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Analysis and Recommendations for the Minimisation of Material Failures

Mechanism of Materials Failure
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Contents

List of Figures	3
List of Tables	3
List of Graphs	4
List of Equations	4
1 Introduction.....	5
2 Disc-Brake System History & Development	5
2.1 Historical Design Factors.....	6
2.2 Material Specifications	8
2.3 Process & Manufacturing Route	9
3 Mechanisms of Material Failure	11
3.1 Friction & Wear	11
3.1.1 Theory	11
3.1.2 Experimental Procedure	13
3.1.3 Analysis.....	14
3.1.4 Recommendations	15
3.2 Thermal Fatigue	15
3.2.1 Theory	15
3.2.2 Experimental Procedure	16
3.2.3 Analysis.....	17
3.2.4 Recommendations	19
3.3 Corrosion.....	20
3.3.1 Theory	20
3.3.2 Experimental Procedure	21
3.3.3 Analysis.....	21
3.3.4 Recommendations	22
4 Conclusion	23
5 References.....	23
6 Appendices.....	29

6.1	Brake-Pad Material's Table	29
6.2	Brake Dynamometer Signals	29

List of Figures

Figure 1	Disc-Brake System Diagram (Shipway, 2017).....	5
Figure 2	Crosley Disc Brake 1949 (Remarkable Automobiles, 2016)	6
Figure 3	Smooth, Slotted and Drilled Brake Discs (NewParts, 2020).....	7
Figure 4	Graphite Flakes in Matrix GCI (Oldfield, 1959).....	10
Figure 5	Coarse Flake Graphite GCI (Oldfield, 1959)	10
Figure 6	Static Friction diagram (Collins, 2019)	11
Figure 7	Kinetic Friction Diagram (Collins, 2019).....	11
Figure 8	Schematization of the Abrasive Wear mechanism (Brando, 2013).....	12
Figure 9	Adhesive Wear (Kopeliovich, 2020).....	13
Figure 10	Schematic on pin-on-disc tribometer (Y. Lyu, 2018).....	13
Figure 13	Worn Brake Disc (The Filter, 2018).....	14
Figure 11	Adhesive Wear Disc-Brake (Ali Mohammadnejad, 2019).....	14
Figure 12	Abrasive Wear Disc-Brake (Ali Mohammadnejad, 2019)	14
Figure 14	Bosmal Dynamometer (Bosmal, 2012)	16
Figure 15	Thermal Induced Crack (Markel, 2013).....	17
Figure 16	Crack Classifications (Markel, 2013).....	17
Figure 17	Hat and outer radius of brake disc (Thomas J. MAckin, 2002).....	17
Figure 18	(Thomas J. MAckin, 2002).....	18
Figure 19	Nail Rust Experiment (BBC BiteSize, n.d.)	20
Figure 20	Rusting Diagram (Holden, 2020)	20
Figure 21	Disc-Brake Corrosion Procedure (Ferrer, 2019)	21
Figure 22	Brake Judder (Fremax, 2018).....	21
Figure 23	Corroded Brake Disc (The Brake Report, 2020)	22
Figure 24	Metal Reactivity List (BBC Bitesize, n.d.).....	22
Figure 25	Brake Dynamometer Signals (Bosmal, 2012)	29

List of Tables

Table 1	Types & Application of Brake Discs (Mahale, 2020)	6
Table 2	Brake-Disc Materials (M. A. Maleque, 2010).	8
Table 3	GCI Mechanical Properties.....	9

Table 4 Brake Pad Material & Weight % (Talib Ria Jaafar, 2012)	29
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List of Graphs

Graph 1 Solidification Graph (Khaira, 2013)	10
Graph 2 Stresses Plot (Thomas J. MAckin, 2002)	18

List of Equations

Equation 1 Static Friction (Ryan, 2016)	11
Equation 2 Kinetic Friction (Ryan, 2016)	11
Equation 3 Specific Wear Rate (Y. Lyu, 2018)	13
Equation 4 Hoop Stress (Thomas J. MAckin, 2002)	18
Equation 5 Radial Stress (Thomas J. MAckin, 2002)	18
Equation 6 Haematite Rust (Holden, 2020)	20

1 Introduction

This paper investigates the mechanisms of material failures within an automotive disc-brake system. The braking system of any vehicle is one of the most critically important systems regarding safety and works by a method of absorbing kinetic energy from the moving components, allowing them to slow down with the assistance of friction. Therefore, the importance of the braking system demonstrates it is evidently indispensable to ensure the advancement of its components for future use, this paper will focus on brake discs.

This Study is split up into several different sections, it initially consists of a brief literature review discussing the history and development of disc-brake systems covering historical design factors, material selections and processing routes. The next section discusses the theory behind three common mechanisms of material failure experienced by a brake disc, an explanation on the experimental procedures utilised to assess each of these, an analysis of each failure mechanism and recommendations to prevent or prolong these failures.

2 Disc-Brake System History & Development

At the end of the 19th Century the development of a braking system for new automotive vehicles was required. In 1902 Frederick William Lanchester an automotive engineer based in Birmingham patented the disc-brake system and it was regarded as one of the most innovative automotive engineering developments in the opening years of the 20th century (Bell, 2018).

The subsequent figure is a diagram of a modern disc-brake assembly with a single piston floating caliper and disc, the system decelerates a vehicle by dissipating its energy in sliding contacts between the brake pads and the discs that rotate with the vehicles wheels (Shipway, 2017). This is done when the brake pedal is depressed, in turn compressing a piston in the master cylinder, forcing brake fluid along a pipe in the system working its way towards the slave cylinders either side of the vehicle for each wheel, this then fills them and pushes the pistons out, sequentially pushing the pads to make frictional contact with the disc.

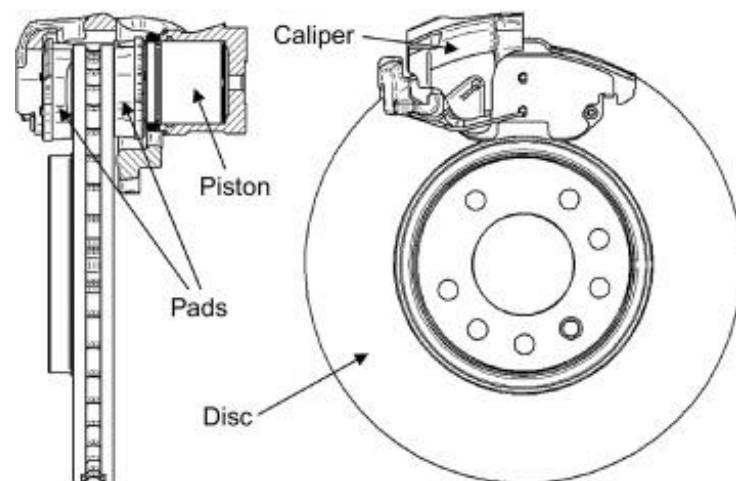


Figure 1 Disc-Brake System Diagram (Shipway, 2017)

