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Geometric Analysis and Maintenance of a Sprocket

THESIS

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Operation and Maintenance Specialization

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T	$[s]$	periodic time
$\mathbf{v}$	$\left[\frac{m}{s}\right]$	velocity vector
μ_0	$[-]$	adhesive friction factor
ρ	$\left[\frac{kg}{m^3}\right]$	density

Abstract

This thesis investigates the geometric deterioration of a three-gear bicycle sprocket assembly and develops a corresponding maintenance strategy based on the observed wear. The sprocket system under study consists of three components with 28, 38, and 48 teeth, each having undergone an extended period of service that altered the original tooth geometry. The principal objective was to quantify the dimensional differences between the worn condition and an estimated unworn reference, interpret the underlying wear mechanisms responsible for these differences, and translate the findings into a practical maintenance prescription.

The methodology combined reverse engineering techniques with 3D laser scanning. After the assembly was carefully disassembled and each gear was prepared with a thin white coating to improve optical response, the three sprockets were digitized individually using a Shining 3D FreeScan Combo laser scanner. The resulting STL meshes were imported into Geomagic Design and Siemens NX, where solid CAD models of the worn geometry were reconstructed. A restored reference model of each sprocket was then produced by adding 0.1 mm of material to the tooth profile in order to approximate its condition prior to wear. Comparative analysis was carried out by superimposing the worn and restored models and generating colour deviation maps for both faces of each gear.

The results indicated that the most significant geometric change was concentrated at the tooth perimeter of all three gears, which is consistent with their role as the primary contact region during chain engagement. The small gear exhibited moderate and relatively balanced wear, the large gear displayed heavy and continuous deterioration along the tooth ring, and the medium gear presented the most irregular pattern, which suggests non-uniform loading and possible local deformation during service. The dominant wear mechanisms identified were abrasive and fatigue wear, with possible contributions from adhesive and corrosive wear depending on lubrication state and operating environment.

On the basis of these findings, a three-level maintenance prescription was proposed, covering preventive, condition-based, and predictive maintenance. The recommendations emphasize routine cleaning, lubrication, tightening checks, and visual inspection, supported by diagnostic instruments such as in-situ chain elongation gauges and surface roughness measurement devices, with intervals adjusted according to riding environment and load severity.

Absztrakt

Jelen szakdolgozat egy három fogaskerékből álló kerékpár-lánckerékrendszer geometriai elhasználódását vizsgálja, és a megfigyelt kopás alapján karbantartási stratégiát dolgoz ki. A vizsgált rendszer 28, 38, illetve 48 fogú egységekből áll, amelyek mindegyike hosszabb üzemidőn ment keresztül, ami módosította az eredeti fogazati geometriát. A fő célkitűzés az volt, hogy számszerűsítsük a kopott állapot és egy becsült kopatlan referenciaállapot közötti méretbeli eltéréseket, értelmezzük az ezen különbségekért felelős kopási mechanizmusokat, és az eredményeket gyakorlati karbantartási előírássá alakítsuk át.

A módszertan a reverz mérnöki eljárást 3D lézerszkenneléssel ötvözte. A szerelvény gondos szétszerelése, valamint az egyes fogaskerekeknek a szkenner optikai válaszának javítása érdekében felvitt vékony matt bevonattal történő előkészítése után a három lánckereket egyenként digitalizáltuk egy Shining 3D FreeScan Combo lézerszkenner segítségével. A keletkezett STL-hálókat a Geomagic Design és a Siemens NX szoftverekbe importáltuk, ahol a kopott geometria szilárdtest CAD-modelljeit rekonstruáltuk. Ezt követően minden egyes lánckerékhez úgy állítottunk elő helyreállított referenciamodellt, hogy a fogprofilhoz 0,1 mm anyagot adtunk hozzá, közelítve ezzel a fogak kopás előtti állapotát. Az összehasonlító elemzést a kopott és a helyreállított modellek egymásra illesztésével, valamint mindhárom fogaskerék mindkét oldalához tartozó színes eltéréstérképek létrehozásával végeztük.

Az eredmények azt mutatták, hogy a legjelentősebb geometriai változás mindhárom fogaskerék fogkerületén összpontosult, ami összhangban van azzal, hogy ezek a területek szolgálnak a lánccal való kapcsolódás elsődleges érintkezési zónájaként. A kis fogaskerék mérsékelt és viszonylag kiegyensúlyozott kopást mutatott, a nagy fogaskerék erőteljes és folyamatos elhasználódást jelenített meg a fogkoszorú mentén, míg a közepes fogaskerék produkálta a legszabálytalanabb mintázatot, ami nem egyenletes terhelésre és esetleges helyi deformációra utal az üzemelés során. A meghatározó kopási mechanizmusok az abrazív és a fáradásos kopás voltak, amelyekhez a kenési állapottól és az üzemi környezettől függően az adhéziós és a korróziós kopás is hozzájárulhatott.

Ezen eredmények alapján háromszintű karbantartási előírás született, amely a megelőző, az állapotfüggő és a prediktív karbantartást foglalja magában. Az ajánlások hangsúlyozzák a rendszeres tisztítást, a kenést, a kötések ellenőrzését és a vizuális vizsgálatot, kiegészítve olyan diagnosztikai eszközökkel, mint a helyszíni lánchosszabbodás-mérők és a felületi érdességmérő berendezések, az időközöket pedig a használati környezethez és a terhelés súlyosságához igazítva kell meghatározni.

Introduction

In the beginning, the first form of bicycles used a very primitive and direct form of motion known as the “pedal-to-wheel” system, which appeared in the early 1800s with designs such as the “Dandy Horse”. The introduction of the chaindrive system created a need for the use of sprockets, allowing pedaling power to be transferred to larger rear wheels, which therefore greatly increased the efficiency and power output of the system. In the 1870s, systems like the derailleur system appeared, which provided the ability for cyclists to shift the chains to different gears to provide better form of adaptability for different kinds of terrains and landscapes.

Sprockets are one of the primary components of a bicycle which helps by converting rotational motion of the sprocket to a linear movement of the bicycle, while operating, the teeth of the sprocket mesh with another primary component known as the chain, this forms a closed loop which allows a continuous transfer of rotational motion in the sprocket into linear movement of the bicycle.

