

The impact of product recalls on businesses and projects

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4 Introduction

Considering the manufacture, life, and usage of a brake disc, this paper will aim to quantify the issue that's they succumb to in terms of mechanical, chemical, and thermal quantities, seeing how the individual factors are related and correlate to each other and the discs properties.

Brake discs have already a set amount of materials they can be made from, this is governed by the cost, lifespan and metallurgical stability, the materials are usually limited within automotive applications to steel alloys, aluminium alloys, or carbon/ceramic composites (Maluf, et al., 2004).

An obvious example of this is cast iron brake discs, being resistant to wear, having an appropriate coefficient of friction, and not being susceptible to cracking or warp under normal operating circumstances. At the other end of the spectrum is a titanium disc, having been heat treated to effect the crystalline structure and reduces the grain size of the material to better improve its high end braking capabilities, but the drawback to having fantastic wear resistance and thermal properties is a high cost (Takahashi, et al., 2000).

4.1 Material Selection

4.1.1 historical design factor(s),

As vehicles increase their terminal velocity from 10Km/h (Maluf, et al., 2004), the necessity for better materials was started, the first example of a calliper/brake disc system was the utilisation of copper discs in the early 1900s, copper being used to do its ease of machinability, abundance and seemingly good thermal capabilities compared to vehicles of the time (Maluf, et al., 2004).

This progressed onto disc brakes being utilised on race vehicles, immediately highlighting the benefits of them over drum brakes, especially so in events such as the 1953 24hr of Lemans and Mille Miglia the Jaguar C-type securing a competitive finish, the first ever car to finish both with disc brake (Maluf, et al., 2004), with the discs having reduced fade, better range of braking and suffering from warp and irregularities. Up to this point brake drums utilised materials such as asbestos to control the temperature of the pads by utilising its excellent wear characteristics, as well as being complimented by using copper particles and bituminous coal as to reduce the heat generated (appendix 1), but as time progressed and vehicle performance increased, better materials were needed (Maluf, et al., 2004).

To reduce the need for dangerous pad materials such as asbestos, the aim on optimising the homogeneity and quality of materials of the disc were considered, this in turn would allow the disc size and thus mass to be reduced, as well as characteristics such as increased life and use. This was a large consideration while swapping from drum brakes to disc brakes, as metallurgy become a wider phenomenon so optimised disc characteristics from modifying the chemical makeup was cheaper and more available to manufacturers. A consideration for the historical design highlights how the design has changed with the time, drum brakes can generate a tremendous amount of braking effort due to a higher friction radius, but in turn suffer from cooling over prolonger braking periods due to lack of ventilation, and while on HGV and large vehicle drums brakes suit the moderate braking force over a large area style, passenger cars needing a high braking force over a smaller distance has very much so effected the need for better disc materials and properties, spurring the change from drums to discs as a safety feature (Imasaki & Okamura, 2007).

4.1.2 Processing and manufacturing

Brake discs require incredibly stringent quality control and assurance methods due to the nature of their use, this is why ECE R90 has been introduced to better govern the quality of the discs, it governs a basic standard of the discs dictating variation in thickness, runoff and surface friction roughness (United Nations, 2017) (appendix 7). This of particular importance for looking at material properties as a low surface roughness could dictate a low manufacturing tolerance, or a specialised surface to increase run in braking performance.

All Brake discs are cast and machined, the casting process is an intrinsic factor in creating the discs specific characteristics, as stated by Okamura et al. a multitude of issues with the casting process can generate disc thickness variation and thus potential causes of premature failure (app. 3), within the manufacturing stages cooling the discs appropriately can have a huge impact on the material properties, Okamura et.al corroborate this stating that disc wear directly correlates to the cooling process, as the rate of cooling directly effects the graphite structure of the material, evident in the quenching and work hardening of other components to improve mechanical properties. Within MMC (metal matrix composite) disc manufacture the methods stay largely the same as casting is a time tested, and cheap method of manufacturing simple geometry parts, a stir casting method is used alternatively due to the necessity to agitate and mix the matrix and liquid metal this method (Ranganathan, et al., 2020).