2.1 Historical Design Factors

Since Lanchester built a vehicle with disc brakes back in 1902, their development has come on in leaps and bounds, back then the disc was paper-thin and made of copper and had a cable actuation system as opposed to the modern-day hydraulic system. It was not until 1949 that disc-brake systems were mass produced by an American company named Crosley who used disc-brakes on all four wheels of their “Crosley CD” model. They were an adaptation of a Goodyear-Hawley design which were utilised on numerous aircrafts and used off-the-shelf aviation parts, they were hydraulically actuated 6-inch discs using a blank and smooth design. Unfortunately, after just two years of production the system was dropped by Crosley for the subsequent two reasons:

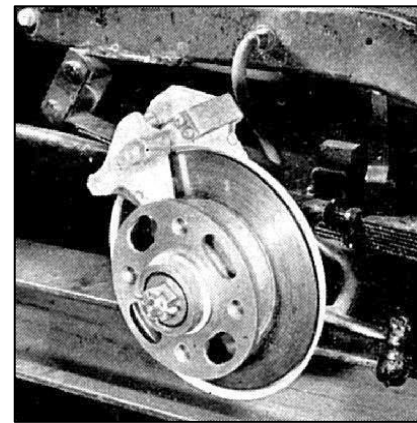


Figure 2 Crosley Disc Brake 1949
(Remarkable Automobiles, 2016)

1. The aircraft alloy components suffered from corrosion
2. Airplanes naturally only utilise their brakes during take-off and landing. Therefore, the continuous use of the brakes resulted in the calliper mechanism to fail prematurely.

(Markel, 2020)

Then in 1953-disc brakes made a breakthrough in the world of motorsport when they appeared on the Jaguar C-Type racing car, and one article claims that the use of the disc-brake system is what allowed the small company to triumph at the 1953 24 Hours of Le Mans and were developed in the UK by Dunlop. Although, it took another two years before the use of modern disc brake systems were utilised in road cars when they were mass produces in the 1955 Citroën DS, which were situated in board near the transmission, were hydraulically actuated and utilised a smooth and blank disc design (li, 2016).

In the modern day, the design of disc brakes has evolved, and they are being engineered so that they are “durable, lighter and self-cleaning” (Mahale, 2020) with the purpose of making the braking system of a vehicle more efficient. There are a selection of different disc brakes used in light-vehicles each with different design factors, as shown in the following table.

Sr.no	Types of Disc Brake Rotor	
	<i>Solid or Vented</i>	<i>Application</i>
1.	Drilled only	Street, all-weather rotor
2.	Blank & Smooth	Street and light weight vehicles
3.	Slotted only	Street, Towing/Hauling, Off-Road
4.	Slotted or Grooved	Trucks and off-road vehicles.
5.	Dimpled	Sports car, weight reduction
6.	Waved	Race & Sports vehicles

Table 1 Types & Application of Brake Discs (Mahale, 2020)

As opposed to drum-brake systems, disc-brake systems run a lot hotter and therefore it is critical that the design geometries of them are efficient regarding keeping their temperature within a safe limit by absorbing and dissipating the heat. Traditionally, disc brakes were designed to be relatively large, as the larger surface area would dissipate the generated heat quicker, unfortunately due to their size their weight had negative effects on vehicle performance and fuel efficiency (Mahale, 2020). Thus, in the modern day this has been taken into consideration so brake discs are now designed considerably smaller for weight reduction. Each of the design variations found in Table 1 comes with their own manufacturing process, and consequently their own machine costs, Dimpled and Wave design discs are at the upper end of the price scale and are essentially only used in sports cars and motorsport applications. Therefore, this section of the paper is only considering the three most used disc-brake designs used in automotive engineering.



Figure 3 Smooth, Slotted and Drilled Brake Discs (NewParts, 2020)

The above figure gives a visual representation of the 3 main modern disc brake design geometries and from left to right are as follows: Blank & Smooth (*Flat*), Slotted & Drilled. Smooth brake discs are the most frequently utilised in light-weight road cars and have a smooth surface finish where the pads make frictional contact. Additionally, this design has the greatest surface area and the most effective at acting as a heat-sink (S.A.M Da Silva, 2019). Furthermore, a blank and smooth design disc is not as susceptible to cracking as the level surface allows the disc to maintain its structural integrity. Although, because of the lack of ventilation on the discs surface it is common that after a high-braking period to experience thermal cracking.

In a slotted or grooved disc design, the slots are angled in direction of rotation on either side of the disc. During continuous and heavy braking causes increased temperature because of friction and generates a layer of dust and gas between the pads and disc. Consequently, due to the design of a slotted disc it allows the gases and dust to easily escape and increases the friction contact between the pad and disc for better vehicle performance (Mahale, 2020). Moreover, the slots allow the pads to clutch the discs better for better braking, prevent brake fade and allows heat to dissipate quicker. One downside of this design is that the slots produce noise through the scrubbing of the pads.

Finally, a drilled disc design dissipates heat faster than the previous two designs as it allows the gases and heat directly to the interior cooling vanes of the disk (NewParts, 2020). Essentially, by a method of

drilling holes it increases the surface area and reduces the mass of the disc. Drilled discs are a compromise between the amount of drilled holes whilst maintaining its structural integrity, although it is known for drilled discs on times to experience material weakening during the drilling processes, also if drilled incorrectly or there are simply too many holes, it can cause cracking (S.A.M Da Silva, 2019).

2.2 Material Specifications

When deciding on a material to be used for a disc-brake it is important to take into consideration the functionality, properties, and possible defects. It needs to be a material with high strength and stiffness as well as first-rate creep and abrasion resistance due to the nature of operation. Also, it should be able to withstand the high temperatures generated by friction from the contact between the disc and pads and it should possess “*Low density and High thermal conductivity*” (Mahale, 2020).

The subsequent table is taken from a study titled “*Material Selection Method in Design of Automotive Brake Disc*” and highlights suitable materials for use in the manufacturing of a disc brake, taking all of the considerations into account.

Properties Material	1	2	3	4	5
	Compressive Strength (MPa)	Friction coefficient (μ)	Wear rate ($\times 10^{-6}$ mm ³ /N/m)	Specific heat, Cp (KJ/Kg . K)	Specific gravity (Mg/m ³)
GCI	1293	0.41	2.36	0.46	7.2
Ti-6Al-4V	1070	0.34	246.3	0.58	4.42
TMC	1300	0.31	8.19	0.51	4.68
AMC 1	406	0.35	3.25	0.98	2.7
AMC 2	761	0.44	2.91	0.92	2.8

Table 2 Brake-Disc Materials (M. A. Maleque, 2010).

Where: **GCI** – Grey Cast Iron, **Ti-6al-4v** & **TMC** – Titanium Alloy and Composite, **AMC** – Aluminium Matrix Composites.

The use of titanium alloys and their composites have the potential to reduce the mass of a GCI brake disc by about 37% (*Assuming the same dimensions*) and AMC’s could see a weight reduction of up to 60% (M. A. Maleque, 2010). Additionally, in comparison to GCI discs, titanium discs have a better resistance to corrosion and heat, and AMC’s tend to have a lower density and thermal conductivity.