There are many different components and factors that affect the entire efficiency and output of the system, for example, the chain and the sprocket geometry themselves can affect the mechanical efficiency of the system. The design of the chain and its lateral flexibility as well as the configuration of the sprockets will have a direct influence on the loss of efficiency in the system.

In this case study, the work uses reverse engineering practices and methods using engineering and CAD modelling softwares such as Geomagic Design and Siemens NX, 3D scanners using laser technology to provide accurate dimensioning and measurements.

This thesis will be investigating the geometry of a bicycle sprocket, the sprocket consists of three separate gears of three separate sizes assembled together. In this case study, the three gears of different sizes also have a different number of teeth, the smallest has 28, the medium sized has 38 and finally the largest has 48. The gears have been subjected to long term use that has therefore caused damage and change to its original geometry specifically in the teeth of the gears. Additionally, the goal of this thesis will be to study, analyze and compare the change in geometry of the teeth of the gears to its original model, after analysis the final goal is to prescribe suitable maintenance operations for the sprocket that will be based on, or related to the type of damage or change detected.

1 Literature Review

1.1 Manufacturing Process of Sprockets

As mentioned previously, sprockets are essential mechanical components used in chain drive systems and it is needed for the purpose of power transmission, the transfer of the torque and the maintaining of the motion control. The structural integrity and accuracy in the dimensions of the sprockets can directly affect the performance of the drive system and its longevity of lifetime. Recently, the manufacturing process of the sprockets has changed and evolved to fit in many stages such as the following, dimensioning of the part, drafting or engineering drawings, compositional analysis, material selection, selection of the kind of manufacturing process, heat treatment, finishing and finally, packaging.

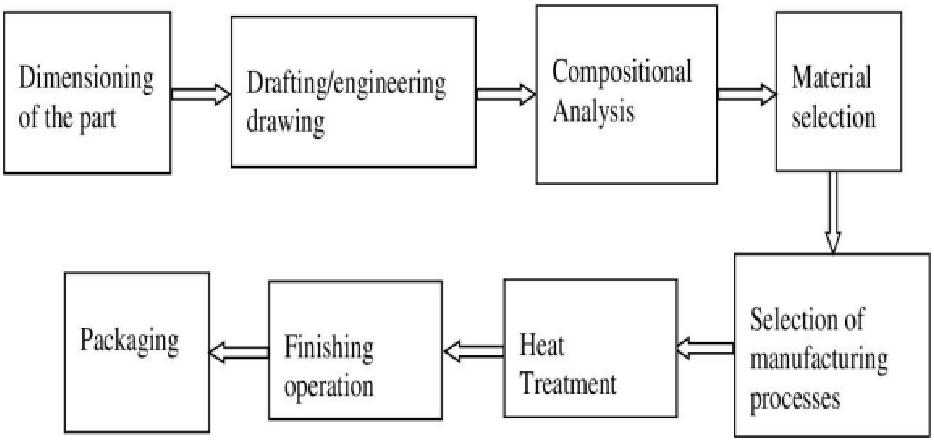


Figure 1: Process Layout [2]

1.1.1 General Manufacturing Methods

The production of sprockets starts by choosing a suitable material and also accurately identifying design parameters such as the pitch diameter, number of teeth and the tooth geometry themselves. The **IRJMETS (2024)** study shows that there are multiple different manufacturing processes for producing sprockets, such as CNC machining, pressing, water jet cutting, cryo-jet cutting, laser cutting, plasma cutting, electrical discharge machining and casting followed by finishing [2]. Although in this thesis only the process of CNC machining and water-jet cutting will be studied.

Each different manufacturing process offers its own unique advantage in factors like precision in the dimensioning, cost-effectiveness and adaptability to different materials. Water-jet cutting is special as a reliable, non-thermal method that significantly reduces heat and therefore removes the possibility of heat-affected zones and does not cause surface distortion. It works by highly pressurized water that is also sometimes mixed with abrasives, this kind of process can achieve accuracy of 0.005 inches. This makes it very good and effective in cutting metallic and composite material sprockets while protecting or not damaging its structural integrity. Although the initial setup costs for this process are higher, this method provides top quality for components requiring strict tolerances and smoother edge finishes [2].

1.1.2 Design and Optimization Process

Accurate analysis and design is also very important in the optimization of sprocket geometry and its mechanical reliability. The **IRJMETS (2024)** research describes a workflow that combines CAD modelling softwares with finite element analysis (FEA) to learn more about the factors like stress, deformation and metal fatigue during operation [2]. The sprocket analyzed in the **IRJMETS (2024)** study was designed in SolidWorks and tested with the help of the ANSYS simulation tools. Through repetitive optimization the researchers were able to achieve a reduction of weight of the sprocket by 40 percent, using an alluminium alloy (7075-T6), the usage of this alloy did not compromise strength or fatigue performance. This version of the optimized sprocket showed a fatigue life of more than 23 million cycles, which confirms the fact that lightweight designs and with the help of computational simulations are very effective strategies for producing high performance and quality components. This example of combination of digital modelling and structural analysis proves that it can help manufacturers predict potential failure points before starting the production process which can help with the reliability and efficiency of the production [2].

1.1.3 CNC Milling and Machining

CNC milling and machining is another manufacturing process used in producing sprockets, presented in the SSRG (2020) study, which focused on the creation of a multi-speed bicycle sprocket using a three-axis CNC milling machine [3]. The process of production first started with the CAD modelling in SolidWorks, the designed sprocket was following the ASME B29 standards, after that the generation of the G-code in MasterCAM, the purpose of this code is to control the cutting path of the CNC machine, feed rate, spindle speed and movement during the machining process. The sprocket was being produced using the HAAS VF-2 CNC milling machine with a 2mm ball end mill which was operating at 2000rpm and also a feed rate of 40mm/min, there was an addition of flood cooling to make sure that the production would minimize tool wear and give a high quality surface finish. The sprocket created showed excellent accuracy in dimensioning, which is confirming that CNC milling can be used to produce precise and accurate results that are repeatable for modern bicycle drivetrain systems [3].

