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Analysis and Recommendations for the Minimisation of Material Failure

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Mechanism of Material Failure

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1. Introduction

This report will investigate the failure analysis of drum brakes. The design and manufacture process will be investigated to see how any stress or wear factors have been discovered and addressed. The materials chosen for this part, as well as any modifications such as coatings or heat treatment will be investigated to see why these have been done and if there were any significant incidents that made the part be designed in such a way. Some literature analysis will be investigated to see what research previous studies and physical tests have discovered.

2. Part and its History

A drum brake is a type of braking system typically found on older cars and bikes but can also be found on the rear of cheaper modern-day cars. The way drum brakes work is when the driver presses the brake pedal hydraulic fluid is pushed through the brake lines and this is done to force the brake cylinder inside the drum brake to press the brake shoes towards the inside surface of the drum brake. The friction between the shoes and the drum is used to slow the vehicle down.(Heisler, 1998)

A drum brake is made up of four main components. The first is the torque plate, this is the backing plate of the system. It is used to absorb the torque being produced by the braking effects. It is also used to support the braking system, making it more rigid and to prevent any debris from entering the system. The second is the wheel cylinder this system uses the hydraulic fluid to exert a force on the brake shoes to press them against the brake drum. Next there is the brake drum. This part rotates with the axle and the part where the brake shoes are pressed up against to create the friction allowing the vehicle to slow down or stop.(Erjavec, 2005) This part is designed to be able to withstand considerable amounts of heat and should be resistant to wear. The final part is the brake shoes. These are a consumable part of the system and are normally made from two pieces of two welded parts of steel. This is the part that is pressed against the inside of the drum to slow or stop the vehicle.(Halderman, 2010) While the life of this component can vary these should be replaced on average every 50,000 miles. They should also be checked often for any damage or deterioration, this can either be observed with a physical check or can sometimes be felt while driving, especially if the braking performance is reduced.

2.1. History

The person who is credited with inventing the drum brake as it is known today is Louis Renault in 1902 who used an asbestos lining on the outside of the drum to dissipate the heat produced by the friction of the shoes against the drum.