On the other hand, both titanium and aluminium composites and alloys are more expensive to manufacture compared to GCI. Thus, for the remainder of this paper only GCI disc brakes are considered as it is the material of choice for almost all automotive brake discs because of its relative ease of manufacture, low cost, and thermal stability (M. A. Maleque, 2010). GCI is a metallic iron

which contains between 2.5 and 4% dissolved carbon within its matrix and is referred to as grey cast iron because of its characteristic colour. One research paper discusses how that the Society of Automotive Engineers (SAE) maintains a specification for the manufacture of grey cast iron for various applications, for light vehicles this is J431 G3000 (Superseded to G10) (V.M.M.Thilak, 2001). This specification had the appropriate range of “*Hardness, chemical composition, tensile strength*” (Priyadarisini, 2018) and further properties obligatory for use in a disc brake. The below table shows the mechanical properties for GCI and were sourced from a published research paper (Aselmo Eduardo Diniz, 2010).

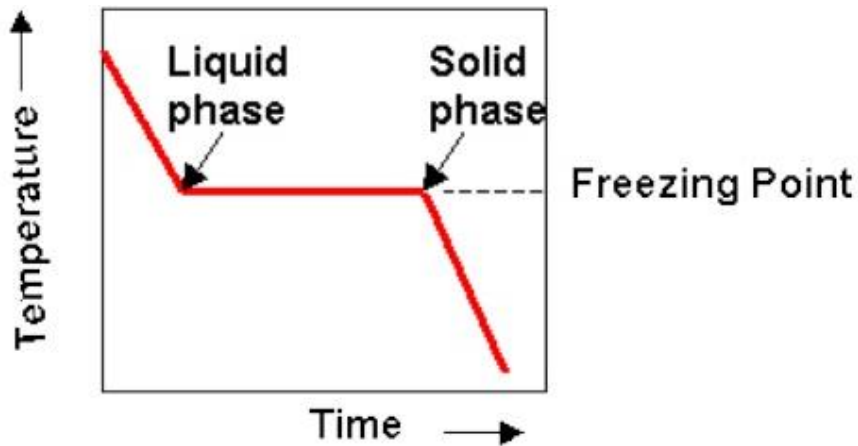
Mechanical Properties	
<i>Tensile Strength (Mpa)</i>	250
<i>Young Modulus (GPa)</i>	105
<i>Fatigue Resistance (MPa)</i>	110
<i>Heat Conductivity (W/(mK))</i>	48
<i>Hardness (HB)</i>	179-202
<i>Relative Damping Capacity</i>	1

Table 3 GCI Mechanical Properties (Aselmo Eduardo Diniz, 2010)

Finally, even though the brake discs are the subject of this study it is also important to mention the material of the brake pads, as this is what will be imposing friction on the discs and in turn causing wear. A commercial frictional brake pad contains more than 10 constituents which are often containing binder resin, solid lubricants, reinforcing fibres, abrasives, wear resistant and other friction modifiers (N. S. M. El-Tayeb, 2008), a table containing commonly used materials and their weight percentage for semi-metallic brake-pads can be found in Appendix 6.1.

2.3 Process & Manufacturing Route

The term “*Cast Iron*” is for a range of irons where the microstructure is characterized by the presence of flake graphite in the ferrous matrix, as previously stated this is between 2.5-4% carbon but it also contains 1-3% silicon and some additions of manganese from 0.1%-1.2% (Singh, 2020). GCI is manufactured by a process route of casting; this is where a liquid material is poured into a mould containing a hollow hole of the wanted shape and then solidified, solidification is essentially the process of transformation of a liquid to a solid. During the solidification process of GCI, the liquid iron changes into its solid state as its temperature decreases. The energy of the liquid is fewer than that of the solid above the melting point, so the liquid is stable above the melting point. On the other hand, below the



Graph 1 Solidification Graph (Khaira, 2013)

as liquid changes to solid, heat is freed, this heat must be repeatedly extracted from the freezing liquid or the solidification process will stop (Sabu, 2015). Solidification occurs by the subsequent processes: nucleation and growth. Nucleation being when a small nucleus begins to form in a liquid and the nuclei then grows as atoms from the liquid become attached to it and growth is the physical process where a new phase increases in size.

According to the composition and cooling rate, iron may solidify with all the carbon in the combined form as cementite this is known as: White Cast Irons. Otherwise, by suitable alteration of the composition and cooling rate, most of the carbon exists in free form as graphite, this is what happens with GCI. A typical microstructure of a GCI can be shown in the below figures, where flakes of free carbon or graphite can be seen in disarray (Oldfield, 1959).

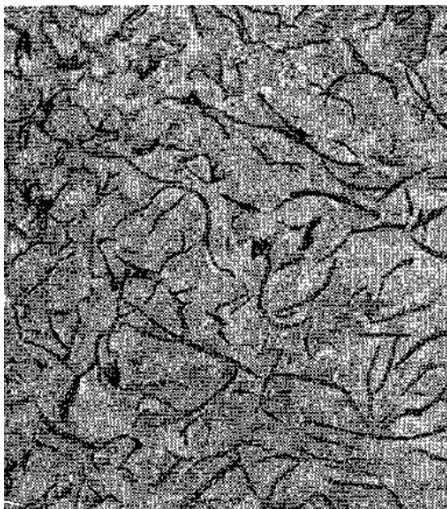


Figure 4 Graphite Flakes in Matrix GCI (Oldfield, 1959)



Figure 5 Coarse Flake Graphite GCI (Oldfield, 1959)

The phosphorus found in GCI lowers the freezing point and lengthens the solidification period so that GCI's can be cast into intricate shapes. Regrettably, this slower solidification enhances the graphite formation, and the crack-inducing effect of graphite flakes reduces the metal's strength and malleability making it brittle. Although they are easy to machine because of this graphite as the metal breaks off in small chips, and they also have a high damping capacity (Walker, 1999).

melting point, the energy of the liquid becomes more than that of the solid. so, beneath the melting point, the solid becomes more stable than the liquid (Sabu, 2015). Thermodynamically, both states have identical energy at melting point and therefore both are equally stable at the melting point. Solidification is most of the time an exothermic process, so

For the manufacture of brake discs, a GCI mixture is poured into an aluminium mould cavity in the desired shape of a disc brake. After solidification, the mould is then compressed in a press and heated to almost 205°C compacting the materials to make them stronger (New Engineering Practice, 2011). Next, the disc is machined using a high precision CNC turning it into a recognisable brake disk, then slots, grooves and dimples are drilled into place before a tolerance check.

3 Mechanisms of Material Failure

3.1 Friction & Wear

3.1.1 Theory

Whilst friction is crucial in a braking system for ensuring surfaces grip it also comes with its issues as it causes potential wear due to magnetising of contact surfaces which attract abraded metal. There are two types of friction: Static & Kinetic, these can be expressed using the subsequent two equations:

$$\text{Static Friction} = f_s = \mu_s F_N$$

Equation 1 Static Friction (Ryan, 2016)

$$\text{Kinetic Friction} = f_k = \mu_k F_N$$

Equation 2 Kinetic Friction (Ryan, 2016)

Where: f_s & f_k – Static & Kinetic Frictional Forces, μ_s & μ_k – Coefficient of static (Sticking) and kinetic (sliding) friction, F_N – Force acting normal to the surface

Static friction keeps a component from moving without being pushed, it must be overcome with a sufficient opposing force before the component will move. Dynamic or kinetic friction is overcoming the static friction between two surfaces and basically removes the molecular obstacles to movement. Furthermore, once movement has begun abrasion continues to occur, but not as much as static friction (Collins, 2019). The following two diagrams demonstrate the difference between static and kinetic friction.

