

University of Wales Trinity Saint David School of Engineering

Analysis and Recommendation for the Minimisation of Material Failures Mechanisms of Materials Failure ACEA7010

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1 Introduction

There are many examples through history of catastrophic events where later investigation found that it was a result or partly down to a materials failure. Some prime examples of this are the Titanic or the Comet air crash. This is when an object breaks or deforms due to the material not being suitable for its use. There are many ways in which a material can fail and some of these will be set out in this report. The author will investigate a component for material failure analysis and investigate the design process which it took, to get to that point in terms of material failure.

2 History and Development of Component

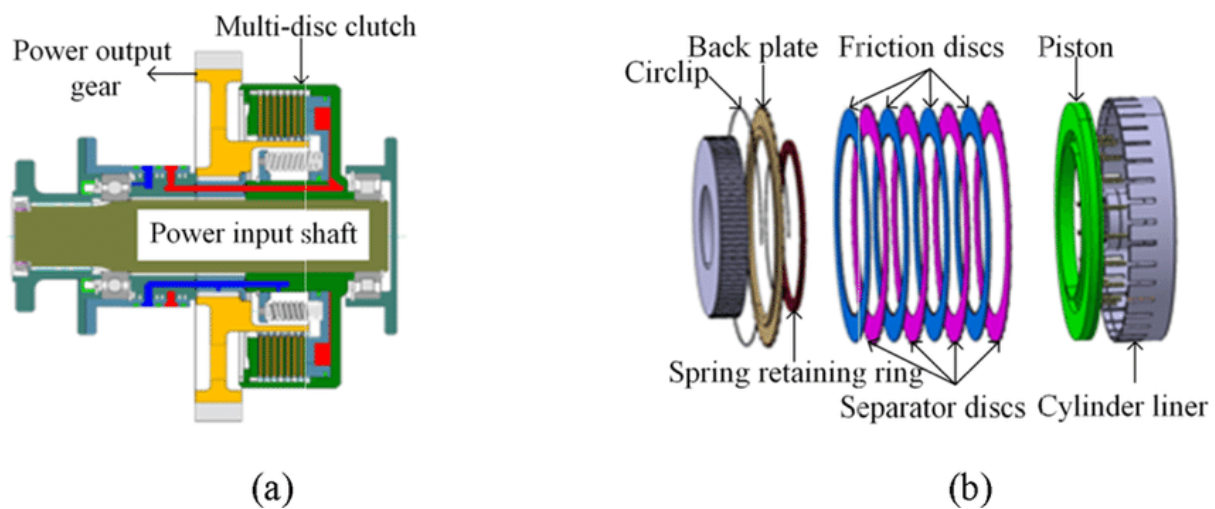


Figure 1-Schematic of Multiplate Clutch Assembly (Wu, et al., 2018)

The component chosen was a plate clutch assembly. The initial development of the clutch started with Karl Benz's first car, realising some slipping was needed to have a smooth engagement of the engines power to the transmission. He first looked at mechanical belts (figure 2), but they would wear too quickly so he then later decided on a cone shaped clutch (Autotech-Nath, 2020). It was then in 1910 when a single plate clutch was introduced as this has a larger surface area to transmit the larger torque now being produced by engines. The development then went into different plate materials to improve the wear and usability. Through the years the materials have changed from surfaces made of leather and cork to now more hard-wearing materials such as carbon, steel, and aluminium. In non-automotive cases, some clutches are made of cellulose, aramid, chopped glass, rubber and brass fibres to make a composite clutch (Frictionmaterials.com, 2020). The benefit of changing the clutch materials is that it can offer more grip when needed for the high torque output such as a race engine. There is also durability concern as some clutch materials will wear away quicker than others so, for say a normal road car use you would want a material that will last a long time as it is

