Optimising carbon-ceramic brake disc design for same-size replacement of cast iron discs

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Image 1 – Carbon-Ceramic (CSiC) Brake Disc Assembly

Introduction

Due to its reduced weight (typically 50%) and increased durability, carbon-reinforced silicon carbide (CSiC) ceramic composite offers a best-in-class alternative to traditional iron or cast iron brakes. However, the application of CSiC brake discs has remained the preserve of the mainstream high-performance OEM market, primarily due to the high unit cost but also due to the re-engineering normally associated with employing CSiC brakes. This is because ceramic composite brake discs generally need to be of a larger diameter to provide comparable performance to a cast iron brake system. This requires significant re-engineering of the brake components, wheels and related areas to accommodate the larger brake disc. This has limited the adoption of CSiC brakes for small volume or niche applications as these engineering costs, combined with the high tooling costs for any new design, make the technology unattractive.

Scope

This project aimed to simplify the re-engineering process in moving from cast iron to CSiC discs by replacing the cast iron brake discs with CSiC brake discs of the same dimensions. To account for differences in specific heat capacity and density a larger CSiC disc is generally required to replace a steel disc to achieve a similar thermal mass and hence similar performance. The material properties of the continuous fibre construction allow a disc of the same dimensions to have comparable thermal performance, providing the potential to replace a cast iron disc on a like-for-like basis. The project therefore focused on CSiC brake discs made with continuous fibre construction.

The project was part-funded by the Niche Vehicle Network and was undertaken in conjunction with Briggs Automotive Company (BAC) Ltd. The project aimed to improve the standard braking system on their supercar, the BAC Mono.

Image 2 – The BAC Mono Supercar

The target was to maintain the existing hub, caliper and other brake components, to keep costs down and minimise re-engineering. A secondary aim was to reduce the weight of the brake disc even further and investigating the impact on performance of increased diameter cooling vents.

Chopped Fibre vs. Continuous Fibre

Chopped-Fibre is the standard material used in the construction of the CSiC discs found on many high performance vehicles, such as Ferrari, Porsche and Aston Martin. This material consists of carbon-fibre cut into short strands and mixed with a resin. Continuous fibre material is made from layers of Poly-Acrylic Nitrile (PAN) cloth, a carbon-fibre pre-cursor, that are laid over each other (typically in a 0°/90° layup) and needled together to produce a matrix structure. The final product generated by each process are similar, however the Continuous Fibre material benefits from higher strength and significantly higher thermal conductivity. The thermal conductivity of ST's high conductivity material is typically 3 times that of the chopped fibre material. The manufacturing process of continuous fibre discs is also more suited to small volume or niche vehicle applications as the parts are machined as opposed to Chopped Fibre discs that are moulded. This results in minimal tooling costs and greater flexibility in production.

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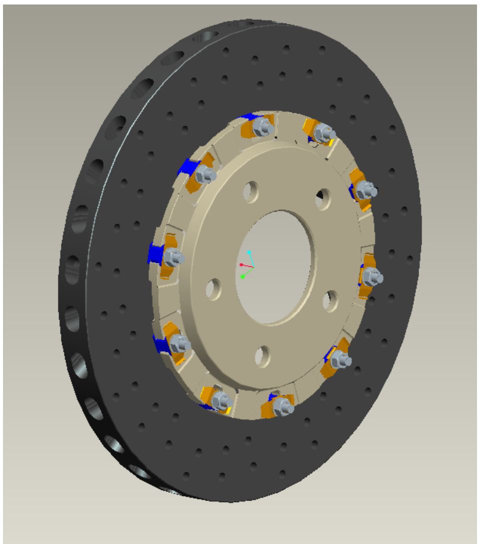


Image 3 – CAD render of the BAC Mono CSiC Brake Disc Assembly

As the project aim was to replace an existing cast iron disc with a CSiC disc, the basic dimensions; outer diameter, inner diameter and thickness were defined by the original disc. However the design of the cooling vents was not fixed and as such it was decided to produce two different designs, the first with 8mm radial cooling vents and a second with larger 12mm vents. Table 1 shows a comparison of the key dimensions between the different designs.

	Outer Ø (mm)	Width (mm)	Inner Ø (mm)	Radial Vent Ø (mm)	Disc Mass (kg)
Cast Iron Disc	295	24	160	10.9	4.4
CSiC Disc (8mm vent)	295	24	160	8.0	1.9
CSiC Disc (12mm vent)	295	24	160	12.0	1.7

Table 1 – Comparison of key dimensions and weight

Both CSiC discs were manufactured by Surface Transforms at their UK plant using continuous fibre material and assembled with aluminium bells using a fully-floating fixing system of ST's own design.

Disc Mass Verification

Surface Transforms has developed a brake disc sizing tool through dynamometer and vehicle testing which is used to verify the mass of ceramic brake discs for specific applications. The principle of the calculation is based on the temperature rise due to transferring the kinetic energy of a vehicle into thermal energy in the disc using its heat capacity. There are two aspects to the thermal calculation;

1. A single stop from the vehicle maximum velocity. This takes no account of any cooling effects or heat loss in the system.

2. A set of multiple stops from maximum velocity with no cool-down time between stops. This makes some assumptions about heat loss in the system, determined using dynamometer test results which remain conservative.