Figure 2: CAD Model of the Sprocket [3]

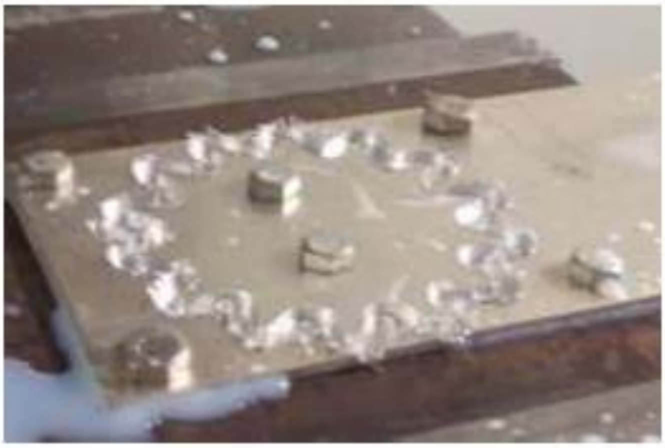


Figure 3: Machining using CNC Milling Machine [3]

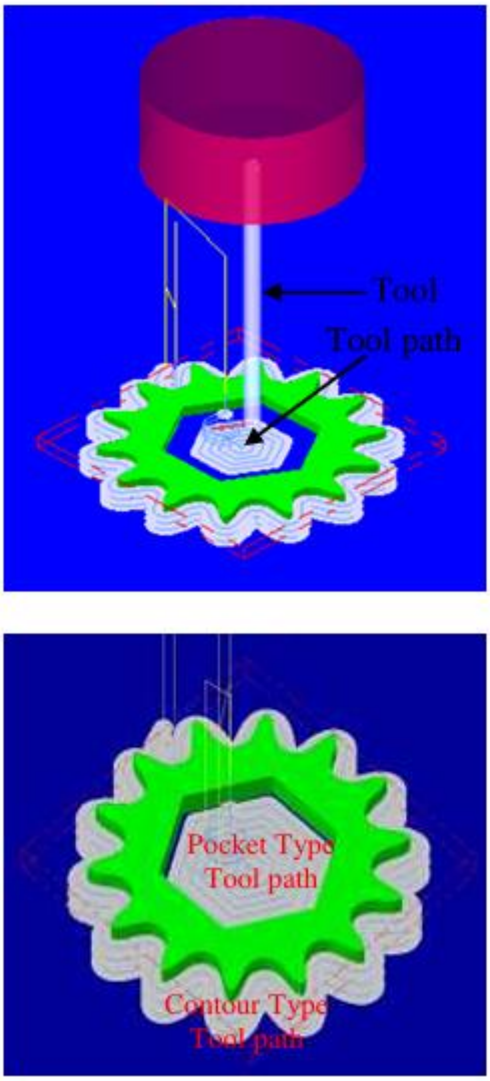


Figure 4: Simulation of the Cutting Process on Master CAM Software [3]

1.1.4 Advantages of CNC Technology

CNC (Computer Numerical Control) technology is responsible for a great advancement in manufacturing processes, it has alot of advantages across many different kinds of industries, mostly it is known and used for the purpose of producing complicated components like sprockets and many other kinds of geometries. The CNC technology basically works by automating the control of machine tools with the help of computer coding and programming, which therefore almost removes the chances of human error and increases precision in manufacturing, reduced time of production and also increases efficiency. Since

CNC machining is primarily controlled through computer programming, it allows for the creation of products that have very complex geometries and tolerances, which is also very important and benefits different sectors of industry where reliability and performance are essential [3]. Since the CNC technology can provide a precision and repeatability. It is therefore crucial in the bicycle industry, where sprockets used in bicycles must have strict dimensional tolerances so that the bicycle can perform properly and also guarantee user safety. With the usage of CNC machines manufacturers can produce sprockets with teeth that are dimensionally precise better than other methods like casting or flame cutting, which therefore reduces the amount of defects the manufacturer produces and maintains high quality products [3].

CNC technology also greatly reduced production cycles in comparison to other traditional manufacturing methods, the time needed between design of product to finished product is much more fast and efficient, which also allows faster prototyping for testing and optimization purposes. Software tools that are advanced aid in the simulation of manufacturing process, which allows for adjustments before the CNC machining begins, this helps reduce waste and prevents unnecessary cost [1]. The addition of lightweight materials like Carbon Fiber Reinforced Plastics (CFRP) in designs that are made with the help of CNC machines is also a very beneficial strategy in manufacturing, because of the high strength in relation to weight ratio in CRFP, this allows lighter components without sacrificing strength or durability which is very important regarding sprockets, this improves the riding experience for the bicycle users and reduces effort required [1]. Production cost of some metallic parts can be high because of the numerous operations required to produce it, this is where CNC technology can help with time-saving and increasing cost-effectiveness [1].

1.2 History of 3D Scanning

3D Scanning first started early on as a very basic optical measurement technology but as the years passed by, it has evolved and changed into becoming a key tool in the industrial, digital and scientific spaces. When studying its history it is evident that 3D scanning technology has had a major integration in areas like optical physics, laser technology and assistance in computational modelling. As the technology advanced and became more integrated into other industries, it has continuously achieved new milestones and standards in accuracy of the measurement, speed of the measurement and also data processing [4].

1.2.1 Early Development of 3D Scanning

The first known 3D scanning technologies first appeared in the 1960s, which basically worked by relying on a light source, cameras and projectors to collect data on a certain surface. Mainly these early technologies and methods were used for the purpose of assisting in research and design. Early systems like these has the capability to recreate 3D shapes, but because at those early times there was very limited equipment and not strong enough computational power, these systems required a long scanning time and constant effort and significant manual calibration [4]. However, in the 1980s with the advancement of computers it was now possible to create 3D models with higher detail, another problem occurred and this time it was to measure a surface accurately. Traditional tools for example tape measure, could not capture or precisely measure objects with complex geometries [4].