expensive to replace a clutch plate in labour costs. In the past asbestos was a favoured material as it has a high resistance to heat as well as, if correctly made a high friction coefficient. However, for obvious reasons this practice was stopped due to the health hazards involved such as mesothelioma (King, 2020) in the 1980's. For higher end and racing a multiple plate arrangement is used. A multiplate clutch is advantageous as it has a much larger surface area and can be had in a smaller space rather than having a singular large plate. This reduces the inertia of the clutch as it has a smaller radius making it easier to accelerate and therefore transfer torque quicker. Modern clutches also often have inbuilt springs to further smooth out the engagement of the clutch to counteract fluctuations in engine rpm (Haynes, 2020). There are also two subgroups of clutches of wet and dry. Most road cars are dry as they are cheaper. A wet clutch is used in some heavy vehicles, motorcycles, and some high-end cars. It is when the clutch is bathed in oil to keep its temperature down and to lubricate the components. This is generally used for more high torque uses so that it avoids excessive wear. (Ferne, 2017).

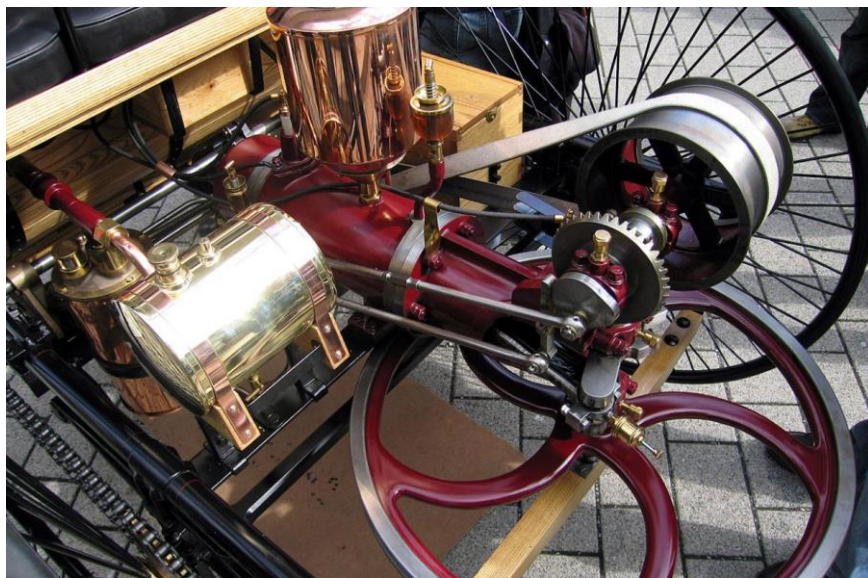


Figure 2-First Clutch Mechanism Using a Belt System (Ben, 2020)

3 Engineering Principles

3.1 Mechanical Properties

There are many ways in which materials can fail whether that is due to the load acting on them, the environment or just general wear. For a clutch assembly there is very little environmental problems as it is sealed within the bell housing. One example of mechanism of failure within the clutch assembly is fracture. A fracture is when a part is broken due to crack propagation. If the wrong mechanical property is chosen for the part, then it may be over engineered or can lead to catastrophic failure. One mechanical property to consider is the strength of the material. This is the ability of a material to resist permanent deformation. Metal is considered very strong as they have a high resistance to breaking. The mechanical properties will vary in a material depending on whether it is in compression or tension. Generally, in most metals the compressive stress is much stronger than the tensile stress. This is because the structure inside the metals can withstand compression better than tension because of the bonds within are easy to pull apart. Strength can be measured using a number of methods in compression and tension. One example could be using a universal testing machine which can put a material under a certain amount of load and see how much it deforms. This will give a stress strain curve which can be used to find out a number of properties of the material such as Young's modulus, strength, elastic limit, and yield point.



Figure 3-Universal Testing Machine (aml Instruments, 2020)

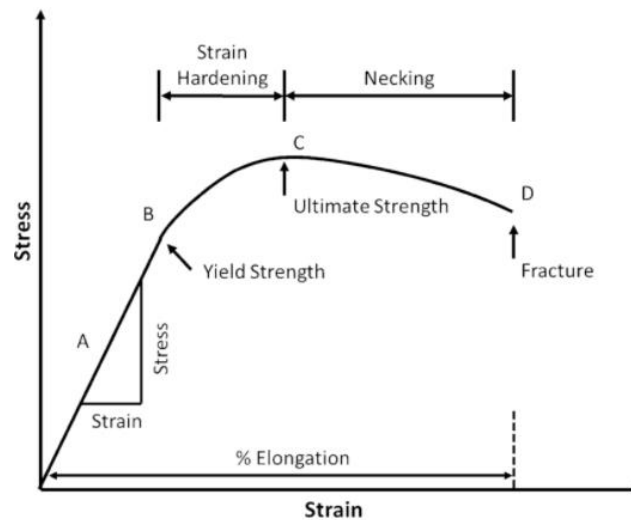


Figure 4-Stress Strain Curve for a Material (Lim & Hoag, 2013)