Each disc design was assessed using this technique to verify that it has sufficient thermal mass for the application without exceeding a recommended maximum operating temperature of 650°C.
The predicted temperatures can be found in Table 2.

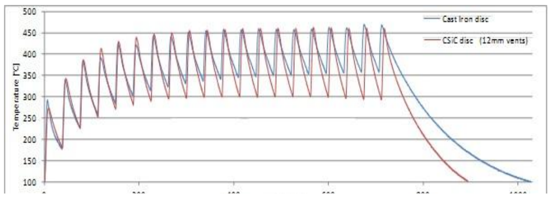
	Single Stop (°C)		Multiple Stops (°C)	
	Front Axle	Rear Axle	Front Axle	Rear Axle
CSiC Disc (8mm vent)	320	172	455	245
CSiC Disc (12mm vent)	350	188	496	267

Table 2 – Predicted brake temperatures

The maximum temperature limit calculated using this tool is 500°C to allow for a margin of safety below the 650°C material limit. The above figures showed that the discs were sized correctly for the application. It is important to state that these calculations do not take into account the cooling vent design.

Disc Strength Verification

A structural analysis was performed on the bell and the disc to confirm that the assembly design was strong enough to safely handle the expected operating loads.
The force experienced by each mounting bolt hole of the disc when stopping from maximum velocity was calculated. This load was then used in a FEA simulation.



Graph 1 – Fade test comparison between cast iron and carbon-ceramic brake discs

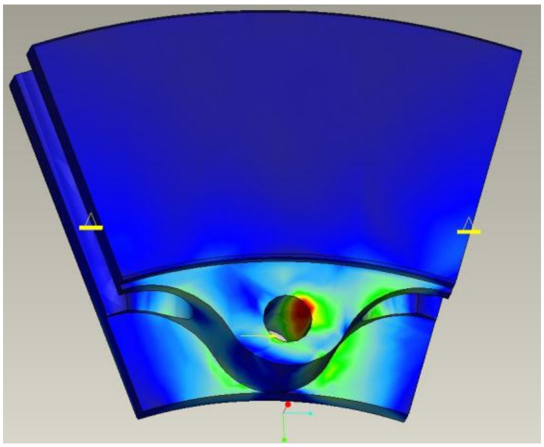


Image 4 – FEA simulation of the brake disc design

The strength of the bell was then investigated using the same process.

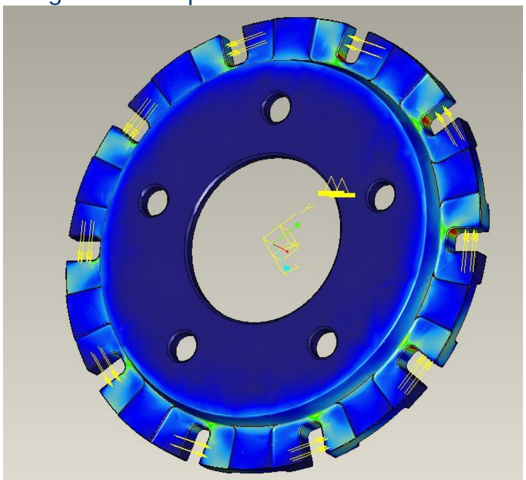


Image 5 – FEA simulation of the bell design

The predicted stresses in both components were demonstrated to be well below the yield strength of the material.

Dynamometer Testing

A comparison of the relative brake performance between the cast iron disc, CSiC disc with 8mm radial cooling vents and CSiC disc with 12mm radial cooling vents was performed on ST's brake dynamometer based at Birmingham City University. The following braking attributes were tested after an initial bedding-in procedure had been performed:

1. Fade
2. Pressure sensitivity
3. High velocity performance

Typical AK master fade tests resulted in similar peak temperature between all three discs, ranging from 463°C to 470°C. Both CSiC discs reached significantly lower temperatures between braking operations than the cast iron disc, demonstrating improved cooling performance. This improvement was most significant with the CSiC disc with 12mm radial cooling vents (see Graph 1).

During pressure sensitivity testing all discs behaved in a similar manor, showing minor variations in coefficient of friction values at various brake line pressures. The cast iron disc had a noticeably greater noise and vibration at low pressures. Comparable to the fade test, all discs achieve a similar peak temperature but the ceramic discs dropped to lower temperatures between stops.

In the high speed stops it is possible to see once again that the ceramic brake discs cool down faster between stops to reach a lower temperature.

Conclusion

Dynamometer testing demonstrated that a CSiC brake disc with continuous fibre construction can achieve the same thermal performance as a cast iron disc allowing for a like-for-like replacement whilst achieving a weight reduction in excess of 50%.
Testing also demonstrated that careful cooling vent design can allow for a reduction in mass without compromising the thermal performance of the CSiC disc. A potential reduction in mass of CSiC brake discs used for other applications can also be explored with far greater confidence as a result of this testing.
It is envisaged that the results of this project, along with additional testing, can be used to develop a revised brake disc sizing tool which also accounts for cooling vent design and can therefore support the production of CSiC discs with further increased efficiency.

Image 6 – BAC Mono CSiC continuous fibre brake disc, weighing just 1.7kg

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