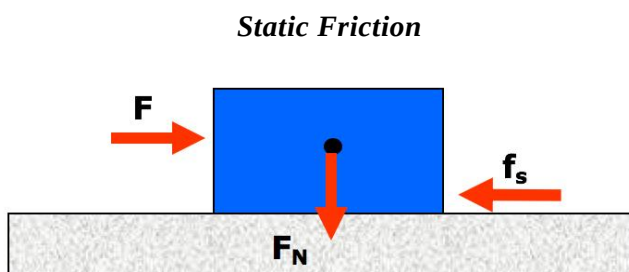


Figure 6 Static Friction diagram (Collins, 2019)

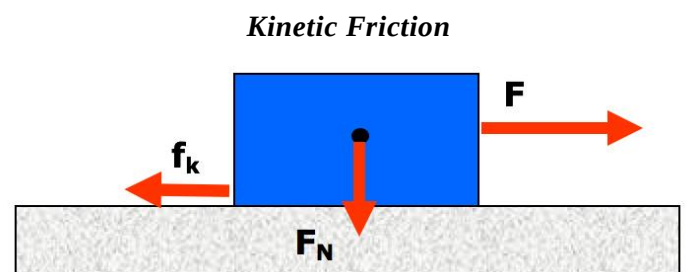


Figure 7 Kinetic Friction Diagram (Collins, 2019)

The degree of friction is dependent on the following four factors:

1. The amount of Asperities

2. The degree of area contact on top of each peak
3. The frictional coefficient of the material
4. The degree of lubrication (*If Appropriate*)

(Holden, 2020)

In tribology friction is defined as the force that occurs between two surfaces that are in contact with relative motion and wear is the phenomenon of mechanical/chemical damage that has an adverse effect on the quality of the materials in contact with each other (Cuffari, 2019). Commonly found wear mechanisms in disc-brake systems are abrasive and adhesive wear.

Abrasive wear happens when two interacting surfaces are in direct physical contact, where one of them has a significantly rougher surface finish than the other. In tribology, asperities are defined as high spots on surfaces that come into contact during wear or friction (P.J., 2013). Under the action of normal load, the asperities found on the rougher surface will pierce the softer surface producing plastic deformations (Stolarski, 1990).

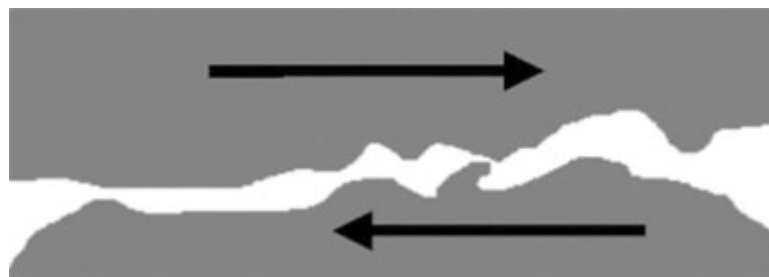


Figure 8 Schematization of the Abrasive Wear mechanism (Brando, 2013)

In the micro-level, the most common mechanisms of abrasive wear are ploughing, cutting and brittle fracture (*cracking*). Ploughing is when the material is shifted to the sides of the wear groove but not removed from the surface, cutting is where a chip forms in front of the cutting asperity and the material is removed from the surface in the volume equal to the volume of the wear groove. Finally, cracking is where the material cracks in the subsurface areas surrounding the wear groove, the volume of the lost material in this case is greater than the volume of the wear groove (Kopeliovich, 2020).

Adhesive wear is a type of wear due to localized bonding between contacting solid surfaces leading to material transfer between the two surfaces or loss from either surface (Masood, 2016). It occurs when high pressures, loads or temperatures cause the peaks on the two contacting surfaces in relative motion to weld to one another and then instantly tear apart, shearing the metal in discrete areas (Paulus, 2019). The figure on the following page shows a diagram of adhesive wear.

Adhesive Wear

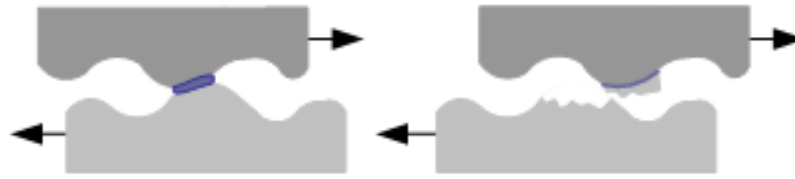


Figure 9 Adhesive Wear (Kopeliovich, 2020)

3.1.2 Experimental Procedure

The friction and wear durability of a disc brake can be tested by means of a pin-on-disc tribometer, a diagram of which can be seen below.

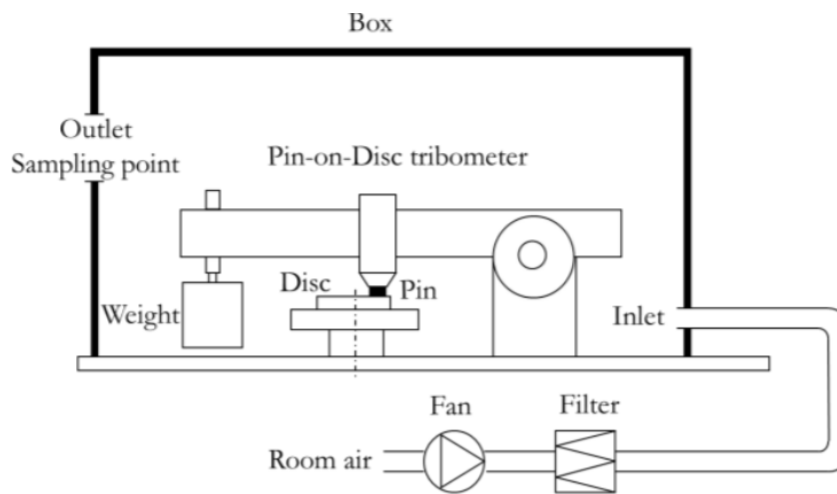


Figure 10 Schematic on pin-on-disc tribometer (Y. Lyu, 2018)

One article from the journal Tribology in Industry explains that a disc brake is horizontally mounted in this configuration and is rotated by a motor. Dead weights are used on the pin sample to add various standard loads, which dependent upon its nominal contact area, leads to different nominal contact pressures. Using a load cell, the tangential force is calculated, and the friction coefficient is determined by dividing this value by the normal load applied (Y. Lyu, 2018). The mass loss of the test piece is calculated by weighing the test piece to the nearest 0.1 mg pre and post-procedure. A K-type thermocouple 3 mm below the contact surface tests the temperature (Y. Lyu, 2018). The specific wear rate of the disc brake can then be expressed using the following equation:

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

Equation 3 Specific Wear Rate (Y. Lyu, 2018)

Where: Δm – mass loss of the disc, ρ - density of the disc Δs – the sliding distance during procedure & F_N – normal load applied to the pin

3.1.3 Analysis

As a result of the simultaneous contributions of mechanical loading, surface conditions, and thermal stresses, the deterioration and failure of disc brakes can be very complex. Disc brakes undergo dynamic loading conditions making it much more difficult to understand failures (Ali Mohammadnejad, 2019).