There is also toughness which is how much a material can absorb energy before fracturing. This has a relationship to strength and ductility but being ductile does not mean that the material is tough (NDT Resource Center, 2020). A material such as iron can be considered to have a low toughness as it can break easily when loaded sharply but be regarded as quite strong. The toughness of a material differs depending on several factors such as temperature and its internal structure. Toughness is measured in a number of ways such as the Charpy V-notch test which is essentially a hammer hitting a v notched groove in a test piece and increasing the energy of the pendulum until the test piece breaks (Wojes, 2019).

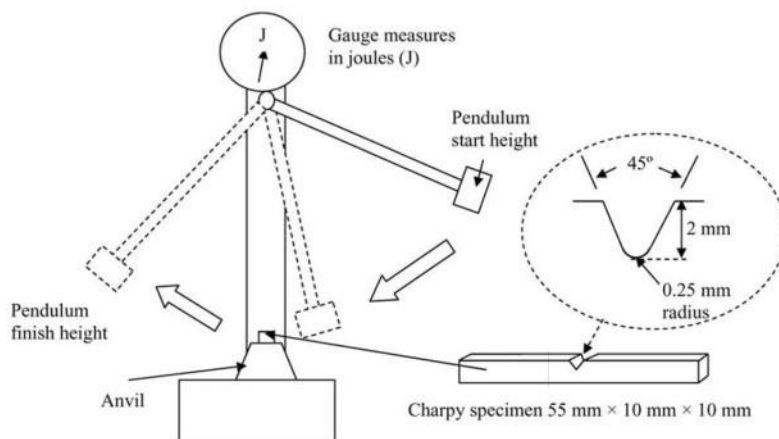


Figure 5-Charpy Test (E.Hughes, 2009)

Furthermore, there is also the hardness of the material. This is the ability of a material to resist deformation when indented (Smith, 2007). This is important in materials that wear as this will largely define how much they wear. An example of a material which is hard is diamond and one that is not hard are gels. There are several ways in which to measure hardness but generally they are a variation of indenting a material with a press and keep going until the indentation gets to a certain amount for a given force (Newage Hardness Testing, n.d.).

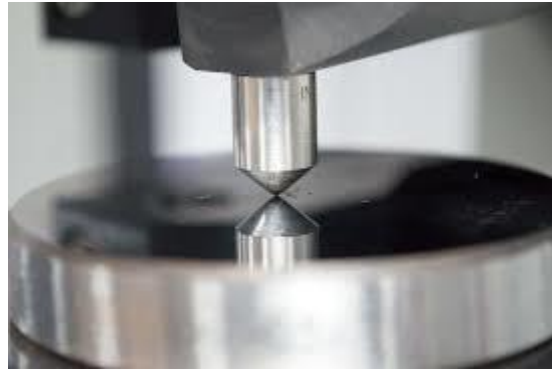


Figure 6-Hardness Testing (Tecquipment Academia, n.d.)

