

Engineered Surface Features for Brake Discs to Improve Performance in Fade Conditions

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ABSTRACT

Driving on the race track is an especially grueling situation for the automotive brake system. Temperatures can exceed the phase transition temperature of the disc material, wear rates of friction material can be orders of magnitude higher than during street use, and hydraulic pressures and mechanical stresses on components can approach their design limits. It is a given that friction material under these conditions will wear unevenly - causing taper and cupping wear - and an associated set of performance degradations will occur, including an increase in fluid consumption (pedal travel increase) and loss of mechanical efficiency (pedal force increase). Some high performance vehicles use surface features on brake discs, such as crossdrilling or slotting, to improve apparent friction levels in aggressive use (as well as to add marketing appeal), and generally accept a significant degradation in lining wear characteristics (both in overall wear rates and in the exacerbation of uneven wear behaviors) in order to achieve this. This paper proposes a method of using the elevated wear rates caused by brake disc surface features to partially correct the uneven wear characteristics inherent in the brake corner design. This in turn results in improved fade and fluid consumption characteristics during aggressive usage, even relative to a baseline disc without surface features.

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INTRODUCTION

The brake system of a high performance vehicle on a high speed race track is in constant competition with the powertrain, absorbing and dissipating a significant flow of energy from the vehicle's engine. Braking power peaks are measured in terms of thousands of horsepower and are driven by the vehicle's speed, mass, and traction limits. Bulk temperature of the brake discs will routinely enter a 600 to 900 deg C range, with surface temperatures considerably higher than this. Apparent friction levels even of a high performance (street-drivable) brake pad can fall below 0.20, versus a typical design range of 0.30 or higher. Hydraulic pressures - especially when pulling over 1.2g on the brakes alone, as some vehicles are capable of - can reach as high as the 15 to 20 MPa range.

Intuitively, these braking conditions cause considerable stress on the brake components and friction material. The high clamp loads generated within the caliper tend to 'open up' the caliper housing from around the disc, which promotes radial taper (uneven wear between the radially inboard versus outboard part of the pad, with higher wear typically on the

outboard region). High pressure applied by the caliper pistons against the inner pad (sliding caliper) or both inner and outer pads (opposed piston caliper) generates distortion of the pad backing plate and localized high pressure in the pad to disc interface under the piston(s), which in turn promotes concave, or "cupping" wear.

Many high performance brake applications use slotting and/or crossdrilling of the brake disc. There are a plethora of reasons, many of which remain controversial as to their merits. Recurring reasons include cosmetic (appearance), and improving high temperature friction levels. However, many implementations of crossdrilling and/or slotting can actually increase the stresses on the brake and reduce performance during race track service, due to acceleration of pad wear.

The present work describes a method of designing a brake disc surface feature pattern that uses one of the negative characteristics of slotting and drilling - that of increased pad wear - to compensate for one of the issues inherent in brake operation on the race track - that of uneven wear (taper, cupping, and doming). To develop this concept, information is organized in the following sections:

1. Review of brake corner performance during race track use
2. Review of the effects of slotting and drilling on performance and wear
3. Theory of Engineered Surface Feature Patterns
4. Case Study 1 - Sliding Caliper
5. Case Study 2 - Opposed Piston Caliper
6. Conclusions

1. Brake Corner Performance in Race Track Conditions

The brake operating temperatures reached in typical high speed race track usage will cause an appreciable amount of fade, or loss of friction - typically on the order of 20-30%. The mechanisms by which this loss of friction occurs are fundamental to the friction process itself, and have been described in numerous works previously (see references [1,2,3,4,5] for a selection, however, there are dozens of works describing this). Only a brief overview is afforded here. Succinctly, most track-capable friction materials operate by an abrasive friction mechanism, in which the clamp load on the pad drives the asperities from the hard, deeply embedded "structural" particles within the pad matrix (steel, iron, and ceramics) into the disc surface. The resultant plastic deformation and ploughing of the disc surface causes resistance to disc rotation. When cold (below 20 deg C) the lining matrix is stiff enough to prevent contact of relative 'low' points in the pad and disc surfaces; instead the higher points contact and can quickly "saturate" (reach a point of maximum frictional interaction, beyond which adding clamp load produces no additional friction force). This results in a lower coefficient of friction. As the brakes warm to an ideal operating temperature (approx. 200-400 deg C for performance pad materials), the lining matrix becomes more pliant and allows more conforming, higher quality contact between the pad and disc, and friction levels rise. However, further increase in temperature weakens and decomposes the friction surface of the pads and can weaken the disc materials as well. Lining structural particles, even deeply embedded ones, will start to tear out of the friction surface and fracture. Friction decreases. In most brake friction sets, a highly dynamic (temperature, speed, and pressure sensitive) tribofilm will form on the pad and disc surfaces, and can range from nearly nonexistent (tenths of a micron thick) and barely visible for performance brake pads at cold temperatures, to thick (tens of microns) and highly visible at high temperatures. This friction film has significant effects on friction and wear properties of both the pads and the disc.