Figure 5: Object Tape Measuring [4]

After 1985, these projection-based systems began to be replaced by laser and white-light scanner systems, which had a positive effect in speed of the scanning process and the precision of measurements. In 1994, a 3D scanner called **REPLICA** was produced which had the ability to produce very accurate scanning of very detailed objects and geometries, this specific 3D scanner used the method of laser stripe scanning [4]. Other companies were also creating their own 3D scanning products, **Cyberware** for instance, had their own high detail scanners, some of them were able to capture colour as well, although a significant advancement, the parameters like speed and accuracy were still a challenge [4]. Another company, **Digibotics**, introduced a 4-axis machine which had the ability to produce a complete 3D model from one single scan, this time the technology did not use laser stripe scanning, but rather the method was based on laser point, the problem was it was slow as a result of this method, also, it did not have the six degrees of freedom that was needed to cover an entire surface of an object. Furthermore, it was not able to generate a coloured surface [4]. It has become evident that 3D modellers were all in demand for the same thing, a scanner which was:

- Accurate
- Fast
- Truly three-dimensional
- Able to capture colour
- Reasonably priced [4]

Figure 6: Replica 3D Scanner [5]

In the year of 1996, a significant progression was achieved with the introduction of a 3D scanner model called the **ModelMaker**, a 3D scanner that was operated manually by hand and was installed with a stripe 3D scanner [4]. This form or hybrid setup was advantageous in the form of being fast and flexible, it was also able to capture colour as well, the **ModelMaker** was marked as one of the earliest example of integrated laser scanning for practical engineering and design tasks, the help of being manually controlled and its ability to digitize scanned data automatically was very beneficial in the area of time-saving and accurate generation of 3D models [4].

Figure 7: Manually Operated and Strip 3D Scanner [4]

1.2.2 Operating Principles of Laser Scanners

As it was described in the **IQvolution** paper, in the 1990s and early 2000s it has been observed that commercial laser scanning products and systems have started to be used not only as research tools, but also as industrial instruments, laser scanners began using triangulation and time-of-flight principles to measure distances and dimensions accurately. These new techniques greatly improved accuracy, the capturing of millions of points per second and creating dense points for the purpose of modelling. This introduction of this kind of laser scanners and portable measurement systems was seen as the beginning of 3D scanners being used as a widely and easily accessible industrial tool. [5]

The main 3 core principles for 3D laser scanning are triangulation, time-of-flight and phase shift.

- Triangulation, is when scanners emit a laser line or dot on an object and record it reflection from a known angle, the distance is then calculated by geometric relationships between laser source, the sensor and the reflection point.
- Time-of-flight, laser 3D scanning systems emit a laser pulse, and measure the time it takes for this certain laser to return, this phenomenon allows for accurate and long range measurements.

- Phase shift, this parameter is important because it works by comparing the phase difference between the emitted laser and the reflected laser, this improves the precision and accuracy for short and medium range scanning. [5]

Each of the three principles mentioned all serve a specific area of application, triangulation scanners have the ability to offer high accuracy scanning for small objects, time-of-flight scanners are more suitable towards larger scale objects like buildings, phase-shift systems are used in areas where rapid data collection is required [5]. The ability to record millions of data points with sub-millimiter accuracy has had a great impact in revolutionizing metrology, which enables the capture of surfaces and environments that previously needed manual surveying [5].

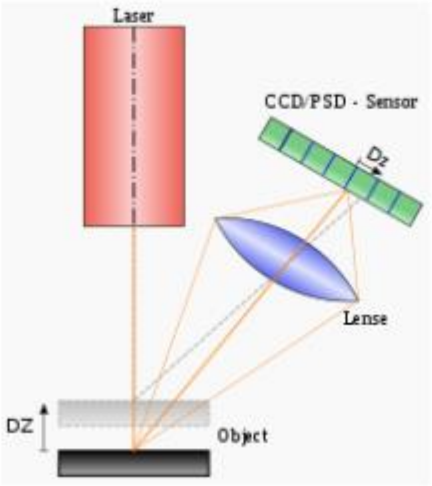


Figure 8: Principle of Laser Triangulation sensor (Two Object Positions) [5]

1.2.3 Evolution of 3D Scanning Applications and Future Trends

The studies show in detail the widespread adoption of 3D scanning technologies in many sectors like the industrial, architectural and civil engineering fields. Laser scanners started to be also used more in the fields of reverse engineering, quality inspection, mining, urban topography and construction site modelling [4]. They also became used in the documentation of historical monuments and accident reconstruction, this is helping provide a rapid and non-contact data extraction which is especially helpful in unsafe conditions and environments. Laser scanners additionally enabled precise and “as-built” surveys that reduced the time and the cost of producing the technical documentation, this process became also very essential for design verification and digital archiving, this helped engineering and allowed them to compare physical objects with their respective CAD Models for dimensional accuracy [4].

In the **IQvolution** article, it supports this advancement in laser scanning by highlighting the role this technology has in reverse engineering and cultural heritage conservation, describing how 3D data collection has simplified the process of replication and restoration [5]. Although modern developments have focused on miniaturization, automation and the integration of other technologies, the studies show that newer scanners have evolved to become smaller, faster and more capable of capturing larger and more complex data sets, as well as capturing better colour resolution [5]. This integration increases the flexibility and accessibility of 3D laser scanners and makes it much more suitable for usage in fields as diverse as medicine, construction and even more advanced fields like virtual reality, the future direction of 3D scanning lies in AI based automation for noise reduction, feature recognition and real-time 3D modelling, an evolution that continues the trend of how 3D scanning constantly improves the accuracy and simplification of operations [5].