The mechanical properties are largely defined by the microstructure of the material. Metal has a crystalline structure with errors, which can lead to the formation of cracks. The structure is made of many crystals which are a number of ions bound together by bonds (Washington University, n.d.). There are three categories of defects within a structure. One is point defects, where there are missing ions and vacancies within a crystal. This causes the bonds between the rest of the structure to be weaker. Another type is line defects which is when there is a misalignment of a whole line of ions. Then finally, there are plane defects which is when there are defects in the surface of the crystal. A notable example of this is along a grain boundary (Libre Texts, 2020). A grain is a single crystal so within a part there can be millions depending on grain size and part size. As there are possibility of defects on the grain boundary the less grains there are the better, as to fill the space the grains have to be larger. This can increase the fracture toughness as there is less opportunity for defects because there are less boundaries (Li & Li, 2006). The main method of inspecting the grain structure of a part is by using an electron microscope. If the edge of the failure is visible it is possible to see how the metal failed through how the grains formation have changes due to the break. These formations can generally be seen when the sizing of the microscope picture is in the order of $100\mu\text{m}$ (Struers, 2021). The grain structure can vary due to a number of things, such as the material composition and manufacturing method like casting, forging, and machining. The structure can have impurities introduced when casting which may cause stress concentrations within the structure. Forging generally does not have this issue due to most of the impurities are removed through the forging process. Another benefit of forging is that it can have a grain flow which can mean that the strength of the part can be increased so that the flow lines are perpendicular to the highest stress direction. Machining can also introduce weakness at the surface as it can cut through flow lines which will leave them exposed at the ends. This is why often untreated machined parts can start to corrode at the exposed sections where it has been cut.

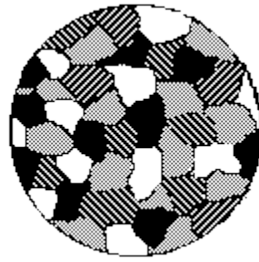


Figure 7-Example of a Grain Structure in Metal (University of Washington, n.d.)

An example of a part breaking due to it not having a high enough strength could be the hub of the clutch disk being ripped out. Generally, this suggests that the metal chosen was not strong enough to withstand the torque acting on the disk. This can also be caused from too high a load being put through it. So, it could perhaps be that the engine has been changed to produce a higher torque and the clutch has not been upgraded to suit the need so is put under too much stress than the disk was designed for. This may also occur if the gear is selected for too high a road speed causing it to increase the speed of the engine too quickly. In this case the locations of the shear are where the metal is thinnest. Part of this may also be due to there being stress concentrations at these points. A stress concentration is a location on a component where there is a higher level of stress than the rest of the part. This could be due to that it has a sharp edge or notch. This is because these are sections where cracks can easily propagate from. Stress concentrations do not need to be obvious they can be microscopic in the surface of the material or in the internal structure itself.



Figure 8-Example of a Fractured Clutch Disk (Schaeffler, 2017)

3.2 Friction/Wear

Another mechanism which affects clutches is friction wear as this is a key part of the operation of a clutch. The amount that the clutch wears vary on a number of factors such as the surface area, force applied, surface hardness etc. The science of friction contact between solid bodies comes under tribology. The reason for wear is the removal of material from the surface. This changes the shape of the mating components so affects its useful life (Ashraf, et al., 2009). There are different mechanisms of wear. One is adhesion and fracture where materials stick together momentarily and then when they are pulled apart ripping some of the surface off. Then there is abrasion and fracture where the surface is ploughed which causes it to change shape and then fracture. There is also fatigue where the constant changing shape on the surface causes a fracture. However, for an automotive clutch this is such a small amount that it is not noticeable to the user until the material has completely worn down. This can be predicted by a number of different models such as the differential wear model and the integral wear model (Grzelczyk & Awrejcewicz, 2015). There are also a number of experimental methods which have been put forward such as having a machine which simulates the use of the clutch through its lifetime (Grzelczyk & Awrejcewicz, 2015). This can then give a value of wear across time. It can also give values of how much the torque changes through the time period. This is because as time goes on the adhesiveness the material is changing so the amount of torque being transferred changes. It is also possible to see the contact pressure around the clutch surface. This can give an indication where on the clutch is having the most force put through it.