The sustained high temperature use of the brake system on the race track also promotes highly accelerated wear of the brake pads, and dramatic shifts in the pressure distribution occur due to distortion of the caliper, knuckle, and pads themselves under the intense braking torque and clamp loads.

This in turn leads to uneven wear of the brake pads (taper wear in the radial and tangential directions, as well as cupping wear under pistons and doming wear under caliper fingers). The shifts in pressure distribution tend to move the centers of pressure in the caliper to regions of the friction interface where the caliper is less stiff in the low pressure range [6]. The loss of stiffness during the initial engagement of the brake, coupled with significant increases in brake pad compressibility due to temperature and uneven wear, leads to significant increase in fluid volume needed to pressurize the caliper. The fact that higher pressure is needed to compensate for fade, and the increase in fluid consumption, lead directly to an increase in brake pedal travel. This increase in some cases can be 50 to 100% higher than when the session began (and in the most extreme cases can cause the master cylinder to reach the limit of its stroke).

Performance of a brake corner in race track conditions is typically characterized in terms of an apparent friction level (relating clamp load and an assumed constant effective radius to brake torque), and fluid consumption. These parameters relate directly to brake pedal force and travel at a brake system level. Most test protocols for evaluating a brake corner in these conditions will subject the brake to a sequence of high speed, high deceleration braking events, and allow the brake disc temperature to rise into and remain in the range typical of race track driving. Additional metrics that are helpful to characterize brake corner performance in race track conditions include lining wear (overall wear, taper wear, and wear versus temperature), and brake torque variation (which can sometimes be realized at a vehicle level as objectionable vibration of the brake pedal, steering wheel, and/or vehicle body).

As an example, [figures 1, 2, 3](#) below show the performance characteristics (Apparent Friction, Apparent Piston Travel, and Post-Test Taper Wear) of an aluminum 4-piston opposed caliper, 18" wheel envelope brake disc, and OEM-spec high performance friction material after an inertia-dynamometer based fade test. The test subjects the brake corner to two fade sections; the first with 10 stops from 100 mph repeated every 10 seconds, and the second (after complete cooling and performance checks) with 20 stops from 100 mph repeated every 10 seconds.

In this example, a 'green fade' phenomenon is observed in the 1st fade section (evidenced by the sharp drop in friction, from 0.35 down to 0.18 in the 1st 5 stops, followed by equally sharp recover up to 0.29). As an aside, the green fade mechanism is not well researched, but can likely be explained by a confluence of factors, including poor pad/disc contact pattern, and a relatively weak green lining matrix (possibly not fully cured) that is subsequently strengthened by thermal conditioning and build-up of a reinforcing tribolayer on the pad and disc friction surfaces. Some researches claim that an "outgassing" phenomenon is at work; however, measurements targeted specifically at measuring outgassing have shown that this is not the case

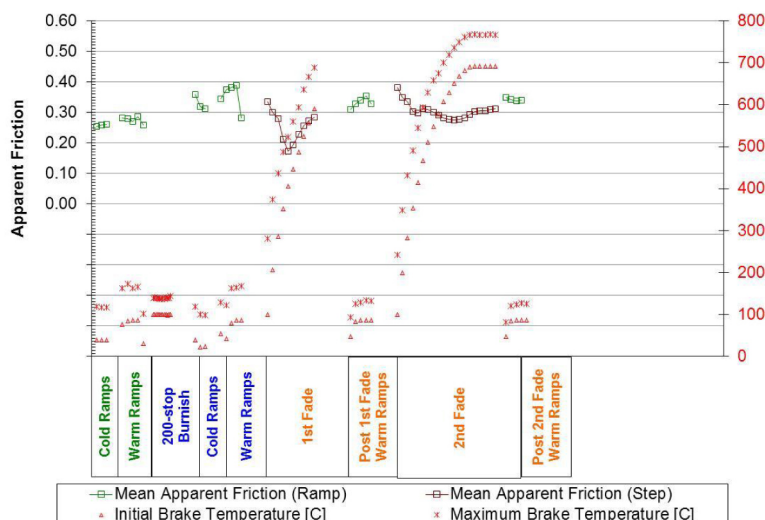


Figure 1. Aluminum 4-piston caliper, OEM performance pads, 18" wheel envelope disc - Apparent Friction during Inertia-Dynamometer Based Fade Test

(from non-externally published report). Friction was more stable in the second fade, decreasing from 0.38 down to a steady value around 0.30 around 500 deg C and seeing a low of about 0.28 around 680 deg C.