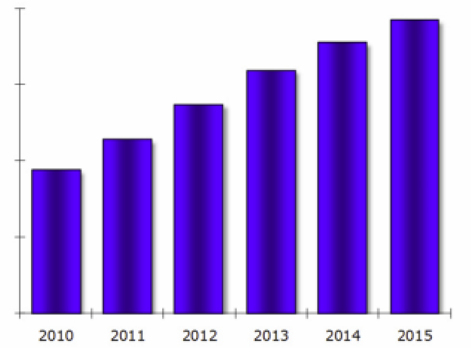


Figure 9: The Worldwide 3D Laser Scanning Market (2010-2015) [5]

1.3 Wear in Sprockets

Wear is the progressive and gradual removal or deformation of material caused by repeated contact between surfaces in relative motion. In the case of in the chain drive, this process occurs mainly between the roller and the sprocket tooth during engagement and disengagement of the system. As the wear progresses, the tooth geometry of the sprocket changes and deforms, the chain pitch elongates and also this causes the transmission efficiency to be decreased [6]. The consequence of these effects leads to misalignment in the system, noise, and premature failure of the chain drive system. Understanding the mechanism and factors that contribute towards the wear of the system is important to improve sprocket lifetime, optimize maintenance schedules and enhance system reliability and efficiency [7].

1.3.1 Main Types of Sprocket Wear

Several mechanisms cause wear in sprockets. The most common types are abrasive wear, adhesive wear, fatigue wear and corrosive wear. In reality, more than one type often occurs at the same time or right after the other.Abrasive wear happens when hard particles or small bits of material get into or cut the sprocket tooth during its motion. These particles may be for example dust, sand or metallic debris that has contaminated the lubricant or oil. This process removes fine layers of metal and slowly polishes the contact surface. Experiments in agricultural machinery showed that in these contaminated environments, wear rates increased by up to 20 - 300 times in comparison to operations happening in cleaner environments [7]. Abrasive wear is the most severe when lubrication is not sufficient enough to flush out or remove the particles from the system, which allows them to remain and circulate through the chain-sprocket contact area [9].

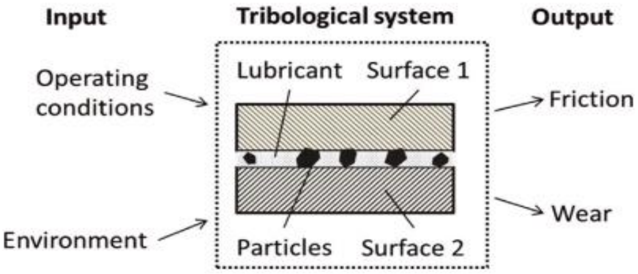


Figure 10: The tribological system for the abrasive wear on the sprocket wheel [9]

Adhesive wear occurs under poor lubrication when metal surfaces come into direct contact. Microscopic welding therefore takes place at the points of contact which is then followed by material transfer when the surfaces slide apart from each other. This results in scuffing and rough and torn surfaces [6]. Once adhesion begins, irregularities in the surface starts to grow and that itself causes and promotes further adhesion and frictional heating. Adequate lubrication prevents this process by maintaining a film between and the chain roller and the tooth flank [6].

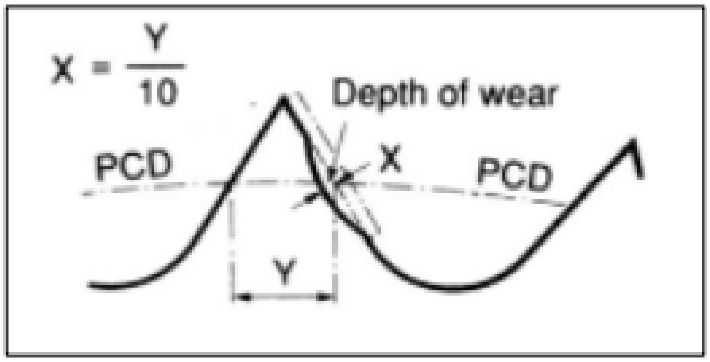


Figure 11: Tooth Wear Measurement [6]

Fatigue wear, also known as pitting, results from the cyclic stress applied on the sprocket tooth surface. Repeated loading initiates microcracks below the contact area. These cracks grow and cause small pits and pieces of material start to detach [8]. In the **Arora et al, Article.** Finite-element analysis performed on an Al-7075 T6 sprocket showed maximum stress concentrations at the tooth root and flank, this is confirming that cyclic loads accelerate surface fatigue.

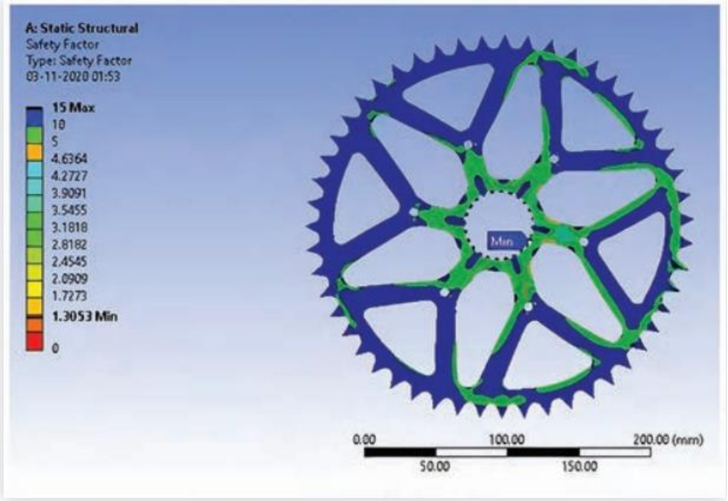


Figure 12: Factor of safety under fatigue loading condition [8]

Corrosive wear is another kind of wear, it develops through electrochemical reactions between the metal surface of the sprocket and moisture in the environment or chemicals. Corrosion products form a brittle layer that flakes away under load. When this layer is lost, it exposes fresh metal underneath it and therefore speeds up further damage. In humid or agricultural conditions, corrosion interacts alongside with abrasion and leads to a accelerated deterioration of the tooth of the sprocket. In real operating conditions, combined wear is very common, the different kinds of wear can start a chain reaction that makes another type of wear more possible. For example, Abrasion removes protective films or layers on the sprocket, which therefore promotes adhesion or corrosion, and after that fatigue cracks form and propagate faster through the material due to weakened surface layer [6].