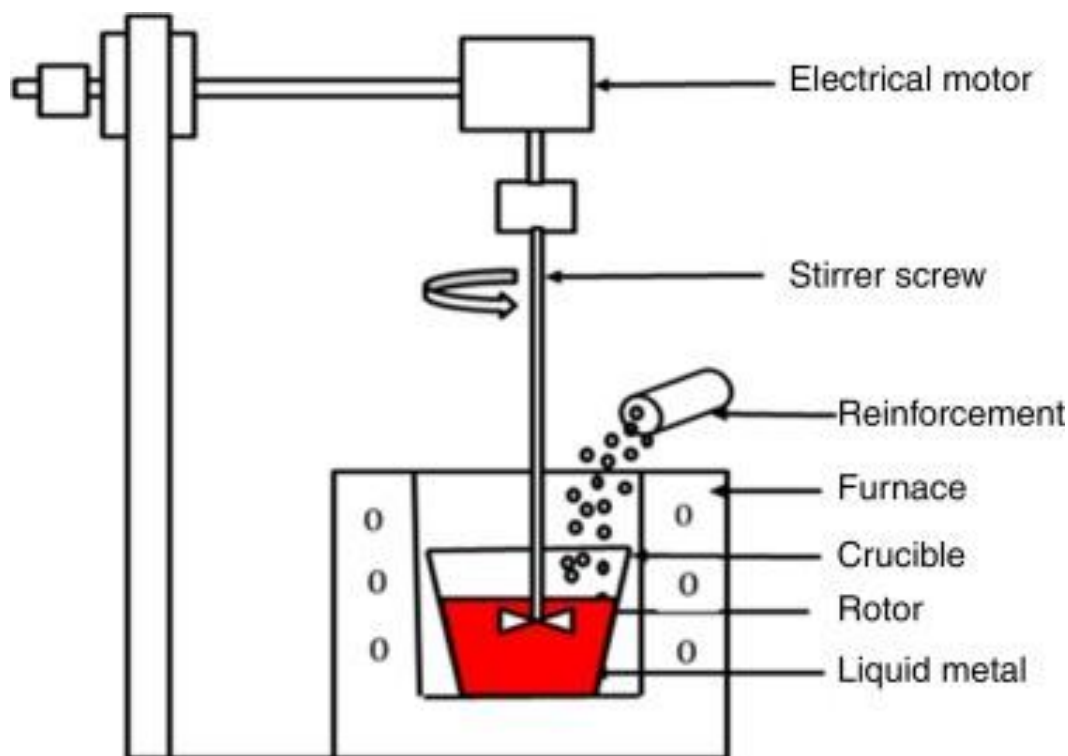


Figure 1 - Stir cast method of manufacturing used in MMC production (Thandalam, et al., 2015)

As rough casting will never be 100% accurate machining will be needed to take the disc within the manufacturers and ECE tolerances, some discs come from factory with spiral patterns caused by this machining tasks, these spiral patterns have the chance to increase crack propagation, cause uneven wear and premature pad (Rodriguez, et al., 2014). This is more

prevalent in ferritic brake discs as casting often leaves with an average roughness (R_a) of less than $1\mu\text{m}$ (Rodriguez, et al., 2014). Rodriguez et al. consider a variety of approaches for refining the surface to a ground-like finish, but utilise brushes as a finishing tool due to their relative inexpensiveness and are a versatile method of polishing and machining to the standards of other machines. Comparative to this is the use of electro discharge machining, the benefit of using it stems from its effect on the graphite structure which Rodriguez et al did not consider, as short pulse duration machining generate less heat, this fails to work harden or generate a case hardened exterior on the disc, the method involves the use of a rotating wheel and a pulsing current eroding the component, the drawback of this being a reported surface roughness of around $8\text{--}8.7\mu\text{m}$ (Ram & Varma, 2018).

The use of grey cast iron in brake discs is largely because of its composition, being easy to cast, source and modify to the necessary properties it shows itself as the sensible material for discs, this is largely due to the materials content. With a content of anywhere from 3.5–3.7%wt carbon (Holme, 1997) it is neither hypo, nor hyper-eutectic if the cooling is controlled enough, a completely ferritic matrix is obtained when the material is cooling still in the eutectoid temperature zone.