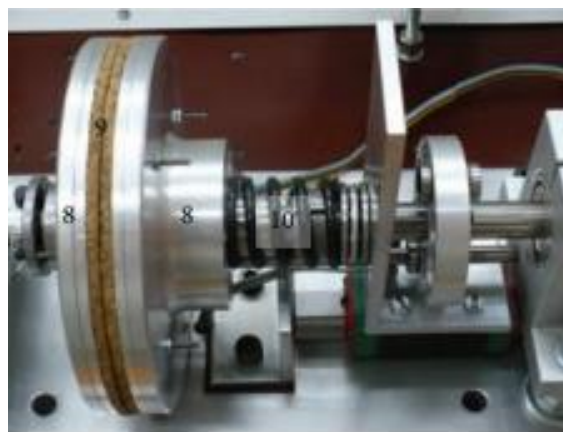


Figure 9-Example of a Clutch Wear Measuring Equipment (Grzelczyk & Awrejcewicz, 2015)

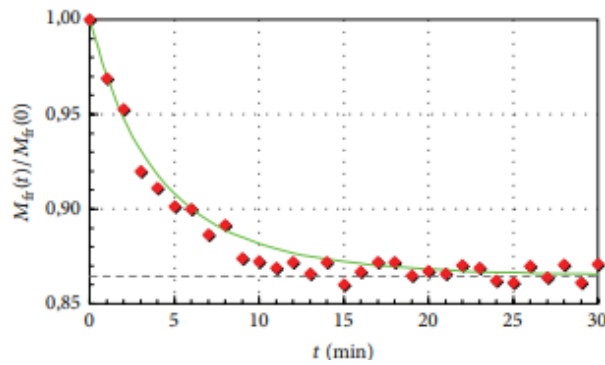


Figure 11-Friction Torque Transmitted by Clutch (Grzelczyk & Awrejcewicz, 2015)

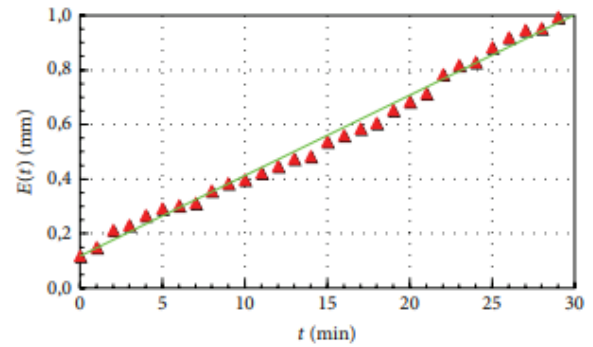


Figure 10- Decrease of Distance Between Clutch Shields During Wear Process (Grzelczyk & Awrejcewicz, 2015)

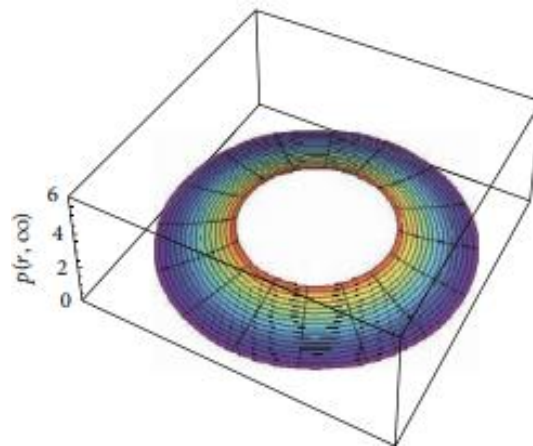


Figure 12-Visual Representation of the Contact Pressure on a Clutch Disk (Grzelczyk & Awrejcewicz, 2015)

Furthermore, another reason for a failure of a clutch disk is known as glazing. This is when the surface of the clutch is smoothed over from the material overheating. This will cause the friction material to have a considerable decrease in friction coefficient and may leave the clutch unusable. The heat may become so excessive in some case that the actual clutch material can begin to burn.



Figure 14-Example of Glazed Clutch Disk (Schaeffler, 2017)



Figure 13-Example of Burnt Clutch Disk (Schaeffler, 2017)

After a catastrophic failure it is also possible to view the effect of wear on a pressure plate. From a case study from (Psyllaki, et al., 2012) it can be seen that using macroscopic observations the surface of the failed part could be seen. This shows signs of ploughing which was discussed earlier in this paper. They also measured the roughness of the surface to produce an anaglyph. This can be done in a number of ways such as using an electron microscope, stylus method, and atomic attraction. They are used to show that the surface is very scored with peaks and troughs. Their findings found that there were random voids within the metal which suggested that there was a ductile rupture of the surface when it was under a high pressure. A ductile rupture is when a component fails due to be pulled apart instead of cracking (Corrosionpedia, 2014). These voids were formed from impurities within the cast metal which caused stress concentrations. These impurities maybe pieces of slag. If it is a poor casting it may also lead to air pockets, which when the component cools and shrinks may lead to cracks forming.