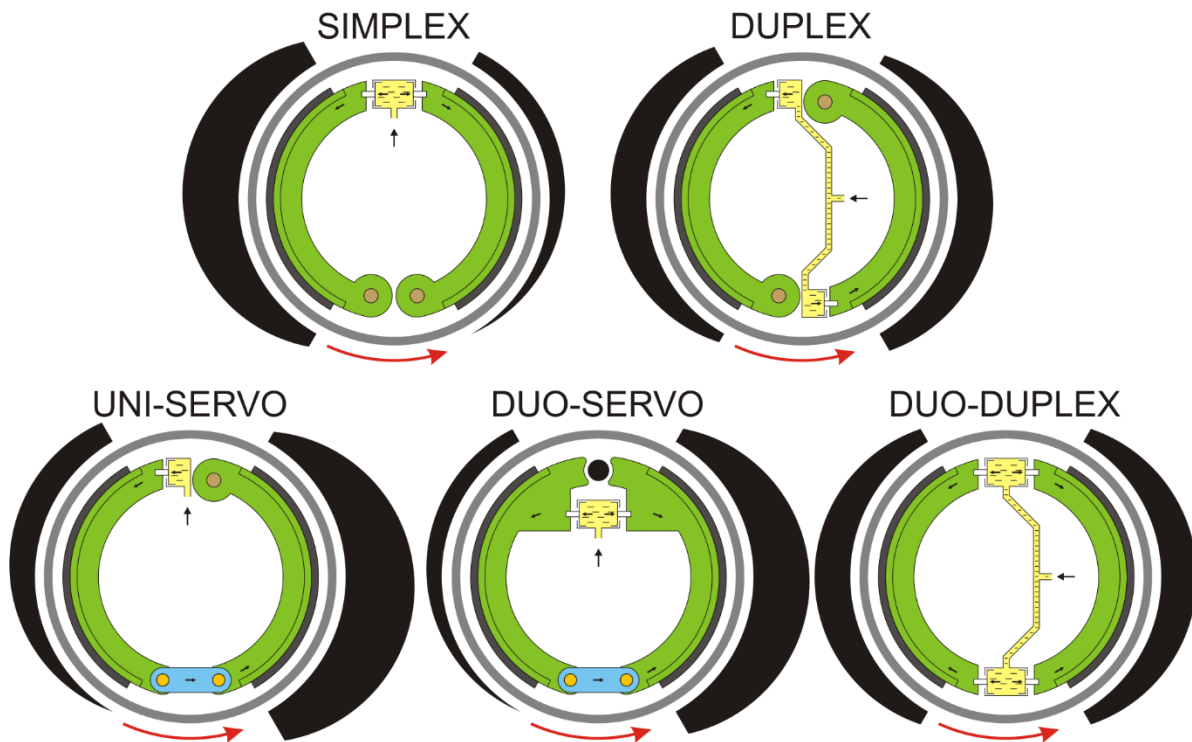


Figure 1 - Drum Brake Designs (Hagino, Oyama and Sasaki, 2016)

Figure 1 shows the different variants of drum brakes. As the speed of cars began to increase the need for more braking performance became evident. In 1919 the Hispano-Suiza H6B used one single brake pedal to operating a braking system that was attached to all four wheels. This allowed for more stopping power but also a more controlled stop.(Vance, 2001)

In the early 1920s the use of hydraulics was introduced into the braking system. If the hydraulic system stayed as a closed loop and there was no damage to the brake lines the hydraulic system was far more reliable than the original mechanical system as it had fewer moving parts that could go wrong. One issue that the hydraulic system had was some water could get into the system and freeze in the winter. Hence why some manufactures continued using the mechanical system. During the 1930s all car manufactures had made the switch to hydraulic drum brakes. (Llewellyn Hedgbeth, 2018)

The next major development was self-adjusting brakes which occurred during the 1950s. As the shoes begin to wear out, they had further to travel to reach the edge of the drum. This system used a thread system which would unwind the shoes as they reached a certain distance from the edge to make it a similar distance to when they were originally fitted. This improved the overall safety for the driver as it gave a similar pedal feel even when the brakes began to wear out. It also allowed for more abrasive materials to be used in sports and race cars of the time as it would allow them to stop quicker but they had less worries about the distance the shoes needed to travel.(Bosch, 2007)

The final big development for drum brakes came from Bosch and Mercedes in 1978 when they introduced anti-lock brakes. This had a sensor in the wheel to detect if the wheel began to lockup

and begin to release and apply the brakes multiple times a second to prevent this from occurring. Not only did this improve the safety for the driver allowing them to remain in control but it also stopped additional wear and heat spots from occurring on the braking system. (Bosch, 2017)

Material	Tensile Strength (Mpa)	Compressive Strength (Mpa)	Shearing Strength (Mpa)	Hardness (N/mm ²)
Grey Iron (260)	200-270	800-1000	250-350	190-240

Table 1 - Grey Iron (260) Properties (Qingdao Casting Quality Industrial Co., 2018)

Table 1 shows the properties for the most common type of grey iron used in the drum brake system. (Hovorun *et al.*, 2017)

3. Theoretical Engineering Principles

The most common material for the drum of this system is cast iron. This is mainly due to the thermal conductivity properties of cast iron which helps dissipate the heat created from the braking force. Aluminium is an alternative to cast iron. It is a better thermal conductor, so it is more applicable in braking system which will have heavier use such as motorsport applications. It is also lighter than cast iron, this reduces the unsprung mass of the vehicle and can improve overall vehicle performance. The aluminium drums can have a steel or iron interior lining to reduce the wear on the aluminium drum as aluminium will wear faster than cast iron. This gives the drum the thermal conductivity properties of aluminium without the need to replace it often.

Drum brakes use a special type of cast iron known as grey iron.(Zhou *et al.*, 2013). This is more conductive and is less resistant to wear compared with standard iron or cast iron. They are made using a process called sand casting. To produce a product through sand casting first a mould needs to be created in the sand, this will be to the specific requirements of the part. Once the mould has been created in two parts it is clamped shut and the molten metal is poured in. The metal is then cooled and removed from the mould. This type of process is relatively cheap and can be used for most designs.(Smith and Hashemi, 2010)

The grey iron is named such due to its grey colour caused by the 2.5-4% (Ghassemieh, 2011) carbon in it and the 1-3% silicon microscopic flakes in the metal. These form graphite during the manufacturing process. The shape and size of the flakes will affect the overall properties of the metal. Grey cast iron has many benefits hence why it is often the choice for the drum. While being brittle due to the graphite it tough and can therefore meet the requirements needed to withstand the forces that a typical drum will see.(Ihm, 2011) Another benefit to grey cast iron is it can withstand heat cycles. This is important with brakes as they can often be heated and cooled multiple times a drive due to the friction of the shoes against the drum. As grey iron has good damping properties due to the graphite content which allows the metal to transfer damping energy into heat.