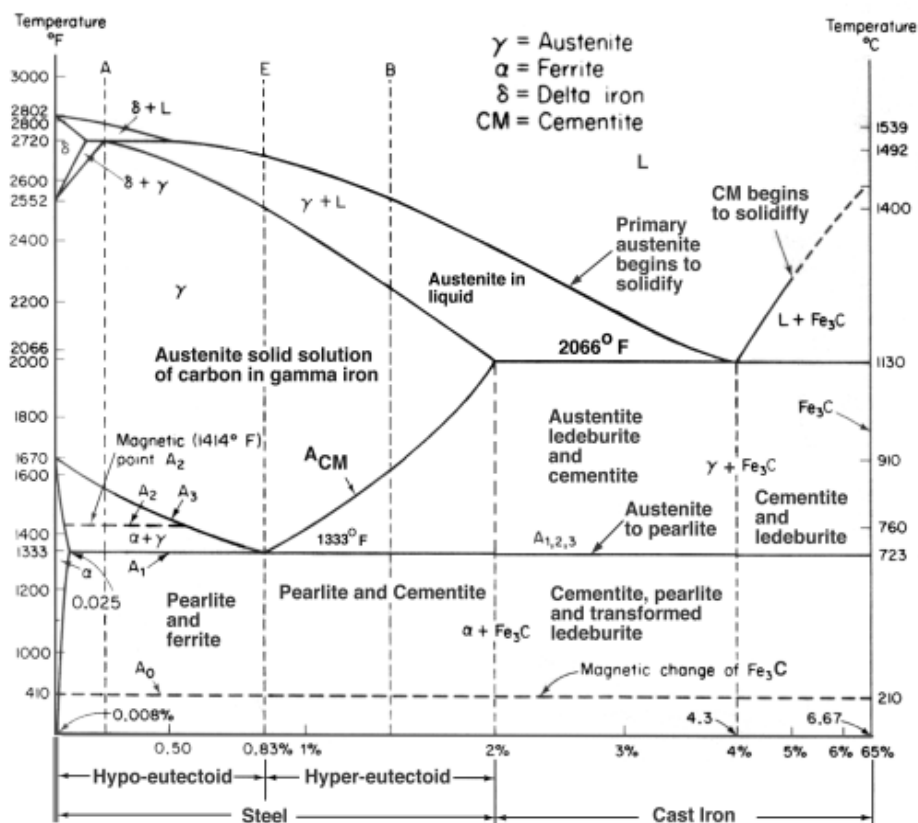


Figure 2 - Cast Iron Equilibrium diagram (Yescas-Gonzalez & Bhadeshia, 2001)

This leads to the use of silicon to modify the graphite structure. As cast iron cools, to properly promote crystal growth inoculants are used to effect the nucleation of graphite and also reduce the temperature hysteresis between austenite and pearlite formation (Mohrbacher & Zhai, 2011). This line of thought is furthered by Mohrbacher et al. in which they stat that adding a 2%wt of Niobium as an inoculant generates a harder and more wear resistant material, it does

this by generating a smaller pearlite-lamellar spacing, the drawback to this being that the discs have a lower machinability causing higher tooler wear.

Comparing this to a composite manufacturing method shows the similarities in processing to cast iron to obtain similar material faculties, with the main goal being to reduce grain size and in turn reduce the probability of cracks propagating due to their non-uniformity (Karunakar & Tamta, 2014), both material utilise this through the use of Silicon addition as an inoculant. Klement et al. further develop this to understand that it reduces creep, by compressing the material in the sintering phase it generates a stronger bond between the particle/bond matrix by achieving a strong internal residual stress, this exacerbated by the differing thermal expansion coefficients of the two materials (Klement, et al., 2018), with the tests having to be in excess of 1350°C to induce any creep, with the generation of a short zone of primary creep, followed by a larger stint of steady-state creep (figure 3).

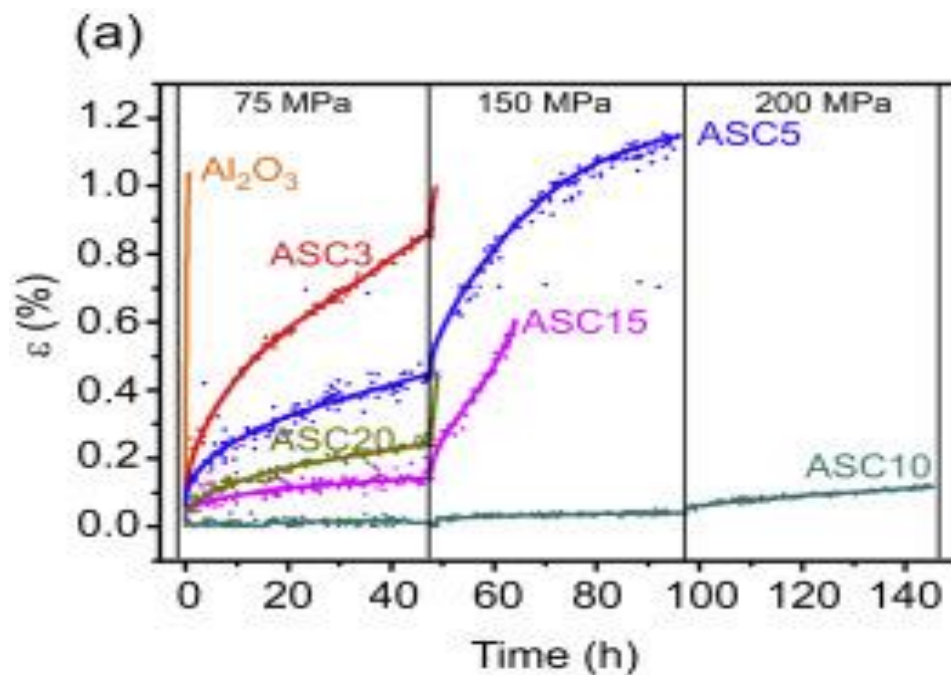


Figure 3 - Example of the low creep before failure values of MMC materials (orange) (Klement, et al., 2018)

4.2 Material Testing Methods

Within brakes the main point of failure is microcracks, these emanate mostly from the aforementioned thermal fatigue and creep, for research and development of discs the analysis of the crack propagation is measured using a combination of Non-Destructive Testing (NDT) and destructive testing.