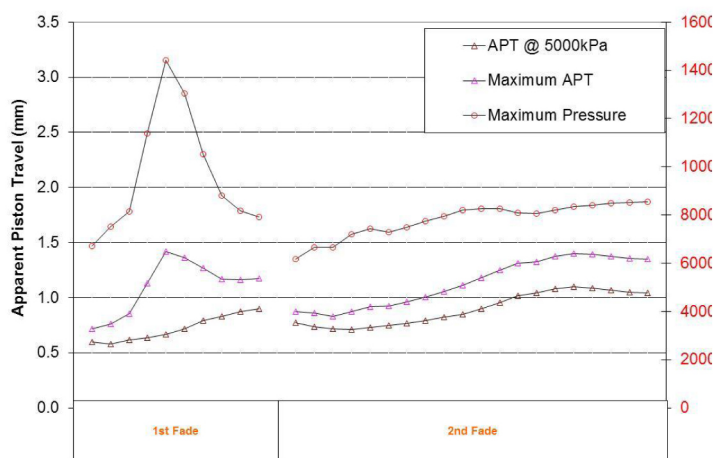


Figure 2. Aluminum 4-piston caliper, OEM performance pads, 18" wheel envelope disc - Apparent Piston Travel during Inertia-Dynamometer Based Fade Test

Fluid consumption, as measured with “apparent piston travel” (the ratio of fluid required to pressurize the brake caliper over the area of the pistons on one side of the caliper) increases from about 0.7mm @ 5000 kPa to a near end of test peak close to 1.4mm - almost double the initial value. Peak APT (which includes the effect of fade and higher pressure needed to achieve the 1.0g deceleration target) increases from just under 1.5mm to around 1.8mm, or a 20% increase.

The post-test lining wear data were measured via an 8-point measurement, tracking the change in lining thickness from the face to pre-drilled micrometer locator indentations in the pad backing plate. Four measurements were taken

approximately 10mm inboard of each of the radial inner and outer edges of the backing plate. The measurements on the inboard pad confirm a measureable amount of “cupping” wear (on the order of 100 microns), which is visible in the bowed shape of the wear profile with higher wear in the center of the pad where the piston force was centered. The outer pad showed radial taper wear, with higher wear towards the outer diameter of the pad. The wear imbalance was on the order of 0.5mm.

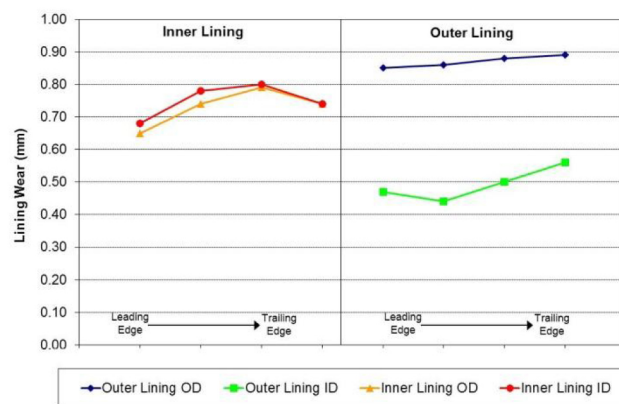


Figure 3. Aluminum 4-piston caliper, OEM performance pads, 18" wheel envelope disc - Lining Wear after Inertia-Dynamometer Based Fade Test

From this example, it can be seen that even on a performance-oriented caliper and brake corner, there are significant degradations in performance in race-track conditions and therefore room for improvement. The significant wear imbalances present in the inner and outer pads are what an “engineered” slot pattern, which is the subject of this paper, will attempt to affect. The type of testing shown in this example will be used in subsequent case

studies to show how fluid consumption and friction levels can be improved with a purposefully-designed slot pattern.

Before this subject is introduced, a short review of the general effects of slotting and crossdrilling is offered.