1.3.2 Factors Affecting Sprocket Wear

The rate of the wear of the sprockets depends on the combined influence of the environmental, material and mechanical factors. Operating environment, for example dusty and sandy surroundings can significantly increase the abrasive wear. In field measurements of open chain drives that are being used in agricultural machines for example, particles mixed inside the lubricants formed an abrasive paste substance that accelerated the removal of the metal [7]. Lubrication is another factor, the lubricant provides separation between the metal surfaces and reduces frictional heat. When oil viscosity decreases due to contamination or high temperature, the film protecting the metal breaks and metal contact begins to occur. This promotes both adhesion and fatigue to happen, maintaining proper viscosity and periodic relubrication prevents these affects from happening [7]. Studies on the systems that are operating in sandy conditions can confirm that monitoring the lubricant condition and friction coefficient can predict the abrasive rate of wear [9].

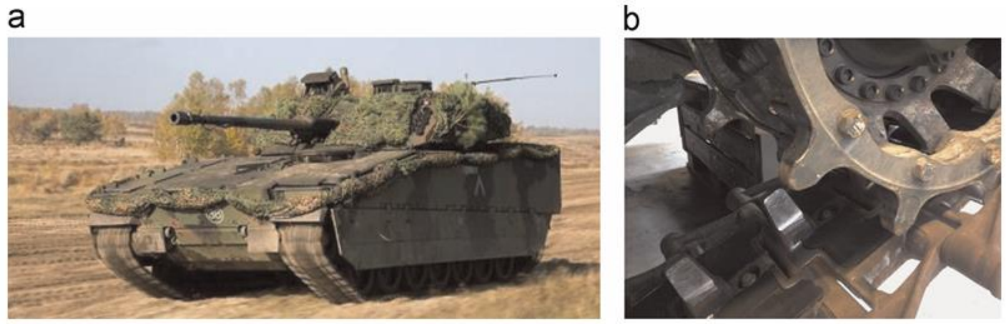


Figure 13: (a) the CV90 infantry vehicle, operating in a sandy environment (left, source: defensie.nl) and (b) the sprocket wheel. [9]

Material and surface treatment, Sprockets that are made from harder or treated materials shows much better wear resistance. Tests on an Al-7075 T6 sprocket with a titanium-nitride (TiN) coating showed improved stress distribution and longer fatigue life [8]. The coating reduced friction and minimized the micro-welding (adhesion) at the contact zones. Similarly, sprockets made from higher - carbon steels or sprockets that are subjected to case hardening processes showed a lifespan increase of up to 200% - 300%, compared to untreated components [10].

Heat treatment and surface finishing enhanced the hardness and reduced initial wear [10].

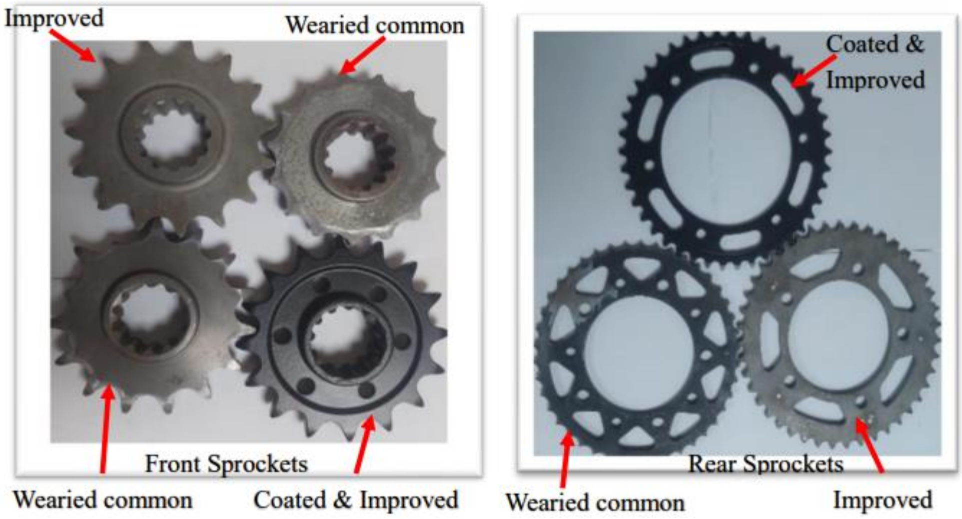
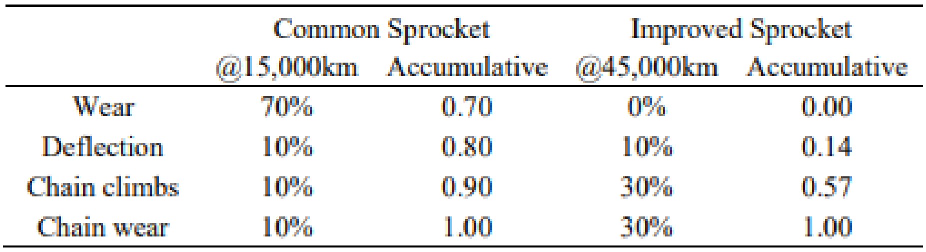


Figure 14: Common sprockets VS the improved sprockets [10]



	Common Sprocket		Improved Sprocket	
	@15,000km	Accumulative	@45,000km	Accumulative
Wear	70%	0.70	0%	0.00
Deflection	10%	0.80	10%	0.14
Chain climbs	10%	0.90	30%	0.57
Chain wear	10%	1.00	30%	1.00

Figure 15: Defects of the common and improved sprocket systems [10]

2 3D Scanning Process Design

This first stage of the thesis focused on creating an accurate digital model(s) of the sprocket system that was to be geometrically analyized. The objective of this task was to generate from the physical sprockets a high quality STL files through a structured scanning workflow. This task also provides the digital foundation required for Tasks 2, 3 and 4.

Disassembly of the sprocket system was the first step, the sprocket system was made up of 3 sprockets assembled together with rivets. These rivets held the small, medium and large sprockets as one unit. The first step was separating the assembly to allow separate access to each sprocket and therefore be scanned as an individual component. A drill press was used to remove the rivets, specifically, a Floor-standing Craftsman Drill Press, the drilling process was done vertically to remove the rivets, the usage of the vertical drilling of the drilling machine allowed for a controlled material removal and ensured that the sprockets were not damaged during disassembly.