Figure 2 - Microscopic Structure of Grey Iron (Cambridge University, 2001)

Figure 2 show how the microscopic structure of grey iron can differ depending on the graphite content and the process used to manufacture it.

3.1. Frictional Wear

Friction is the force that occurs when two materials move against each other. The type of friction seen in a drum brake system is dry friction as there is no lubrication between the drum and the shoes. The shoes are formed of a rough material which gives them a high coefficient of friction. When the shoe presses against the drum the energy is transferred from kinetic due to the rotating wheel into thermal energy which is what allows the vehicle to slow down or stop. This frictional force is why the shoes begin to wear after a period of time and need to be replaced. If they were never replaced the metal under the abrasive material would then begin to rub against the drum which will not only decrease the braking performance but can also cause damage to the system.

Material Description	Application(s)	Approximate Year
Cast iron on steel	railroad car brake blocks and tires	prior to 1870's
Hair or cotton belting (limited by charring at about 300° F)	wagon wheels and early automobiles	ca. 1897
Woven asbestos with brass and other wires for increased strength and performance	automobiles and trucks	ca. 1908
Molded linings with shorter chrysotile fibers, brass particles, and low-ash bituminous coal	“ “ “	ca. 1926
Dry-mix molded material to replace cast iron brake blocks that produced metallic dust that shorted electric train rails	London underground	ca. 1930
Flexible resin binders developed along with more complex formulations	brake drum linings	1930's
Resin-bonded metallic brake linings	industrial and aircraft applications	1950's
Glass fibers, mineral fibers, metal fibers, carbon and synthetic fibers to provide semi-metallics with higher performance than asbestos (beginning of safety issues with asbestos)	automotive and trucks	1960's
Non-asbestos (fiberglas) materials	brake drums on original equipment cars	1980's
Suggested use of carbon fibers	automotive brakes	1991

Table 2 - Brake Shoe Materials (Blau, 2001)

Table 2 shows how the material choice for the shoes has changed as research on the subject has grown and new materials for the given use have been discovered to be better alternatives.

3.2. Thermal Fatigue

Thermal fatigue is a fatigue failure with macroscopic cracks due to temperature fluctuations, spatial temperature gradients, and high temperatures under confined thermal deformation resulting from cyclic thermal stresses and strains. Without mechanical loads, thermal fatigue might occur.(Spera, 2009). Careful consideration of thermal fatigue needs to take place with parts that are often heated and cooled throughout their life span. One common cause of thermal fatigue is macroscopic deformations. This can occur when a part is not evenly heated and cooled thus producing hot and cold spots, these colder spots hinder the thermal expansion of a part which can lead to thermal fatigue.(Balandin, 1961).

Thermal deformation can occur when a part is exposed to heat cycles or extreme temperatures. This can cause the shape of the part to either be temporarily or permanently deformed. (Haimei, 2011). For parts that have strict tolerances this can lead to damage or complete failure. To prevent this from happening the material choice is important and should be selected based on the intended use. Testing should be done until the part fails to find out how it behaves under extreme conditions. Coatings can also be applied to the metal such as an anodised copper coating to improve the thermal conductivity of the metal and reduce the chance of failure.

3.3. Corrosion

Corrosion is the name given when refined metals return to their natural oxidised states, most commonly when they are exposed to the air and react with the oxygen in the air.(Shaw and Kelly, 2006) Corrosion is not always a negative effect as certain metals can benefit from the corrosion depending on the intended use. Aluminium and copper form a protective layer when oxidised, this prevents the oxidation process from further corroding the metal, thus preventing any further material loss.(McCafferty and McCafferty, 2010).

Other materials such as iron are not positively affected by corrosion. This is because when iron oxidises it forms rust. The rust that forms has no protective qualities for the iron meaning once rust has begun forming on a part it will continue to rust even if it is cleaned off.(Gräfen *et al.*, 2000). Rust will continue to deteriorate the metal if not treated correctly. The addition of salt either in the air or in water can accelerate the effects of corrosion.