2. Effect of Brake Disc Surface Features on Brake Corner Performance

Previous research published involving controlled comparisons between crossdrilled (or in some cases slotted) discs and their plain-faced counterparts indicated some general trends held up over comparisons between multiple different brake disc geometries, friction materials, and caliper designs [7]. These general trends included:

- Decrease of apparent friction at low temperatures (approximately 100-200 deg C) with respect to plain-faced discs. This is due to the frictional contact between the pad and rotor being generally more concentrated, due in turn to a reduction in friction interface area and a higher degree of wear non-uniformity. The concentrated contact results in a higher percentage of the frictional interaction becoming 'saturated' (when the normal force applied is sufficient to force the maximum micromechanical interaction of the pad and rotor for the contact condition present), and also reduces the effect of area-sensitive adhesive phenomena.
- Increase in apparent friction at high temperatures (approximately 400-600 deg C) with respect to plain-faced discs. This is due to the hot pad material becoming more compressible and extruding into the slots or drilled features of the rotor. This adds a direct shear interaction between the subsurface pad material and the slot or drill hole edges.
- Increase in pad wear rate, sometimes as high as 30%. This is due to the edges of the rotor surface features damaging and preventing buildup of a robust, protective tribofilm on the pad surface, and due to the direct impacts and subsequent fracture of structural particles at the lining matrix against the rotor surface feature edges. The increase in wear rate is generally observable throughout the operating temperature range.

It has also been shown that crossdrilling in particular can increase high-speed rotor cooling, due to increased airflow. Due to the strong evidence of the effect being related to airflow (and not so much the surface area increase), the cooling benefit is likely limited to crossdrilling only and not slotting.

It is the accelerated wear of the brake pad when used with crossdrilling or slotting that forms the basis for developing patterns to correct wear imbalance issues. This concept is developed in the next section.

3. Theory behind "Engineered" Patterns

There are two key brake lining wear imbalance issues that can be targeted with an engineered surfaced feature pattern. Radial taper wear, the tendency for the pad to wear faster towards the outer edge of the pad, and cupping wear, the tendency for the pad to wear faster directly under the caliper

pistons can both be reduced. As the method for developing the surface feature pattern differs for these two wear imbalance mechanisms, they are addressed in separate subsections:

Radial taper wear correction

As shown in section 1, brake corners subjected to sustained race track use will suffer fade, an increase in fluid consumption, and will develop significant taper and cupping (or doming) wear. The uneven wear is partly responsible for the increased fluid consumption and fade. Section 2 established that adding disc surface indentations such as slotting or drilling will greatly increase the pad wear rates at high temperatures. The basic concept of an "engineered" disc surface feature pattern is that the elevated wear rates caused by the surface features are used to counter-balance the uneven wear patterns that develop with high performance use.

Intuitively, a pattern would therefore be designed to maximize the density of the surface features in the region of the friction surface where pad wear tends to be minimal - e.g. towards the radial inner edge of the outboard disc surface, or towards the radial inner and outer edges of an inboard disc surface (with less density in the center region).

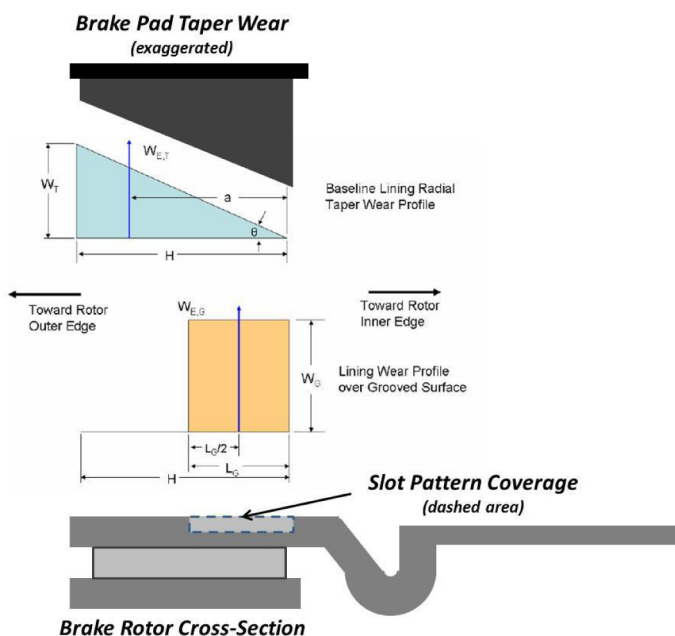


Figure 4. Illustration of "Moments of Wear" due to Effects causing Radial Taper Wear and due to Slot Pattern

The top (blue shaded) graphic in figure 4 illustrates a simplified radial taper wear pattern. W_T represents the wear imbalance (usually with higher wear towards the disc outer diameter). The dimension 'a' represents the center of wear (the wear volume is equal on both sides of this dimension). The dimension 'H' references the radial height of the swept area of the disc. The light orange shaded graphic represents