Figure 16: Floor-standing Craftsman Drill Press

Figure 17: Rivet Removal Process Using Drill Press

Once the fasteners have been removed the sprockets seperated cleanly into three individual parts, the small, medium and large sprockets, the medium sprocket had the crank arm still attached to it, therefore it has to be removed with a hydraulic press machine, the sprocket was laid flat on its surface and the hydraulic press was aligned to remove the crank arm without damaging the teeth of the sprocket or causing any major bending to the structure.

The rivet removal process needed to be carried out carefully because the purpose of this study is to analyze the real worn geometry of the sprockets, therefore any improperly controlled force, slipping of the drill or unnecessary contact with the sprocket body had to be avoided so that no additional wear or damage happens.

For this reason, the disassembly process was treated as a prepatory engineering step for analysis rather than just a disassembly process.

The removal of the rivets in a controlled way, the original condition of the sprocket surface and also the tooth regions were preserved for the following scanning and also modelling stages.

Figure 18: Hydraulic Press Machine

Figure 19: Crank-arm Removal Using Hydraulic Press Machine

Figure 20: Sprocket System Before Disassembly

The laser scanning process requires consistent surface conditions to make sure that an accurate capture of the geometry is possible. The surface of the sprocket was dark, oily and worn out, which would interfere with the laser sensor and would have reduced scanning accuracy. For that reason each sprocket was coated with a single layer of white automotive spray paint, and the reason for only a single layer is for the purpose of not creating additional surface thickness on top of the sprocket surface. The white coating improved the light diffusion, reduced the glare and enabled the scanner to detect edges and tooth surface more reliably and accurately. The coating thickness was negligible relative to the dimensions of the sprocket teeth and did not effect the scanning results.

It is important to minimize the coating thickness as much as possible as to make sure that even the smaller difference caused by the wear are not hidden or undetected by the 3D laser scanning process, therefore providing as accurate result as possible.

Figure 21: Sprocket System After Disassembly

After the disassembling and coating the sprockets, the scanning process was performed using the **Shining 3D FreeScan Combo**, a portable high accuracy laser line scanner that was suitable for scanning mechanical parts. The laser line mode was selected because it provides precise results for metallic components with complex edges such as sprocket teeth. The **Shining 3D FreeScan Combo** is specifically good for this study due to the following reasons, in the laser scanning mode which was used, it has a very high scanning accuracy, which was sufficient for the purpose of this study. Each sprocket was placed individually on a turntable. The turntable allowed smooth rotation of the sprocket during scanning, which helped make sure the scanner captured all surfaces, including tooth flanks, inner edges and the hub region.

Figure 22: Shining 3D FreeScan Combo

During the scanning process the turntable was gradually rotated while holding the scanner above the sprocket. This process ensured continuous coverage of the laser scanner with sufficient overlap between frames. The sprocket were rigid and small and the white coat removed the need for positioning markers. The scanner used its internal tracking to align frames during data capture, this setup allowed a complete scanning procedure without missing any areas or producing blind spots, the scanning session for each sprocket was consistent in terms of the setup and execution in order to maintain and obtain uniform data quality across the three separate parts.

Also, the selection of the scanner is important because the sprockets contain some relatively small geometric features, for example, the tooth flanks and tips, where the wear is expected to be more concentrated there.

A scanner with insufficient accuracy, could have reduced the reliability of the comparison between the worn and the restored models that would be generated from these scans, for this reason, a high accuracy scanner was needed to make sure that the comparison would be as reliable and accurate as possible.

Detailed scanning was also necessary for reverse engineering and also to ensure that the model was suitable not only for visualization but also for the later stages of this study where the interpretation of the wear pattern is to be studied.

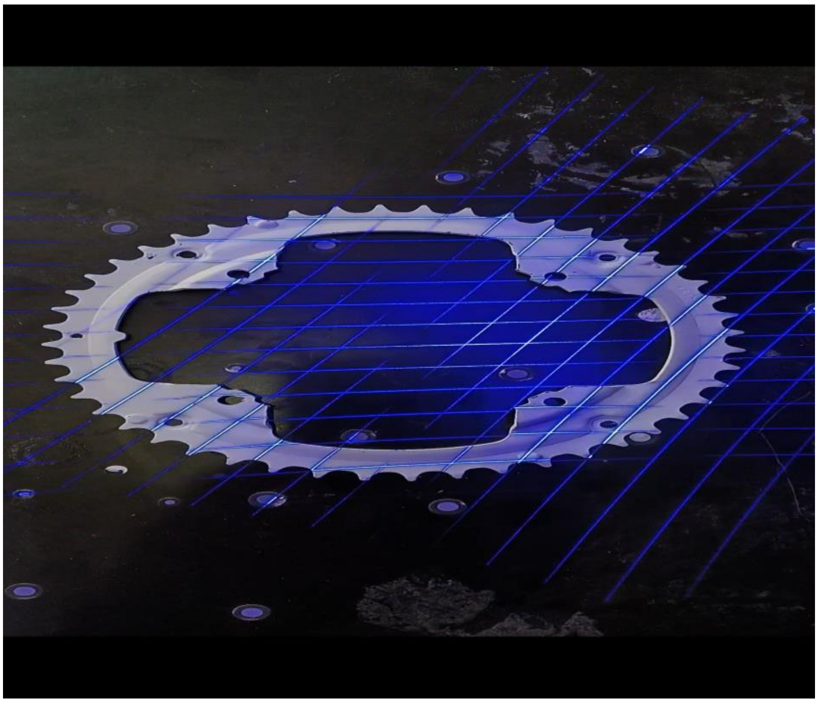


Figure 23: Laser Scanning Process

After the scanning process was completed, the FreeScan software generated raw point cloud data for each of the sprockets. The software converted these point clouds into triangular mesh files automatically. The output format chosen for all components was STL, which is the standard format for mesh-based digital models. Each sprocket generated one STL file.

The scanning successfully captured the full geometry the teeth and the outer profile. Minor hole-filling or smoothing occurs automatically during the STL file creation, but there was no need for advanced cleanup or merging. Each sprocket was captured properly in a singular scan, so therefore no multi-scan alignment was needed. At the end of this step, three STL mesh models were produced, one for each sprocket.