Figure 3 - Corrosion of Cast Iron

Figure 3 (Lodge Cast Iron, 2020) shows an example of corroded vs non corroded cast iron. One example of corrosion prevention in iron is galvanizing. This is when a layer of zinc is applied to the outer layer of the iron to prevent the effects of corrosion. The most common method is hot-dip

galvanizing, this is when the iron is taken to the bare metal and all grime is removed from the surface. It is then dipped in a vat of liquid zinc; the part is removed and left to cool. This forms a protective layer over the layer to resist the effects of corrosion.(American Galvanizers Association, 2012). The part is often painted over the zinc layer which provides an extra layer of protection. If these protective layers are chipped or damaged and not treated quickly the iron will begin to oxidise and this will spread over the part.(Haynes, 2018)

4. Experimental Procedures

4.1. Thermal Fatigue

The report being considered for this part investigated 'thermal seizures in automotive drum brakes'.(Singh *et al.*, 2010).

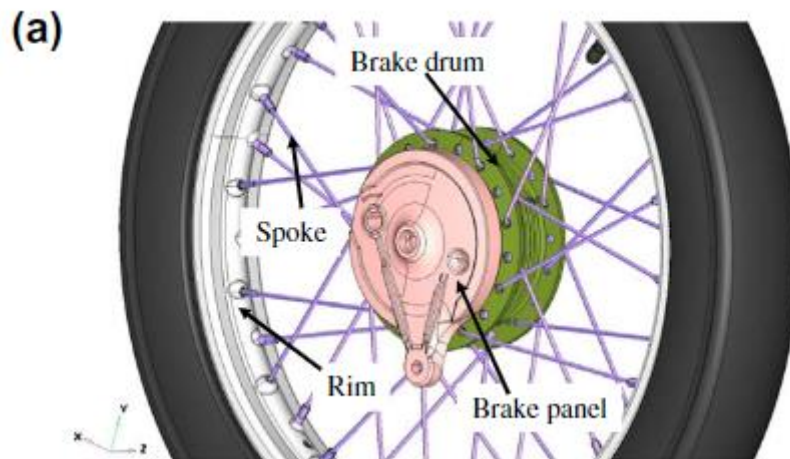


Figure 4 - Bike Drum Brake Design

Figure 4 shows the different components being tested in this investigation. This is from a motorbike, but the results can be translated to other drum brake systems.

Since drum brakes are an enclosed system it is harder to dissipate the heat generated under braking compared with modern disc brakes which are exposed to the air. If too much heat is built up in the system, it can lead to brake fade which will decrease the stopping force of the brakes. Hence why it is important to efficiently dissipate the heat generated without affecting the structural integrity of any of the components.



Figure 5 - Seized Drum Brake

Figure 5 shows a drum brake which has seized and damaged the drum.

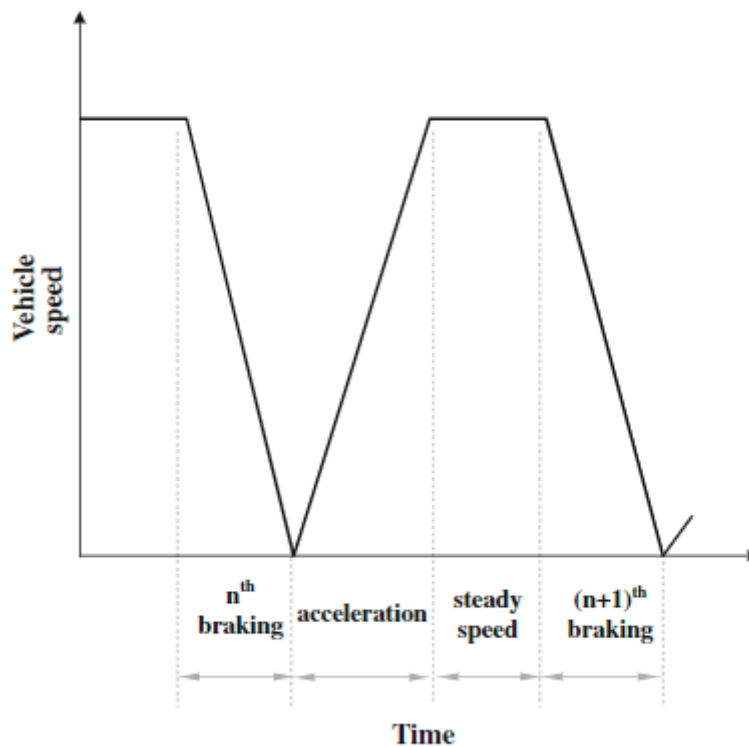
Three main factors were investigated as to why the system had a thermal failure. The first was the chemical composition of the metals, the second being the hardness of the materials and the final factor being excess free ferrite in the drum. As previously discussed, the graphite content and structure in grey iron can affect its properties. It was discovered that graphite content was below the recommended amount for this application. A test to find the hardness of the drum liner was conducted using a Brinell hardness tester. (N. Dowling, 1993) This test involves indenting a test piece with a hardened steel or carbide sphere with a 1mm diameter. A load of 10kg was placed on the test piece. The diameter of the indent is measured with a microscope and equation 1 is used to calculate the hardness of the test piece.