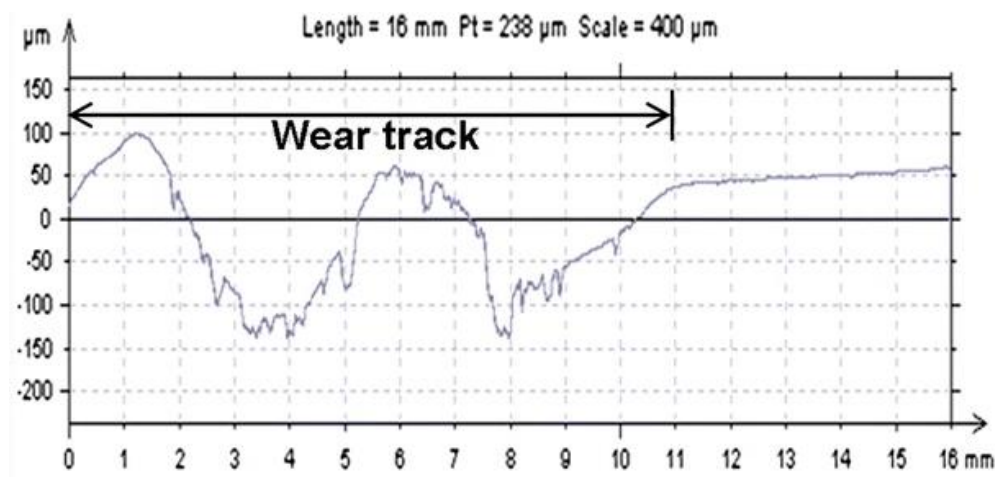


Figure 15-Example of Roughness Diagram of Pressure Plate (Psyllaki, et al., 2012)

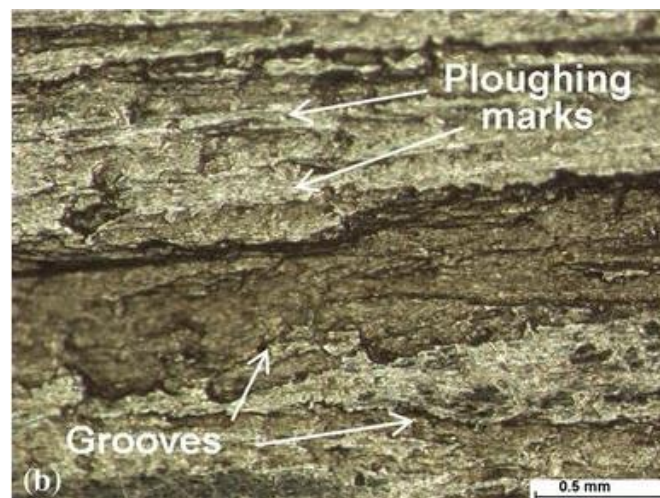


Figure 16-Visual of Worn Pressure Plate (Psyllaki, et al., 2012)

3.3 Thermal Fatigue

Another mechanism of failure that needs to be considered is the temperature of which the clutch is working at. If the pressure plate of the assembly overheats there are examples where it has fractured. A way of finding if it was overheated is looking at the surface of the metal. If the part has overheated on metal, there is sometimes a heat tint to the surface. This generally occurs because the clutch has been slipping which suggests it is rubbing more generating heat from the friction. The failure is caused because the metal is repeatedly being expanded and then cooled again, which causes shrinking known as thermal fatigue (Xin, 2013). This causes any cracks to grow and if left long enough can cause the pressure plate to fracture as can be seen below. The factors that affect the thermal fatigue of metal is considered as ductility and toughness. A highly ductile material tends to be more resistant to thermal fatigue and also to crack initiation and propagation, (P.Boyce, 2011) but then it would not be strong enough to take the pressure needed for a driveline.