4.2.1 Destructive testing

Utilising Tribological testing allows multiple routes to be tested at once, the benefit of the test is that it gives quantifiable data in terms of the disc performance, showing temperature changes, friction drop off, material used and friction coefficient, when utilised by Lyu et al they described initially the wear rate for each disc to be;

$$k = \frac{\Delta m}{\rho * \Delta s * F_N}$$

Where Δm is the change in mass, Δs the distance, and F_N the normal force applied to the disc, as immediately visible the calculation states the material lost but no other overbearing factors of why, Lyu et al discuss this in stating that for further estimation a pad-on-disc tribometer was used, utilising a thermocouple to take average disc temperature accordingly, the issue with this is having no correlation of wear effect at a specific point, weight loss is correlated with travel of the pad as they are assumed to be related, but as previously mentioned cast iron has well matched criterion of thermal properties such as resistance to thermal expansion of $5.8(10^{-6} \text{m}/(\text{m}/\text{c}^\circ))$ compared to aluminium's $11.2(*10^{-6} \text{m}/(\text{m}/\text{c}^\circ))$, meaning that within testing this thermal expansion would have to be accounted for, as well as the temperature at which the disc glazes and no longer is able to offer optimum coefficient of friction and thus wear characteristics.

Comparative to better understand the thermal properties and crack propagation with brake discs a friction test that was undertaken by Sawczuk et al. was analysed, this test utilised the equation;

$$\mu_a = \frac{F_t}{F_b}$$

With the momentary coefficient of friction being equal to tangential force relative to the discs radius, over the total temporary pressure applied to the brake disc, as the test also measures temperature the drop off of friction can be coincided with temperature, giving the glazing temperature of the disc.

As stated by Sawczuk et al. for modelling the thermal properties of the material the friction test allows the component to be cyclically loaded with pressure and temperature, allowing the fatigue and expansion to be accurately measured, the inherent drawback is that with no method of testing factors such as runoff with the test active, as especially in cast iron discs warping is a large issue (EBC Brakes, 2013), further correlations cannot be made only estimations.

4.2.2 Non-destructive testing

Furthering the work of Sawczuk, to better understand the cracks, a RMG 4015 crack depth probe was used, the benefit of using this system opposed to a conventional ultrasonic testing method is that the results completely rely on the materials permeability, and obviously not having to account for impedance, beam spread, and wavelength. The lack of data on ultrasonic testing cast iron components mostly lies in the necessity of preparation in NDT, to increase the probability of detection of flaws the surface has to be clean and absent of detritus, with the issue of surface roughness and unevenness skewing the reading being reduced through appropriate probe frequency (Guo, et al., 2006), but in terms of couplant the viscosity of the couplant has to be incredibly high to properly penetrate the flaws, as leaving an air gap in the crack would give the flaw an unrealistic size, especially when utilising A scan with an angled probe to better present the flaws depth opposed to its length (Society of Automotive Engineers, 2018).

Further examples utilised in this test were the use of dye penetrants, as a visual aid they allow the depth, width and spread of cracks in a component, but the limitation being that they offer no objective value apart from an estimate or indicator, as well as often needed a smooth surface to be used as a rough or porous surface will capture penetrant and give false indications, the smoothing often comes in the form of machining, which in itself can cover, reduce the depth or modify the flaw (International Atomic Energy Agency, 2000)/

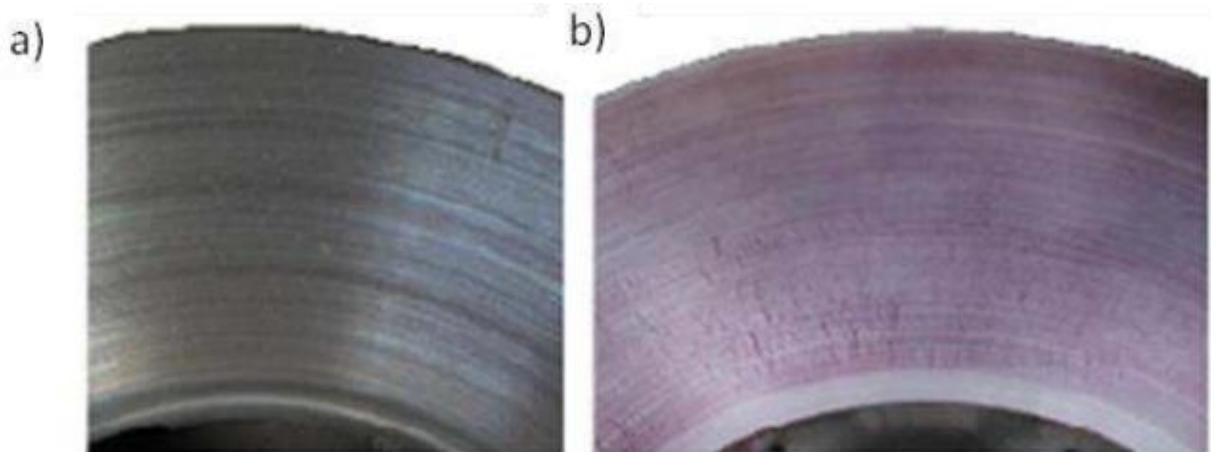


Figure 4 - Dye penetrant example on cast iron brake discs (Sawczuk, 2018)