Equation 1 - Brinell Hardness

$$\text{Hardness} \left(\frac{n}{\text{mm}^2} \right) = \frac{\text{Load}}{\left(\frac{\pi * \text{Ball Diameter}^2}{2} \right) * (\text{Ball Diameter} - \sqrt{\text{Ball Diameter}^2 - \text{Indent Diameter}^2})}$$

It was found that the hardness met the requirements of the part.

Although the graphite content of the material was slightly low it was deemed that none of these factors were a contributing factor to the failure so further testing was required. A new test was done which ran the wheels at 50 kph and maximum braking force was applied without the wheels locking. This would generate the maximum temperature in the brakes. The test procedure can be seen in graph 1.



Graph 1 - Braking Test Procedure

This was repeated 60 times for each material and the temperature was measured every 10 tests.

Four different materials were tested all with varying ferrite content in the grey iron. These were tested for the drum, wheel rim and panel. An example of the different ferrite content can be seen in figure 6.

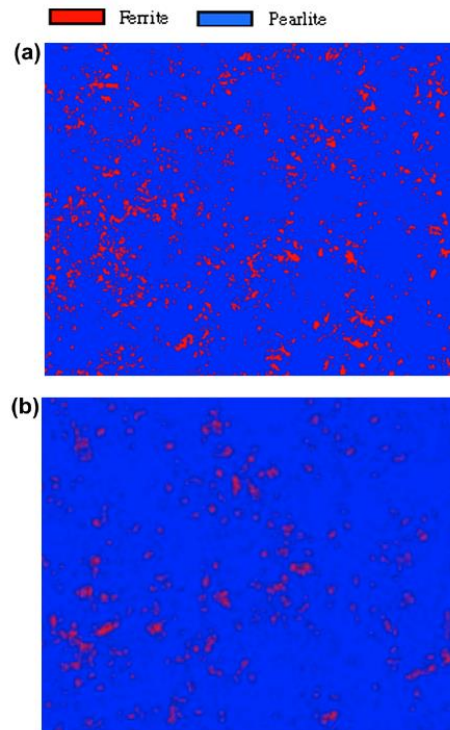
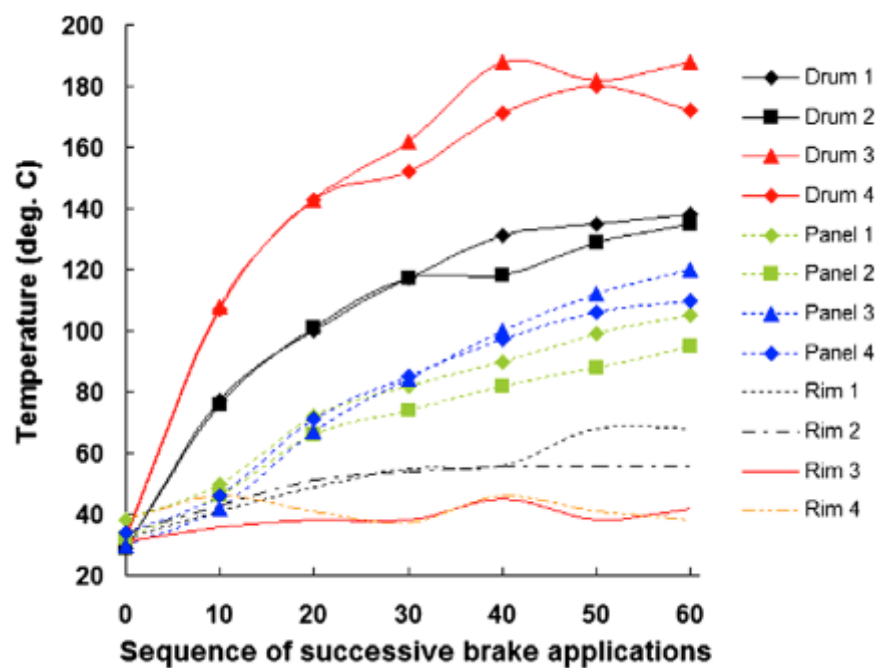


