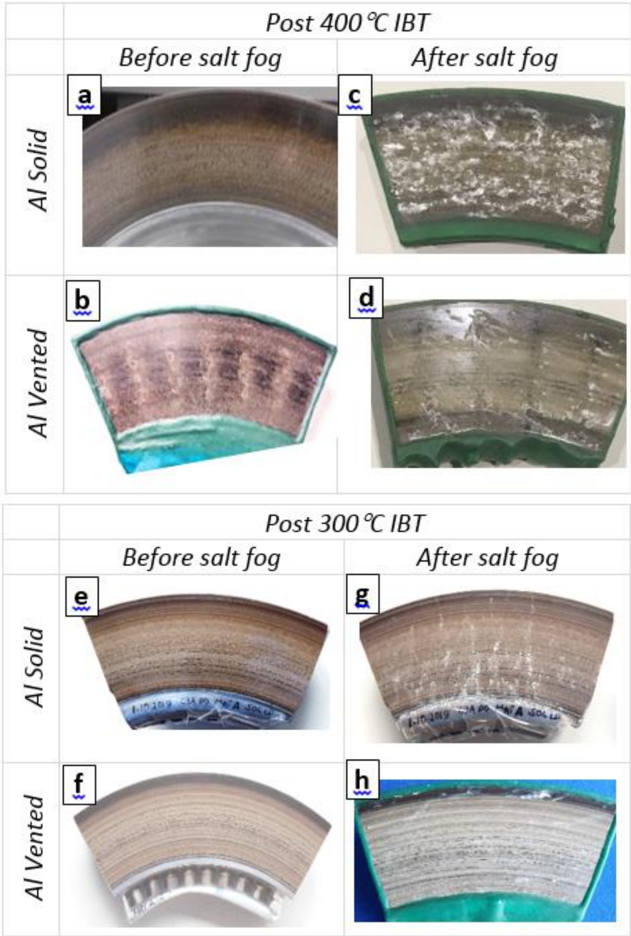

Figure 10 Photographs showing surfaces of the brake discs before corrosion testing test and after exposure to 68 hrs of salt fog corrosion. Vented disc shows only very little superficial corrosion

While these corrosion would be of concerns, one must note that Al corrosion products are usually highly voluminous and can sometimes be misleading than it actually is. Nevertheless, solid Al discs showed pronounced corrosion on the surface than the vented ones after both 400°C and 300°C IBT tests. Vented Al disc after the 400°C test (Fig.10d) shows significantly lower corrosion on surface compared to the solid one. While, vented Al disc after 300°C IBT tests shows very promising results with only a few corrosion spots that are relatively small (Fig.10h).

3.6 Degradation mechanism

The AK Master results at 300°C max are highly encouraging and gives us confidence to explore further the use of PEO ceramic coated Al alloy as a potential brake disc candidate for such an extreme severity application despite of challenges with materials strength, especially at higher temperatures of 400°C IBT that are less likely to be of concerns for EVs. Compelling performance in particular with respect to extreme high adhesion, high wear resistance and good heat dissipation have been confirmed. Key degradation mechanisms that have been observed include:

Stage 1 – The PEO porous top layer acts as a keying base for the brake pad material during initial bedding-in cycles and thus creates a composite tribolayer giving a stable CoF for most vehicle running conditions including up to 300°C max operational temperatures.

Stage 2 – Once the surface temperatures reaches relatively high typically 300°C IBT, micro-crack and crack-propagation in the coatings start due to high thermal loads. However, these are kept at microscopic levels and gross coating damages or losses have been minimized due to coating's resilience to thermal and mechanical stresses. Despite of cracks, coating undergoes minimal wear and these micro-cracks have been partially filled with the pad material and causes no gross concerns in subsequent corrosion resistance.

Stage 3 –Above 400°C IBT, the coating goes extensive thermo-mechanical stresses due to large CTE variations between the coating and the substrate thus leading to coating micro-detachment and subsequent filling of these regions by the pad material causing electrical contact with the substrate and forming galvanic corrosion cells. This is even more pronounced on vented disc due to insufficient material thickness at the vented slots.

Stage 4 – When stage 3 has been achieved, further accelerated deterioration is likely by initial galvanic corrosion, subsequent stress corrosion cracking of the substrate leading to premature failure of the system. High wear synergy (corrosion enhanced) will likely take place due to large cathode (pad material): small anode (exposed Al substrate) ratio.

While all the above leads us to require disc surface thermal management by conduction (maximise masking), convection (appropriate vent design and to give higher cheek thickness) and /or higher strength alloys with lower CTE may also be appropriate candidates to suppress the CTE difference. Moreover, further work is needed e.g. to identify a more suitable brake pad such as NAO pad with minimal metallic components (Fe, Cu etc.) that can accelerate galvanic corrosion.

4. Conclusions

The following conclusions can be drawn from this work:

- Both solid and vented Al discs behave similarly, although average friction was slightly higher for the vented disc.
- 300°C IBT tests suggest the PEO coated Al disc can be a suitable candidate in terms of acceptable CoF, minimal disc and pad wear and low disc run-out. 300°C dynamometer and subsequent corrosion tests showed very minimal or negligible corrosion of the brake disc.
- For use above 300°C, other approaches including smart braking, engine management, options including disc and pad materials selection need to be considered to enable the Al brake disc concept and will require further research.
- 400°C IBT testing appears too aggressive for the PEO coated Al brake discs in the current situation considering the large CTE mismatch and post braking corrosion tests.

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