4.3 Analysis and Consideration of Materials Properties

4.3.1 Manufacturing stage

The manufacturing stage largely emphasizes the important of the grain structure and size of materials, this is due to the wear and friction characteristics that they can generate. The quality of the casting process is a large factor within this, Maluf et al define the content of a variety of irons used by GM (appendix 5) alongside the statement that “*gray cast iron alloys, depending on the chemical composition and cooling speed, present microstructures with the carbon shaped as graphite flakes over matrices that can be ferritic, ferritic-pearlitic, and pearlitic*”, although this was a pre-discussed the point it further backs up what was mentioned as well as backing up the further statement by Okamura et al., who defines that within brake disc manufacture an improper gating method modifies this graphite cooling, making the material no longer homogenous in terms of hardness and strength.

4.3.2 Thermal

The main consideration with any well used brake disc is the cracks, to quantify their effects on the brakes performance a test ran on MMC discs and cast iron discs individually, initially the an aluminium ceramic composite disc had the coefficient of friction of 0.52μ , compared to a cast iron disc of 0.5μ (Lyu, et al., 2018), the use of mmc to better control brake temperatures and performance are furthered by the three discs operated at an intensely low temperature, this is less likely due to the low pressure applied on the tribology probe, and more likely due to the 120 minutes continuous braking, this would corroborate the higher pressure having a lower coefficient of friction, as at this pressure and showing the test end temp, the discs very likely would've glazed (EBC Brakes, 2013).



Figure 5 - Cracks in a brake disc caused by thermal stress and fatigue (Lakkam, 2013)

Table 1 - Lyu et al test results table (Lyu, et al., 2018)

Test	Cast iron	Aluminium – 0.5MPa	Aluminium – 0.6MPa	Aluminium – 0.9MPa	Aluminium – 0.5MPa (reused)
μ	0.5	0.54	0.55	0.49	0.53
T_{end}	-	164	186	245	131

A side effect of many thermal issues, including the aforementioned prolonger braking durations is the disc cracking, Lakkam state that the cracks propagate due to thermal fatigue, propagating from cyclic thermal load and thermal expansion while under a compression load, considering the test comparison to Lyu et al, discs temperatures of up to 380°C were see with a comparative coefficient of friction of 0.4 μ . Xin develops on this to state that the thermal fatigue lifespan is determined by the materials ductility, opposed to the strength, he also considers both isothermal and anisothermal fatigue, a brake disc encounters isothermal fatigue when a compression cycle is imposed on the material at a constant temperature, while anisothermal is imposed when component temperature and strain vary wildly, displaying a light braking situation, and then heavy repetitive braking (Xin, 2013).

4.3.3 Mechanical

As discussed earlier within the manufacturing stage the graphite structure is a major factor of consideration, its effect on the material hardness is major as evident in figure.4, displaying on components that as expected hardness and yield strength are interrelated due to their both reliance on the microstructure within the components, a further point brought up in a study by Meyers et al. is that fatigue strength is not a function of hardness, however also finding that materials with a lower maximum nodule size did have a higher resistance to fatigue.