Figure 6 - Grey Iron Ferrite Content Comparison

The results for the test can be seen in graph 2.



Graph 2 - Brake System Temperatures

Rims 1 and 2 used aluminium cast rims and rims 3 and 4 used spoked rims. It was found that failures only occurred for this test on spoked rims and not with the alloy rims suggesting this was a contributing factor to the failure.

The final conclusions of the report found that the spoked rims had a higher average temperature than the alloy rims under the same conditions. It also found that the thermal expansion of the spoked rims was 40% higher than the alloys and this led to the clearances needed for the brakes to work properly to become misaligned. This was the main contributing factor of the failure. To prevent this failure from occurring the parts were redesigned to adjust for the new clearances required and this prevented the failure from occurring.

From this report it can be deduced that when looking at the brake system regarding thermal failure, not only should the brake system be considered but also any attaching part. This is because when the heat is being dissipated away from the drum any other parts attached to it which have thermal conductive properties will begin to absorb the heat. As the aluminium alloy rims are a good thermal conductor (Baudouy and Four, 2014), they can absorb the heat generated by the braking system and distribute it efficiently. If this problem were found again it would be suggested that the tester, consider a different wheel material or design to try and dissipate some of the heat away from the braking system which can improve the whole brake system.

4.2. Friction Failure

The report being considered for this part investigated 'Microstructure of the worn surfaces on drum in brake systems'.(Erdoğan, Yavuz and Erçetin, 2015). To conduct the experiments for this report samples were taken from a failed drum and were emiered down each with different grit emery paper, then placed in an ultrasonic bath to clean each sample. A Vickers hardness test was conducted on each test piece. This test consist of using a pyramid diamond to indent the test pieces at an angle of 136°.(Smith and Sandly, 1922)

Equation 2 - Vickers Hardness

$$Hardness \left(\frac{N}{mm^2} \right) = 1.854 * \left(\frac{Load}{(Mean\ of\ two\ diagonals)^2} \right)$$

Grey cast iron was the metal used in the drum and the chemical composition can be found in table 3.

Table 3 - Grey Iron Chemical Composition

C	Si	Mn	P	S
3.73	2.25	1.01	0.0313	0.0347
Cu	Cr	Ti	Ni	Fe
0.187	0.162	0.0132	0.0102	92.5

After investigation under a microscope, it was determined that the failure had occurred due to a combination of frictional fatigue and corrosion. Using a brake shoe that is too abrasive can cause scouring on the surface, it can also put the drum through heat treatment which weakens the structure of the part. The scouring on the drum resulted in corrosion of the iron. As this occurred on the inside of the drum it would not be observed during a visual inspection of the part. This was another contributing factor to the failure.

To reduce this chance of this occurring it would be recommended that the choice of material for the brake shoe with regards to its coefficient of friction should be carefully considered. If the coefficient of friction is too high, then it can result in the type of failure seen in this report and can also wear out the brake shoes quicker meaning more maintenance will be required on the system. If the coefficient is too low, then the braking force required to slow the vehicle down at an acceptable rate will not be seen which can be dangerous for the operator.

4.3. Manufacturing Defects

The report being considered for this part investigated 'Manufacturing Process Defects of Automotive Brake Drums' (Daems *et al.*, 2016). This report outlines some of the issues that can arise through the manufacturing process.