A case study investigating wear induced failure of disc brakes carried out a pin-on-disc experiment and then compared and correlated to results obtained from a failed brake disc. Loads were altered in the test procedures from 10-60N. The force range was decided as results demonstrated that tests with below 10N took a substantial amount of time to see an even trivial alteration in the specimen's weight as opposed to loading larger than 60N which resulted in deformation and excessive wear within a few minutes to the extent where no data could be extracted from the experiment. Each test was run for 50m and the pin was moving on the disc with a velocity of 0.25 m/s, tests were carried out up to a total of 1000m and interrupted every 250m to measure weight loss (Ali Mohammadnejad, 2019).



Figure 11 Worn Brake Disc (The Filter, 2018)

The study investigated the wear mechanism of grey cast iron and its root cause of crack formation failure for brake discs. It found that cracks were formulated because of the wear and critical loading conditions propagated perpendicular to the sliding direction. Furthermore, it was discovered that in some areas inside cracks were filled with “chip-like and fine spherical particles” (Ali Mohammadnejad, 2019), which are characterized to be oxide particles in nature. Also, oxide particles have substantial attributions to abrasion and consequently a loss in weight of the disc brake, these particles were generated during the procedure and were resultant of the temperature increases at the frictional contact points between the pads and discs. As well as abrasive wear there was adhesive wear mechanisms that contributed to the loss of weight during the procedure. In critical conditions the contact point between the pads and discs is harshly damaged by adhesive wear, in the case study the disc surface has some minimum roughness, and the applied load is high enough that metal on metal adhesion on the contact area is inevitable, the sticking layer is so weakly bonded to the disc it shortly after will be detached from the surface (Ali Mohammadnejad, 2019).

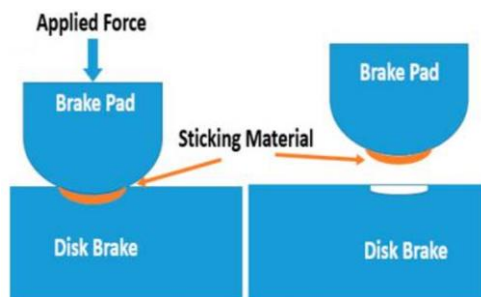


Figure 12 Adhesive Wear Disc-Brake (Ali Mohammadnejad, 2019)

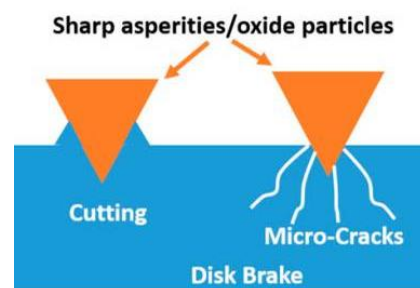


Figure 13 Abrasive Wear Disc-Brake (Ali Mohammadnejad, 2019)

Finally, the case study highlighted the relationship between the applied load and the friction coefficient, as during a test with a load of 40N the friction coefficient was larger than that of a load of 20N. The contacts points between the asperities got larger as the applied load increased during the experimental procedure, consequently resulting in a larger friction coefficient (Ali Mohammadnejad, 2019).

3.1.4 Recommendations

The wear of a disc brake leads to brake emissions in the form of dust and particulate matter than have a negative impact on human health, with the continuously increasing tightening of emissions regulations and standards, surface treatment of brake discs to reduce this wear has become a popular research area. The most popular being the utilisation of coatings. There are an array of types of coatings that have been explored to help prevent wear some of these techniques are as follows:

- Galvanizing
- Electrochemical coatings
- vapor deposition
- conversion coatings
- Thermal spraying

(Yena Engineering, n.d.)

Thermal spraying is a popular method for applying coatings to GCI disc brakes, this is when the coating substance is heated and then sprayed onto the metal component and is usually carried out by an external electrical source which can make an arc or plasma (Yena Engineering, n.d.). There is an assortment of different potential materials that can be deposited by thermal spray techniques such as hard metal carbides that are mixed with iron and are one of the most used cermet's for producing highly wear resistant coatings, where a "*cermet*" Is a blend of a metal-oxide ceramic and metal materials. Furthermore, carbides have an optimum blend of hardness, ductility and toughness which makes them ideal for GCI disc brakes, commonly used hard metal carbides include tungsten carbide and chromium carbide (Omkar, 2019).

3.2 Thermal Fatigue

3.2.1 Theory

TF (*Thermal Fatigue*) also known as thermomechanical fatigue refers to the fatigue failure with macroscopic cracks resulting from cyclic thermal stresses and strains and happens because of fluctuation in temperature, spatial temperature gradients, and high temperatures under constrained thermal deformation (Xin, 2013). It particularly arises when combined with surface frictional forces, like that found in a disc-brake system from the contact between the disc and pads.

It is a dramatically severe form of fatigue as unlike normal high-cycle fatigue which occurs at stresses which are well below its point of yield (*Elastic Range*) it is driven by thermal strains that force the deformation well into the plastic flow regime. Consequently, the maximum stresses are well above yield (*Plastic Range*) (Campbell, 2015). This phenomenon is commonly found in casting in which part of the casting experiences a high alternating temperature as opposed to other parts of the casting which remain at a lower temperature “*The Phenomenon is seen in grey iron disc brakes*” (Campbell, 2015).

In TF, compressive stresses are formed by the bolting load at high temperatures, or if the material the component is made from has a high coefficient of thermal expansion. The coefficient of thermal expansion essentially describes how the size of a component will vary when there is a change in temperature. When a component has a lower coefficient of thermal expansion or when the component cools, tensile stresses are generated (Xin, 2013).

During the design process of a component TF tests are undertaken, they utilize an external heating and cooling source that will heat and then cool localised areas of sample components at a rapid rate. Characteristically, the test specimen is designed to have a sharp single edge which will act as an initiation site for cracks, then during thermal cycling, the specimen is completely unrestrained so is free to expand or contract. This is so that only the mechanical strains because of the thermal gradients are experienced by the specimen (Nagesha, 2017), and after an array of heating and cooling cycles cracking may happen. The failure indicator for TF for the most part is strain as opposed to stress, these thermal stresses are generated by cyclic material expansion and contraction when “*temperatures changed under geometric constraints*” (Xin, 2013). Finally, the TF lifespan of a component is primarily down to the ductility of its material as opposed to its strength.

3.2.2 Experimental Procedure

In 2012 the Society of Automotive Engineers (SAE) introduced a new standard “*SAE-J2928 – Brake Disc Thermal Cracking Procedure for Vehicles Below 4540kg*” this is a laboratory method and criteria which determines the moment of initiation of a crack in a disc and their propagation during high energy braking events (Bosmal, 2012).

The SAE J2928 test procedure works by a method of subjecting a brake disc to 150 heat cycles, this is performed on a dynamometer. The subsequent figure shows a LINK model M3000 Brake Dynamometer used at the BOSMAL Automotive R&D Institute Ltd. It allows the testing of both drum and disc-brake systems at full scale in the range of functional tests and durability and allows to record in real time for disc temperature as well as a wide array of other signals

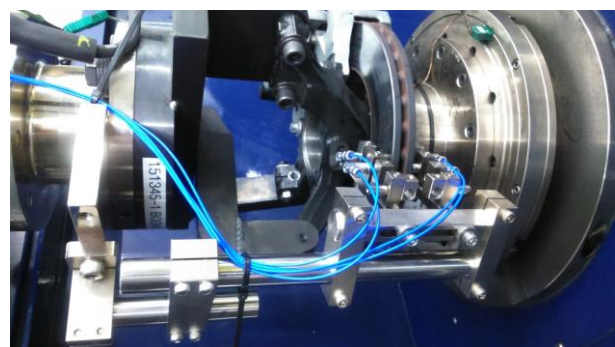


Figure 14 Bosmal Dynamometer (Bosmal, 2012)

(Bosmal, 2012). Please see Appendix 6.2 to see a table of all the available signals the dynamometer can record.