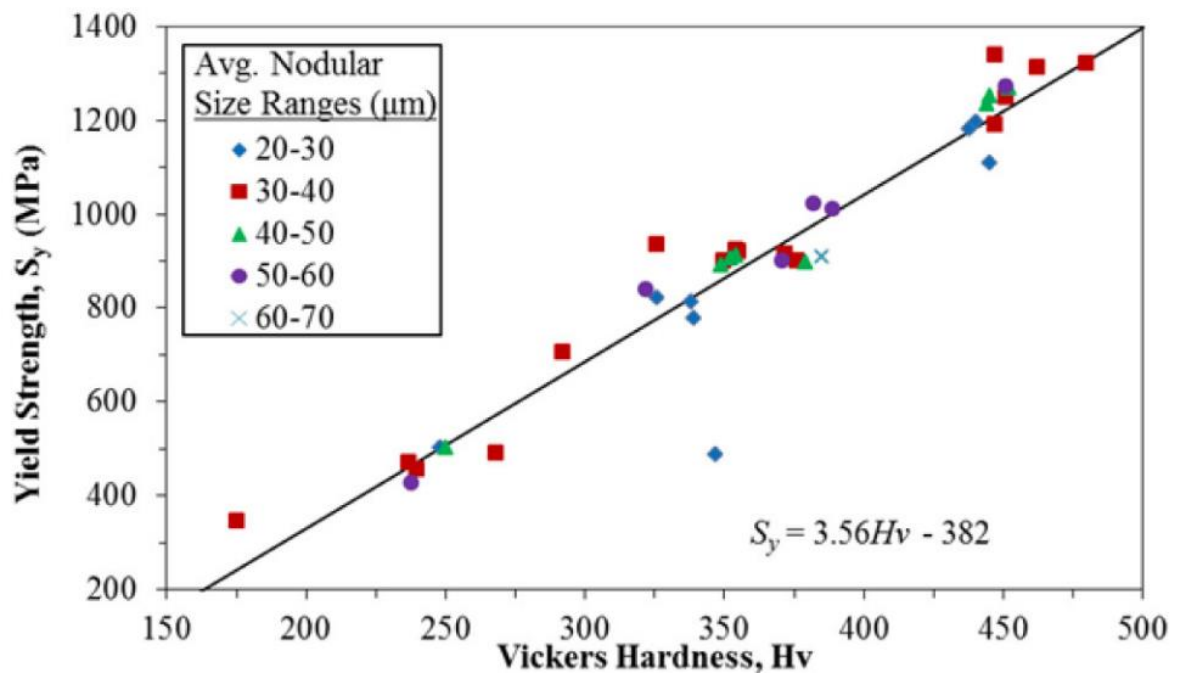


Figure 6 - Vickers hardness vs Yield strength in varying nodular grain size cast irons (Meyer, et al., 2015)

Further developing on the pre-covered points allows the elaboration of fatigues effect on the discs, the force generated by a pad is designed to not take it out of the zone of elasticity, or generate enough load across cycles to make it visible on what would be expected of the S/N curve (Koetnuyom, 2000), although as backed up by Smart et al. when subjected to a residual cyclic load and corrosion, significant creep can be produced, with high temperatures being a further catalyst for creep, although a consideration of this is the homologous temperature, which when considered to be over 0.4 extends it to an zone where creep can occur, but as the operating temperature of most cast iron discs is approximately 503.15°K with a melting point of 1811.15°K the ratio is 0.26, putting it well out of risk of immediate creep and failure.

Defining this resistance to fatigue is simple displaying the data outlined in fatigue test (figure 5), all curves matched similarly bar $R=-7$ and $R=0$, this is obviously due to the fact that $R=0$ is a static test being subject to a constant load and $R=-7$ having a maximum amplitude of 600Mpa and a minimum of -1050Mpa, taking it into the zone plasticity and thus damaging it further. The issue of compressive fatigue in brake discs is also subject to a variety of temperatures, and as seen in the test below under very low compressive forces ($<75\%S_u$), in a further test by Koetnuyon et al. when the addition of less strain, but higher heat was introduced the cycles were severely reduced, at 300°C the discs lasted till the 11th cycle on the second iteration, these

incredibly low fatigue values are attributed initially to the cyclic softening and hardening of the disc, or that at the higher temperature as the iron has expanded, the movement allows a greater opening of voids between the graphite flakes, also work hardening the pearlite matrix which is especially evident in eutectic mixtures.