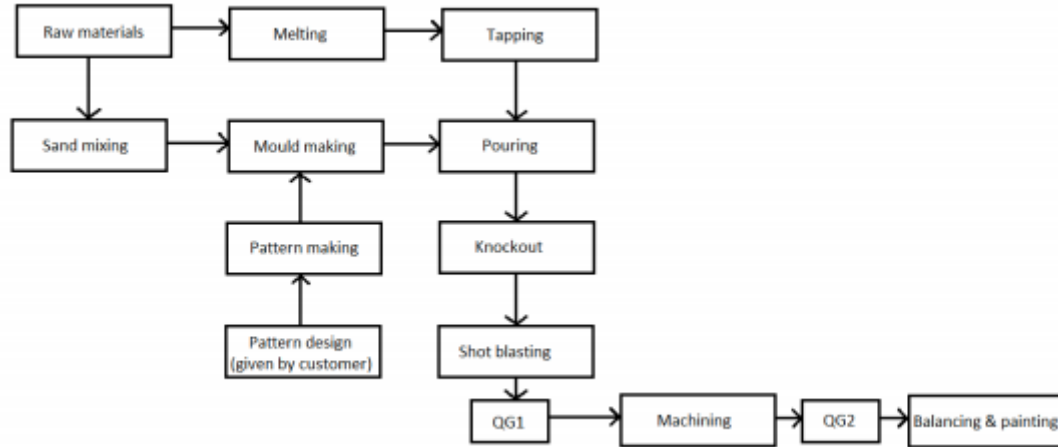


Figure 7 - Grey Iron Manufacturing Process

Figure 7 shows the manufacturing process of the brake drum.

The meting process is when the mixture of metals is created, and this will change depending on the final desired metal. The pouring process needs to be done in a certain amount of time to prevent any scabbing or holes forming in the metal.

Equation 3 - Pouring Time

$$\text{Pouring time (s)} = \text{Constant Factor} * \left(0.95 + \frac{\text{Thickness (inch)}}{0.853} \right) * \sqrt[2]{\text{Mass (Pound)}}$$

Equation 3 is the equation used to calculate the maximum pouring time without a defect occurring. The cooling time after the melting process depends on the mass of the metal but it can range form 30 minutes to an hour. The next process is shot blasting where any sand or other debris is removed from the metal by firing small steel balls at the metal. Once the metal is clean a visual inspection can occur which will reveal any initial defects.

The part is then machined, this process will vary depending on the metal used and the requirements of the part. Once the machining is complete another inspection for defects is done as some defects are only revealed after the machining process.

Table 4 - List of Defects

Defects before machining		Defects after machining			
SD	Sand drop	BHBR	Blow hole brake surface	MB	Mould break
MB	Mould break	BHT	Blow hole top	SHR	Shrinkage
MC	Mould crush	BHF	Blow hole flange	SCB	Scabbing
BH	Blowhole	BHB	Blow hole bore	SI	Sand inclusion
MM	Mismatch	F/O	Flange oversize	SLG	Slag inclusion
SHR	Shrinkage	F/UC	Flange unclean	DM	Damage
RS	Rough surface	T/UC	Top unclean		
SCB	Scabbing	M/F	Machining fault		
DM	Damage	ECC	Eccentricity		
ECC	Eccentricity	SD	Sand drop		

Table 4 shows a list of defects that can occur before and after machining.

Shrinkage can occur when the mould is not formed correctly as this can impact the pouring time of the molten metal into the mould and cause a defect. Scabbing can occur when any lubrication mixes with the sand in the mould. This weakens the mould which can cause defects. Facing sand can be used to try and prevent this from occurring.

Blow holes are mainly seen at the top of the cast as this is the part filled last. To reduce the effects of this cooling vents can be implemented in the mould. Machine faults can either be down to faulty equipment or user error.

Knowing this information can help reduce the chance of having manufacturing defects as the causes are known and thus an attempt to prevent them can be made. This report also found that the main cause of defects during this process came from the mould. Therefore their advice was to ensure the sand used in the mould was of the correct standard and the mould preparation was up to a standard to produce a part with less chance of defects occurring.

5. Conclusion

This report has shown that if careful consideration towards the material properties of a brake drum system is not taken it can lead to a catastrophic failure. Multiple factors effect the use of a brake drum system during normal use and preventative measures should be taken to reduce the chances of these occurring. The system can have continued wear that will not instantly effect the system but will weaken it and could cause complete failure later in its lifespan.

Further work could be conducted investigating alternative materials such as aluminium for the drum as this is a lighter and stronger material that is less impacted by corrosion.

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