The SAE J2928 test procedure works by a method of subjecting a brake disc to 150 heat cycles with the use of a brake dynamometer, a heat cycle being when a disc is cold and then brought to a high temperature causing a disc to expand and contract creating fatigue and this causing cracks and structural failure (Markel, 2013). The objective being to thermally and mechanically stress the brake disc so any defect in the structure is exposed, J2928 also covers how to document and classify cracks (Markel, 2013)

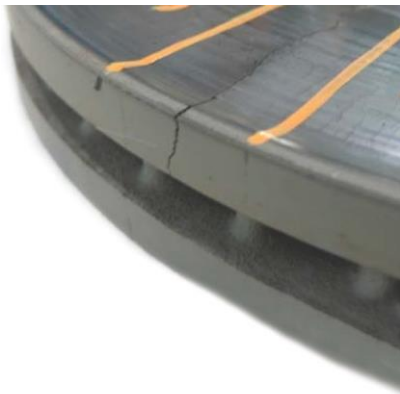


Figure 15 Thermal Induced Crack (Markel, 2013)

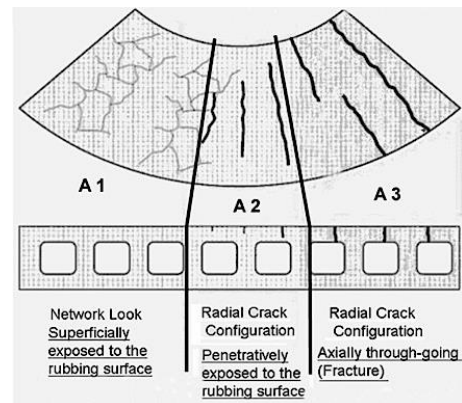


Figure 16 Crack Classifications (Markel, 2013)

3.2.3 Analysis

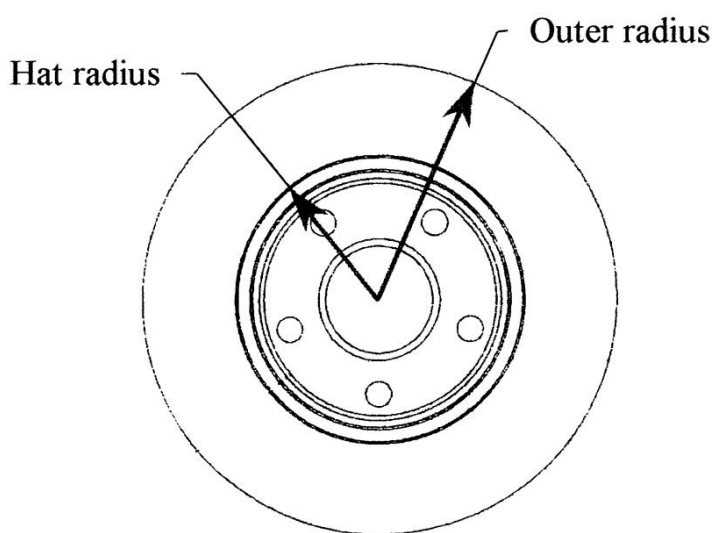


Figure 17 Hat and outer radius of brake disc (Thomas J. MAckin, 2002)

As Previously stated, braking induces the brake disc surface to heat at an exponential rate, which can lead to extreme temperatures. Although, the hat of the brake disc which can be shown in Figure 17 experiences little or no fluctuation in temperature. Therefore, the hat constrains the surface of the outer braking surface. Thus, the stresses in the disc-brake system are approximated by assuming that the hat maintains at room temperature and constrains the thermal displacement of the outer radius (Thomas J. MAckin, 2002).

The restriction provided by the hat is analogous to the internal pressure on the annulus of the disc's outer radius, creating major constraint stresses in the external radius. A case study investigating thermal cracking in disc brakes states that the average increase in disc temperature is roughly 220°C, which generates a constraint pressure of 100MPa (Thomas J. MAckin, 2002). According to this restriction pressure, stresses in the hoop and radial directions are produced and are expressed as:

$$\sigma_1 = \frac{pb^2(a^2 + r^2)}{r^2(a^2 - b^2)}$$

Equation 4 Hoop Stress (Thomas J. MACKin, 2002)

$$\sigma_2 = \frac{pb^2(a^2 - r^2)}{r^2(a^2 - b^2)}$$

Equation 5 Radial Stress (Thomas J. MACKin, 2002)

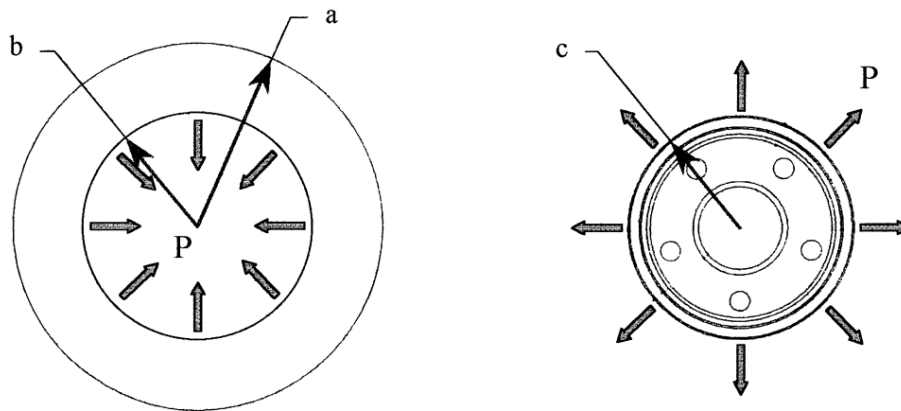
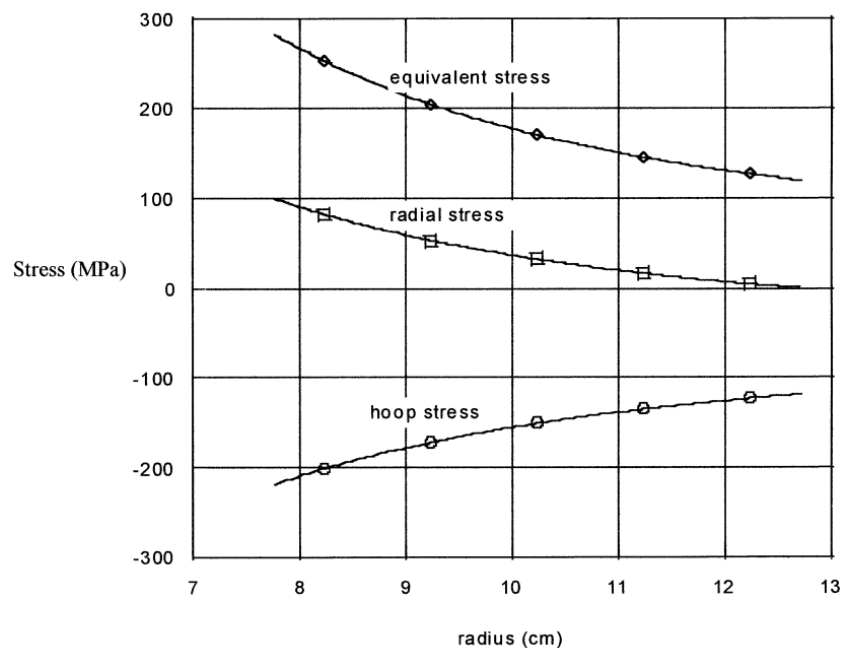


Figure 18 (Thomas J. MACKin, 2002)

Graph 2 shows a plot of both the hoop and radial stresses exerted onto the disc brake in the case study as well as the equivalent Von Mises stress. the grey cast iron used in the study has a yield strength of 215 MPa and a modulus of elasticity of 90GPa.