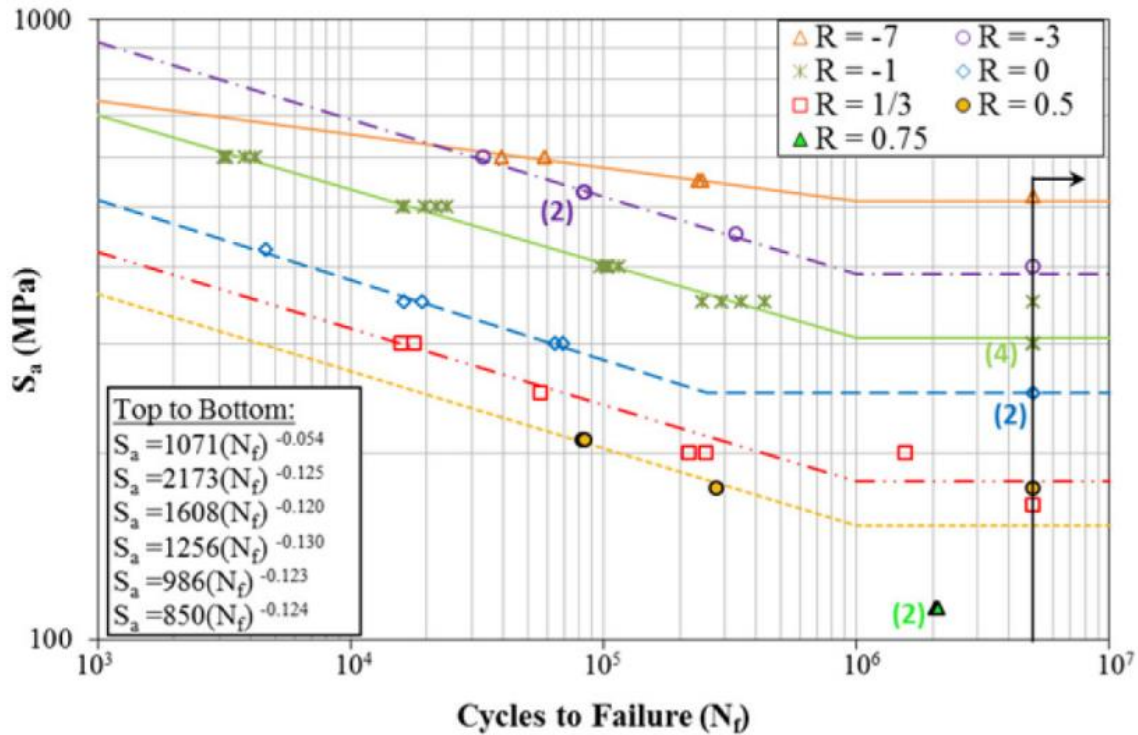


Figure 7 - S-N curve for Cast irons (Meyer, et al., 2015)

4.3.4 Chemical

Considering how corrosion effects the failure of the component the main consideration will be how corrosion effects disc brakes performance, in terms of low temperature corrosion the growth of an oxide film with minimal (0.0391-0.2415mmpy) didn't contribute to the discs coefficient of friction, on the other hand it did massively effect the discs 'stiction' or its ability to maintain friction to reduce movement, with corrosion amounting to 23µm the force needed to move the discs with an applied force reduced to 5kgf from the initial 22kgf. This was noted that is because of the surface area and not due to any bimetallic corrosion.

Considering the previous statement, Smart et al. corroborate this in a similar test that displayed corrosion generating a >5 µm thick compressible, friable layer on the disc after a matched 24hrs in an environmental simulation box, but also thinner <100nm less compressible layer developed itself on the surface when iron was subjected to corrosion for 380 days in a brine solution, this hard outer layer not only effects the braking effort by having a modified friction coefficient (Lakkam, 2013), but also in doing so generated uneven wear characteristics of the disc as stated by Gweon et al, leaving it susceptible to warping and cracking due to the high temperature concentration caused by increased surface area round the points of corrosion (Imasaki & Okamura, 2007).

5 Conclusion

After the discussion and analysis of primarily the grain structures within cast iron, considerations to its manufacture, life, and failure were all researched and compared, to accumulate the contributing factors to the manufacture;

- The inoculant amount effects the grain structure by increasing or reducing the cooling time, with a slower cooling time generating more homogenous and larger amounts of graphite
- Casting is the go-to method due to its low cost and ease of use, it does present a multitude of issues if done improperly, with the main being hardness zones around the casting gates leading to potential disc warpage or cracking
- To ensure appropriate tolerances for leaving the factory under regulatory constraints, the discs are machined using a brush grinding method to remove the high spots, although EDG is a potentially solution for more accurate grinding, it has yet to be implemented largely due to possible cost and time and the fact it produces 8x less the quality of surface finish

These considerations led to be understanding why cast iron fails in mechanical and thermal and chemical amplitudes, prompting research that can be concluded as;

- Overworking a brake disc in temperatures excessive of its operating range promote the growth of oxide films, creating a surface where more force is needed to generate stiction
- Constant cycling of the discs exceeding the working temperature range generated a failure in the form of a reduced coefficient of friction and cracking of the disc
- The corrosion although short term may not have an effect on the discs grain, will reduce braking capabilities somewhat

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8 Appendices

8.1 Appendices 1 – Historical Composition of Friction Brake Materials

Table 2 - Historical Composition of Friction Brake Materials

Material Description	Application(s)	Approximate year
Cast iron or steel	used in blocks and other components of railroad car brakes	1870
Cotton, hair or copper	cart wheel and the first automobiles	1897
Asbestos tissue and other wires to increase strength and performance	trucks and automobiles	1908
Bronze particles with low ash content bituminous coal, produced with internal reinforcement of short fiber	trucks and automobiles	1926
Material molded from a dry mixture of post-metallic to replace the fragile cast iron brake pad on electric trains	London subway	1930
Flexible resin developed with agglutinant elements more intricately formulated	drum brake reinforcement	1930
Metal alloyed with resin	for aeronautic industry use	1950
Glass, mineral, metallic, carbon, and synthetic fibers to give semi-metals better performance than amianthus (beginning of the discussion about amianthus safety)	automobiles and trucks	1960
1980Compounds without amianthus	drum brakes and car equipment	1980
Suggestion of carbon fiber use	automotive brakes	1991

8.2 Appendices 2 – Initial disc material considerations

Table 3 - initial Disc Material Considerations (Lakkam, 2013) (Xin, 2013) (Maluf, et al., 2004)