Figure 17-Example of Fractured Pressure Plate Due to Overheating (Schaeffler, 2017)

One method of testing this is having samples and putting it through the thermal cycles which is less of a thermal gradient than that predicted to have caused the damage. Then this can be repeated increasing the temperature difference until the sample begins to fail. The average temperature difference from the starting and final value is often described as the thermal shock resistance (Davidge, 1991). A way of preventing this could be by using a coating on the pressure plate which can withstand higher loads than that of the base metal. However, the friction properties of that surface would also need to be considered.

3.4 Fatigue

Fatigue is the mechanism of which a part breaks when it has been through a number of loading cycles. The amount of fatigue which goes through a part varies depending on temperature, loading, and environment (Polak, 2007). Fatigue failure is a result of the initiation and then the propagation of cracks. To improve fatigue resistance a coating is sometimes applied to the surface as this is where cracks usually emanate from (Jeddi & Palin-Luc, 2018). Fatigue can be catastrophic as a part can break without warning with a fluctuating load well below the yield point of the material (Mathers, n.d.). An example of a part which can suffer from fatigue in the clutch assembly is the diaphragm spring. This is the spring which engages the clutch, so it is used for every gear change which suggests it goes through a lot of cyclic loading through its lifetime.



Figure 18--Fractured Diaphragm Spring from Fatigue (Performance GMBH, n.d.)

The way in which this is tested is literally just cycle the part through typical conditions over and over until the part breaks. From this the fatigue life can be calculated which is the total number of cycles a material can go through under a single loading scheme (Test Resources, 2021). Another way of testing is a visual inspection after the failure to see that it was a fatigue failure. A visual cue when viewed under a high magnification electron scanning microscope is what is known as beach marks which radiate from the origin of the failure. These become coarser as the crack propagation increases and eventually ends in a ductile failure (Mathers, n.d.). Often fatigue failure cracks propagate from notches or areas where there are sharp corners known as stress concentrations. These are areas where there are higher stress concentrations than others and are where parts are expected to break if they do. To combat this often parts are added material in these areas if possible. Another option is to design the part so that the edges are curved and not have sharp edges spreading the stress across a larger area.

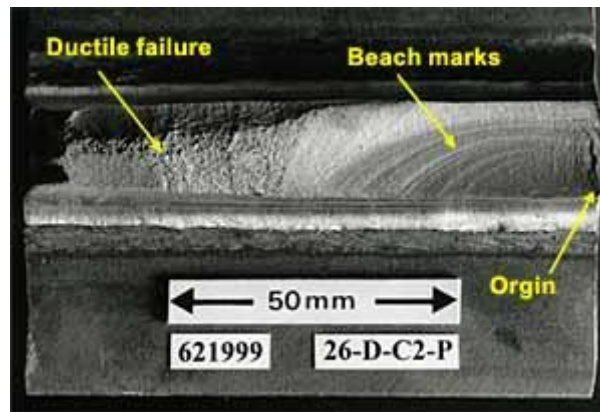


Figure 19-Metallic Structure of a Metal Fracturing Due to Fatigue (Mathers, n.d.)

The number of cycles can be plotted on a graph which can then be put next to the amount of stress applied. This can be used by an engineer to choose which material to use depending on how the load is acting on the part and the expected life cycle. This gives an endurance limit of where the part is expected to break. If the frequency of the testing procedure is high enough it can lead to self-heating which may cause a change in the internal structure. (Jeddi & Palin-Luc, 2018). So, it is important to not have too high a frequency to simulate the actual use as close as possible but still in a shorter period of time than real world testing.

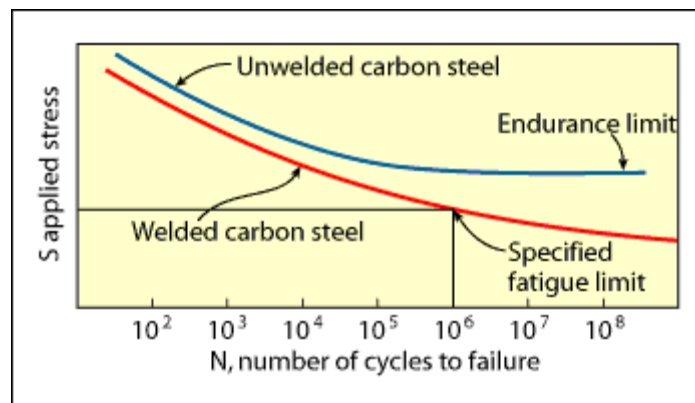


Figure 20-Fatigue Life Graph (Mathers, n.d.)