Graph 2 Stresses Plot (Thomas J. MACKin, 2002)

The above graph demonstrates that the mean equivalent stress is approximately 180MPa. Furthermore, it also shows thermal stresses that surpass the materials yield strength adjacent to the hub and extend approximately 1 cm out from the hub that are created by the braking temperatures. In addition, when braking, the brake disc yields compression, while residual tensile hoop stress sets in while cooling

(Thomas J. MAckin, 2002). The thermo-mechanical mechanism accountable for the failure of the disc brake considered in the case study is the cycling between compression and stress, in step with the brake temperature. The below figure shows a brake disc that has failed because of these thermal stresses and has been taken from the case study.

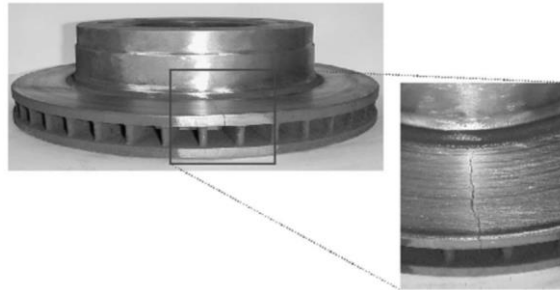


Figure Failed Brake Disc from a Ford F-250 Pickup Truck (Thomas J. MAckin, 2002)

3.2.4 Recommendations

One method of eliminating thermal cracking in disc brakes is to increase the yield and fatigue strength of the brake disc material. Improvements in life as well as fatigue strength are proportional to the depth of the compressive stress imparted. The fatigue strength of a component can be increased by a method of peening which is a process of working a metal's surface to improve its material properties. Peening the surface of a material will reduce tensile stresses and produce compressive residual stress that prevents cracks from being initiated. Forms of peening include shot peening, the use of high-speed bullets, high-frequency impact therapy, and laser peening (Can Yildirim, 2012). Via many fundamental processes, iron can be reinforced to increase its yield strength, some of these methods include:

- Work hardening
- Solid solution strengthening by interstitial atoms
- Solid solution strengthening by substitutional atoms
- Refinement of grain size
- Dispersion strengthening, including lamellar and random dispersed structures.

(Total Materia, 2003)

The work of the interstitial solutes of carbon and nitrogen is the most distinctive feature of iron strengthening. These elements play a vital role on interacting with dislocations and in combining preferentially with some of the metallic alloying elements used in steel (Total Materia, 2003). Other methods include decreasing the braking temperatures and to-re-design the hub-disc unit to eliminate constraint stresses. New brake materials that can work at significantly higher temperatures have been found. This, however, contributes to the need for heat shielding around the brakes, the use of materials that carry higher temperatures and a drastic re-design of the whole disc-brake system. It is also

challenging to achieve advanced designs that incorporate cooling into the bakes and add substantial cost to the brake unit (Thomas J. Mackin, 2002).

3.3 Corrosion

3.3.1 Theory

Corrosion is the phenomenon where a refined metal is naturally converted to a more stable form such as its oxide, hydroxide or sulphide state which leads to deterioration of the material (TWI, n.d.). Corrosion is dependent on the environment and metal will corrode when it reacts with another substance such as oxygen, hydrogen, and electrical currents.

With disc-brakes the main mechanism of failure because of corrosion is rust, this happens when the iron used to make the component is in contact with water and oxygen. Oxidation is defined as the loss of electrons or increase in oxidation state of a molecule, atom, or ion in a chemical reaction, then there's reduction which is a gain of electrons or decrease in the oxidation state of a molecule, atom, or ion and

finally there's redox which is short for **reduction-oxidation** which is where one chemical species is reduced, while another is oxidized (Helmenstine, 2020). Rusting is a redox reaction whereby oxygen acts as the oxidising agent and iron acts as the reducing agent (Veerendra, 2020). Additionally, the iron reacts with the water and oxygen to form hydrated iron oxide, but both are needed for rust to occur, as shown in the subsequent figure (BBC BiteSize, n.d.).

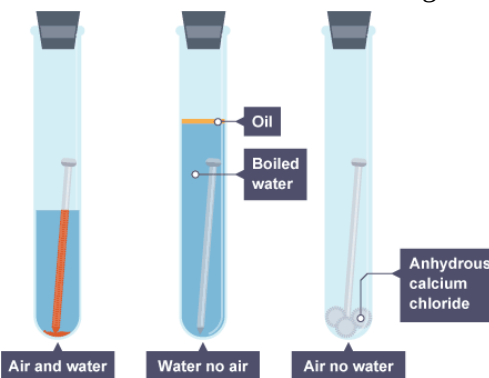
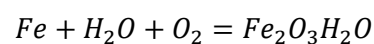


Figure 19 Nail Rust Experiment (BBC BiteSize, n.d.)

There are two types of rusting of iron: hematite and magnetite, the chemical formula for hematite can be expressed as: Fe_2O_3 . Hematite is the mineral form of iron oxide. The second is magnetite, which is also an iron oxide mineral and can be expressed as: Fe_3O_4 . The more common of the two is hematite and is the combination of iron and oxygen which gives the familiar brown rust, the below expression shows how hematite rust is produced. Also, it is worth noted that H_2O is also added, as it is a hydrated form of the oxide.