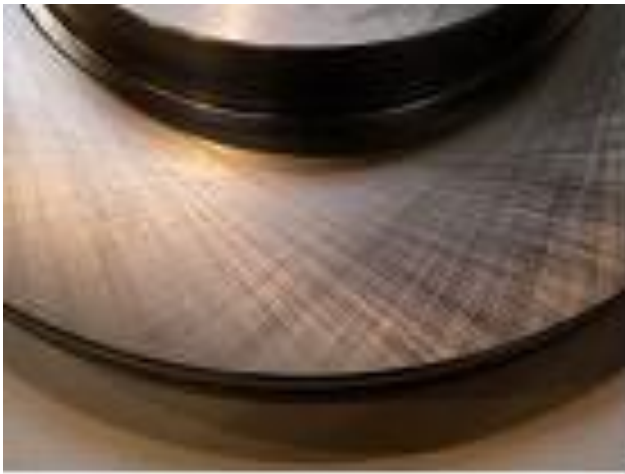
	Cast iron	Aluminium MMC	Carbon/Ceramic composite
Wear characteristics	• Slight amount of flexibility within the disc, but often leads to shatter • High chance of uneven wear •	• Matrix material can be utilised to harden the material • Resistant to wear even after being overworked	• Low chance of crack propagation • High compressive strength • Very linear stress/strain curve
Thermal characteristics	• Moderate thermal conductivity • Easily warped • Difficult to glaze	• Thermal conductivity is dependent on the materials matrix and additives • Easily glazed	• Low thermal expansion • High glazing point • High resistance to fatigue
Cost (a corner)	£75-300	£120-2500<	£2500+

8.3 Appendices 3 – Potential issues caused by casting

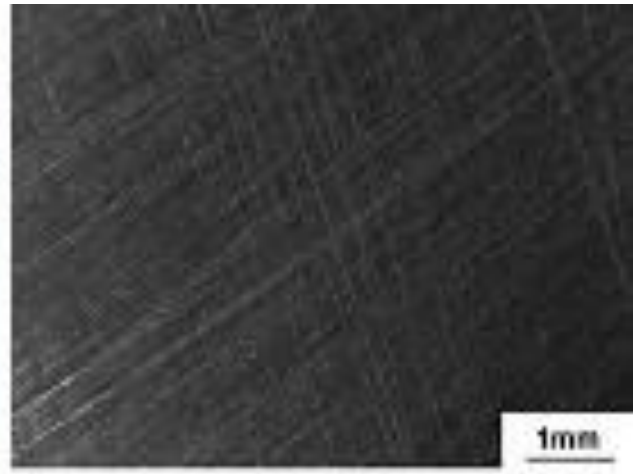
Casting issue	Result
Gas porosity	Weak casted material caused by voids
Cooled too quickly/slowly	Effect on the graphite microstructure
Wrong/inefficient gating design	Excessive wear around the gating position

Table 4 – Potential issues caused by casting (Imasaki & Okamura, 2007)

**8.4 Appendices 4 – Example of factory machine wear on brake discs
(Rodriguez, et al., 2014)**



(a)



(b)

8.5 Appendix 5 – Chemical composition of Iron employed by GM Brazil (Maluf, et al., 2004)

Table 5 - Chemical Composition of Iron Employed by GM Brazil (Maluf, et al., 2004)

Element	Metallic Alloy			
	A	B	C	D
%C	3,20	3,20	3,60	3,70
	3,60	3,60	3,80	3,90
%Si	1,90	1,90	1,80	1,75
	2,40	2,40	2,20	1,95
%Mn	0,60	0,60	0,60	0,50
	0,90	0,90	0,80	0,80
%P	Max	Max	Max	Max
	0,20	0,10	0,10	0,10
%S	Max	Max	Max	Max
	0,12	0,10	0,12	0,13
%Cr	-	0,25	0,10	Max
		0,40	0,25	0,20
%Mo	-	0,40	0,30	Max
		0,50	0,60	0,10
%Cu	-	-	0,30	Max
			0,45	0,40

8.6 Appendix 6 – Relationship between the cyclic strain and amplitude and the crosshead stroke

Table 6 - Lyu et al Test results regarding cyclic strain in brake discs (Koctniyom, 2000)

Cycles	Cyclic Strain Amplitude (peak-to-peak)	Stroke (mm) in Tension	Stroke (mm) in Compression
1 st 50 Cycles	0.001536	0.15800	0.1000
2 nd 50 Cycles	0.004516	0.32550	0.2314
3 rd 50 cycles	0.007500	0.44520	0.3309
4 th 50 Cycles	0.010480	0.54356	0.4143

8.7 Appendix 7 – ECE R90 Disc maximum values

Table 7 - Disc Brake Maximum values dependant to ECE R90 (United Nations, 2017)

	Vehicle Category	
	M ₁ , N ₁ , O ₁ , O ₂	M ₂ , M ₃ , N ₂ , N ₃ , O ₃ , O ₄
Thickness Variation	0.015mm	0.03mm
Cheek thickness variation (for ventilated disc only)	1.5mm	2.0mm
Lateral run-out friction surface	0.050mm*	0.15mm*
Location bore variation	H9	H9
"Top hat" parallelism	0.100mm	0.100mm
Location face flatness	0.050mm	0.050mm
Friction surface roughness**	3.2µmm	3.2µmm

* n/a in the case of a floating disc. ** Ra-value according to ISO 1302:2002.