Figure 21-Fatigue Testing Machine for Diaphragm Spring (Zwick Roell, 2021)

4 Recommendations

There are a number of things which can be done to avoid the failure mechanisms set out in this paper. To avoid fractures there are a number of methods. One is the selection of the correct material. This will be using testing methods on the samples and selecting the material which is best suited to the job. This can include just sample testing at the beginning and then move onto whole component testing as the process goes through. To further make sure that the part does not break a safety factor could be included in the design to make sure that any unusual load does not break the part. Along with this the actual design can be made to avoid as many stress concentrations as possible as this means perhaps a cheaper metal could be used.

Furthermore, a rigorous quality control process could be a benefit to make sure that the parts have minimum errors within that may lead to a failure. This can be done depending on the expense possibly. For high end expensive application each individual part could be scanned to see for any voids or errors. If lower end, then making sure to use the best method possible for the cost e.g., using forging over casting.

To prevent wear on a clutch disk itself is quite difficult apart from material selection. As the nature of how the disk works it is necessary to have certain amount of abrasion so that it can generate friction. So, picking the correct material for the correct use is paramount, for example if the clutch is only going to be used for a limited amount of torque for a short amount of time using a softer compound would be more suitable. If it is high temperature, then a carbon ceramic option would be better to handle the higher temperatures.

For the wear prevention of a pressure plate perhaps a coating could be used to harden the surface. This can come in a number of forms such as carburizing (infusion of carbon), nitriding (infusion of nitrogen), and variations of the two. Such will harden the surface of the material whilst keeping the internal metal with the same material properties (Speciality Steel Treating, 2021). However, the coating needs to be considered with the thermal fatigue as the surface then may change temperature at a different rate as the inner. So perhaps another coating on that which may prevent thermal fatigue. These coatings may include various compounds such as ion-plasma coatings, electro-spark alloying and thermo-reactive diffusion (Ivanov, et al., 2003).

Surface treatment can be split into two categories. Adding material and removing material. Examples of adding is the nitriding and carbonisation. Removing could be shot peening. This is a cold process which puts the surface under compressive stress by causing plastic deformation of the surface (TWI, n.d.). Such a method is often used with springs to reduce the

effects of fatigue. That occurs as it improves the surface finish, so that cracks do not propagate as easily. Shot peening also has a number of other potential benefits such as improved stress and corrosion resistance (Pandey & Deshmukh, 2001). Surface treatment can also be as simple as having an extremely fine finish with very little surface roughness, but it is often less expensive to add a coating than remove material.

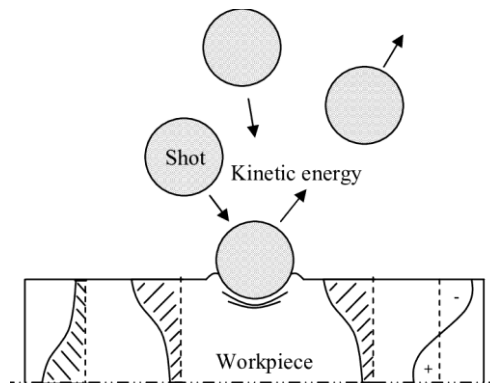


Figure 22-Shot Peening (Maawad, et al., 2010)

5 Conclusion

To conclude the author found that there were four main reasons for a material failure within the clutch assembly. This includes fracture from incorrect material choice for the amount of force going through it. It was also due to wear, although this is necessary on the disk it can be prevented on the pressure plate which is not classed as a consumable part. There are also two types of fatigue of mechanical and thermal. They can both be averted by use of coatings and correct material choice through testing and modelling of the expected life of the part.

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