Equation 6 Haematite Rust (Holden, 2020)

The subsequent figure gives a visual aid to Equation 6

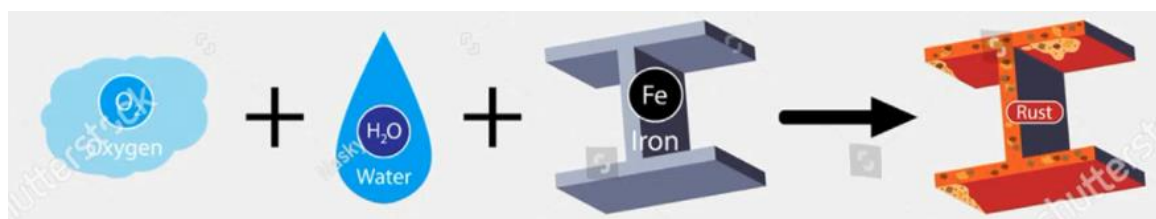


Figure 20 Rusting Diagram (Holden, 2020)

3.3.2 Experimental Procedure



Figure 21 Disc-Brake Corrosion Procedure (Ferrer, 2019)

To demonstrate the level of which a disc-brake will rust by corrosion and the rate of which can be carried out by the subsequent experimental procedure. Corrosion of the disc brake can be intensified by an array of artificial speed-up methods. This work remains committed to the apparatus and technique set out in ASTM B117-1, a standard addressing the conditions necessary for a regulated corrosive environment to be produced. A salt spray cabinet and a continuous and indirect water solution spray are exposed to the samples for a span of 72 hours. The solution consists of a salt concentration of 5%, the pH of which fluctuates from 6.5 to 7.2, and is atomized by a nozzle (Ferrer, 2019). The corrosive atmosphere, e.g., a temperature of 35 ± 2 °C as well as a regulated RH of 95 percent, is preserved within steady state conditions. To facilitate uniform corrosion deposition over the cast iron surfaces, specimens are maintained at $\pm 30^\circ$ from the y axis and perpendicular to the stream of mist (Ferrer, 2019).

3.3.3 Analysis

In a disc-brake systems rust induced by corrosion is known to lead to a growth in noise, vibration, and harshness (NVH) which in turn reduces the efficiency of the system and is also known to lead to corrosion adhesion between the disc and pads which can cause severe damage and overall material failure (Apec Braking, n.d.). Additionally, this corrosion induces the phenomenon of brake judder, forced vibration whose frequency is directly proportional to the angular velocity at wheel and thus, to the speed of the vehicle (The Brake Report, 2020). The judder travels upwards from the braking system through the vibration and steering wheel, generating a severe judder.

The reason that corrosion causes brake judder is that rust causes fluctuations in the geometry of the brake disc, it causes a temporary growth in the brake discs thickness variation until the vehicle is in motion and the brake is applied, the frictional material of the pads consequently removes the small build

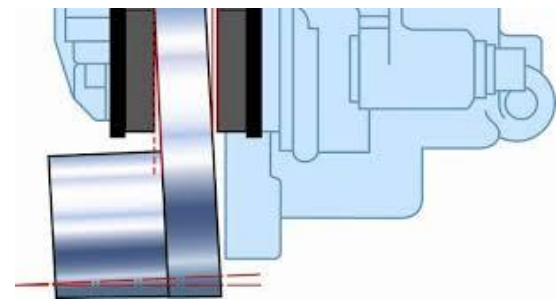


Figure 22 Brake Judder (Fremax, 2018)



Figure 23 Corroded Brake Disc (The Brake Report, 2020)

up of rust on the surface of the disc where they are in contact with one another. A case study from “*The Brake Report*” stated that the overall vibration response of the disc-brake system is proven to be linearly proportional to the disc thickness variation and thus, to the thickness of the corroded layer (The Brake Report, 2020). Finally, disc thickness can be reduced by corrosion, which will reduce its mechanical strength which could result in structural failure.

3.3.4 Recommendations

Galvanizing is a preventive tool for rust. A thin layer of zinc coats an iron or steel component. This prevents oxygen and water from accessing the underlying metal - but zinc also serves as a sacrificial metal. Sacrificial metals are more reactive than iron and lose their electron in preference to iron, consequently preventing iron from losing its electrons and becoming oxidised (BBC Bitesize, n.d.).



Figure 24 Metal Reactivity List (BBC Bitesize, n.d.)

Furthermore, another method of prolonging the rusting process of GCI brakes is to utilise oxide coatings, such as: Aluminium oxide (Al_2O_3), titanium oxide (TiO_2) and chromium oxide (Cr_2O_3), these are widely used materials for tribological applications requiring both wear and corrosion resistance (Omkar, 2019), making them ideal for a disc brake. An oxide coating is formed when

aluminium is the anode in some electrolytes and oxygen is liberated at the surface. As the oxide grows into the metal as the reaction phase proceeds, the very last formed oxide is extremely thin and non-porous and is situated at the metal interface (Abouleta, 2020).

4 Conclusion

To conclude this report has highlighted the importance of the advancement of components for future use. Furthermore, it gives an insight into the importance of minimising material failures and some methods of doing so. This paper has justified the use of GCI for the mass production of disc-brakes, although for optimum braking performance and efficiency, the consideration of an alternative material could prove beneficial. For example, carbon ceramic brakes which at high temperatures are also less resistive to deformation meaning they should have a longer lifespan in comparison to GCI brake discs. Additionally, carbon ceramic disc-brakes do not corrode, even when in contact with water or salt during the winter seasons (Haj-Assaad, 2012).

If this study were to be repeated, the opportunity for real-world testing of the experimental procedures outlined in this paper would be advantageous to grasp a better concept of their mechanisms. Finally, further work could include investigating other mechanisms of material failure experienced by GCI disc brakes such as fast fracture and creep.

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6 Appendices

6.1 Brake-Pad Material's Table

Ingredients	Formulation (Weight %)									
	SM1	SM2	SM3	SM4	SM5	SM6	SM7	SM8	SM9	SM10
Resin	10.0	10.0	9.0	9.0	9.0	9.0	9.0	8.0	12.0	9.0
Kevlar	-	-	2.0	-	2.0	2.0	-	-	-	3.0
Steel fiber	20.0	23.0	31.0	20.0	30.0	31.0	22.0	24.0	22.0	25.0
Organic fiber	5.0	-	-	10.0	2.0	2.0	10.0	8.0	7.0	5.0
Copper fiber	-	-	2.0	6.0	2.0	3.0	6.0	-	8.0	3.0
Graphite	16.0	19.0	7.0	13.0	15.0	7.0	13.0	11.0	16.0	6.0
Antimony	-	-	3.0	-	3.0	3.0	-	-	5.0	
Iron oxide	34.0	24.0	18.0	9.0	16.0	18.0	9.0	15.0	3.0	21.0
Novacite silica	-	3.0	-	3.0	-	-	3.0	2.0	6.0	3.0
Alumina oxide	-	2.0	1.0	5.0	2.0	1.0	2.0	2.0		2.0
Zinc oxide	1.0	-	1.0	-	2.0	-	-	3.0	-	2.0
Rubber	-	3.0	4.0	3.0	3.0	3.0	3.0	3.0	3.0	5.0
White rock	-	-	2.0	3.0	2.0	3.0	3.0	6.0	3.0	3.0
Barium	8.0	10.0	20.0	19.0	8.0	18.0	20.0	14.0	-	7.0
Friction dust	6.0	6.0	-	-	4.0	-	-	4.0	15.0	6.0
TOTAL	100	100	100	100	100	100	100	100	100	100

Table 4 Brake Pad Material & Weight % (Talib Ria Jaafar, 2012)

6.2 Brake Dynamometer Signals

The LINK M3000 test station allows to record in real time on time line the following signals:

- Braking torque
- Rotational speed
- Linear speed
- Deceleration
- The pad/shoe temperature
- The disc/drum temperature
- The brake pressure
- Acceleration
- Fluid displacement
- Actual inertia
- Cooling air temperature
- Cooling air flow
- Image from the HD camera
- DTV - disc thickness variation
- Noise peak level
- Noise peak frequency
- Noise peak duration
- and many more...

Figure 25 Brake Dynamometer Signals (Bosmal, 2012)