A controlled scanning process was needed to maintain a consistency in the data collection from all three sprockets, since the later stages of this study will depend on comparing the geometries, any difference or change in data collection caused by inconsistent scanning conditions could have affected the reliability of the results.

The scanning setup, scanner position and also the rotation method for each sprocket helped ensure that the generated STL files reflected accurate data from the scan, rather than just variations introduced during data collection.

Device: FreeScan Combo
Calibration: 05.06 - 12:30
Scan Mode: Laser Mode
Post-Processing: In Progress
Measurement: -

Mesh Optimization
Optimization: ○ None ● Standard ○ Med ○ High
Smooth: ○ Low ● Med ○ High
Remove Small Floating Parts: 100
☑ Max triangles: 20000000
☑ Remove Spike
Recommended parameters: off

Remaining memory: 51% CPU: 84% GPU: 22%
Left Mouse: Rotate | Middle Mouse: Pan | Scroll Wheel: Zoom
Triangles: 291,944

Figure 24: Mesh Optimization on Shining 3D Software

The completion of the mesh optimization stage confirmed that the data derived from the scanned data was suitable for the reverse engineering work. At this point the sprocket geometry has been fully transformed from a physical component into a digital form that could be examined and processed and also reconstructed.

This stage was also important because it reduced the distance between measurement and modelling, also it made it much more efficient.

The scanning stage documented the condition of the sprockets, and also prepared the foundation for creating the CAD models necessary for carrying out the geometric comparison.

The optimization of the mesh helped by not only preserving the worn geometry of the sprockets but also reduced minor irregularities that might interfere with modelling steps.

A more stable geometric foundation or basis, helped keep the scanned data form close to the actual condition of the sprockets.

This stage also had practical importance and relation to the next chapter, as the quality of the mesh will directly affect the unnecessary surface disturbances, if the mesh contains surface disturbances or missing details, then these issues may appear in the reconstruction process and therefore will cause the restored model to be less reliable and also therefore making the comparison unreliable.

Clear geometry was also important for the tooth profile of the sprockets, as that is where most of the wear is expected to be.

3 Creation of Sprocket CAD Models

As described in chapter 2, the three sprockets were first separated and disassembled from the original assembly, prepared by a thin surface coating of white paint and then scanned using the Shining 3D Freescan Combo, this process produced three STL mesh models that represented the actual physical condition of the sprockets after a period of long term use and wear. Although these mesh models portrayed the visible geometry of the scanned sprockets, they were not sufficient for the dimensional modification of the sprockets which will be needed for a controlled engineering comparison, therefore the CAD reconstruction is necessary.

The purpose of chapter 3 is to transform the scan based mesh geometry into reconstructed CAD models that can be used as the engineering reference models, the scanned sprockets represent the worn condition of the sprockets, their teeth profiles have been affected by operation, therefore the role of the CAD reconstruction is to rebuild the sprocket geometry as a solid model and also create an estimated unworn version of each sprocket for comparison which will be the objective of the next chapter.

Unlike a parametric CAD model, STL files is composed of a large number of triangular mesh elements connected together, which is good for storing scanned shapes but it does not provide solid parameter features that can be edited such as sketching or dimension changing, for this reason the scanned geometry was used as a reference data rather than a finished finalized model. For each sprocket, the scanned model was therefore used to determine basic proportions of the part, for example the relationship between the inner and outer regions, the number and the distribution of the teeth and the overall shape of the part. Since this study is focusing on the wear of the tooth profile of the sprocket, the geometry of the teeth had to be interpreted carefully because it will serve as a basis for the rebuilding of the profile for the sprockets that represent them before being worn and in an undamaged condition.

Because the sprockets were different in size, each model had to be reconstructed individually. The small sprocket contained 28 teeth, the medium sprocket contained 38 teeth and the large sprocket contained 48 teeth, the different number of teeth in each sprocket directly defines its functional geometry and determines the circular spacing of the tooth pattern.

After the scanning of each sprocket, this allowed the progression into the next step which was to generate a solid CAD model for each sprocket using the help of the reverse engineering features of the software. In this process the mesh geometry of the worn sprocket was the one used directly to generate these models, which basically means that the models were created and derived from the mesh itself, rather than creating them independently. The reverse engineering tools in the software interpreted the mesh and generated the solid geometry while at the same time they preserved the main dimensions and shape of the scanned part. There are now 3 separate solid models for each sprocket which was necessary for the next step, which required the controlled and manual editing of the tooth geometry, without the conversion into a solid CAD model, this modification would have been practical.

Figure 25: Small Gear CAD Model (Worn)

Figure 26: Medium Gear CAD Model (Worn)

Figure 27: Large Gear CAD Model (Worn)

Once the solid CAD models of the worn sprockets have been generated, the next step was to restore the tooth geometry in order to simulate the unworn condition of the sprocket tooth geometry before the long period of use and before it was subjected to wear and deformation. This restoration was needed so that a comparison can be made for the tooth profile before and after wear which will be the objective of the next chapter.

The restoration process was carried out by working on the tooth geometry of the solid CAD model that been generated from the scanned data. The generated tooth form was used as a reference and then the tooth profile was edited through sketch based modification, an additional 0.1mm was introduced to the tooth geometry. This value was selected in order to approximate the original condition of the tooth before the different types of wear removed material and deformed the surface and geometry of the sprocket tooths.

The purpose of this correction to the tooths was not to create a completely new or unique sprocket design. It was to produce a reasonable engineering estimate of the unworn tooth geometry while remaining consistency with the scanned dimensions of the real part.

The same procedure was used for all three sprockets. Each worn solid CAD model was taken as the base geometry and then the corresponding tooth profile of each model was edited to include 0.1mm addition to their surface. Therefore this resulted in the creation of three separate restored CAD models of the sprockets that represented them in the estimated unworn condition of the sprocket system. Using the same method and the same correction value for each model ensured consistency in the later comparison.

At this point, each of the three sprockets had 2 solid CAD models representing them individually, one model shows their state after a long term period of wear and therefore deformation (State when they were scanned), and the other model represents them in a state which was estimated to be their condition before being subjected to a period of long term wear and deformation, (Original State).

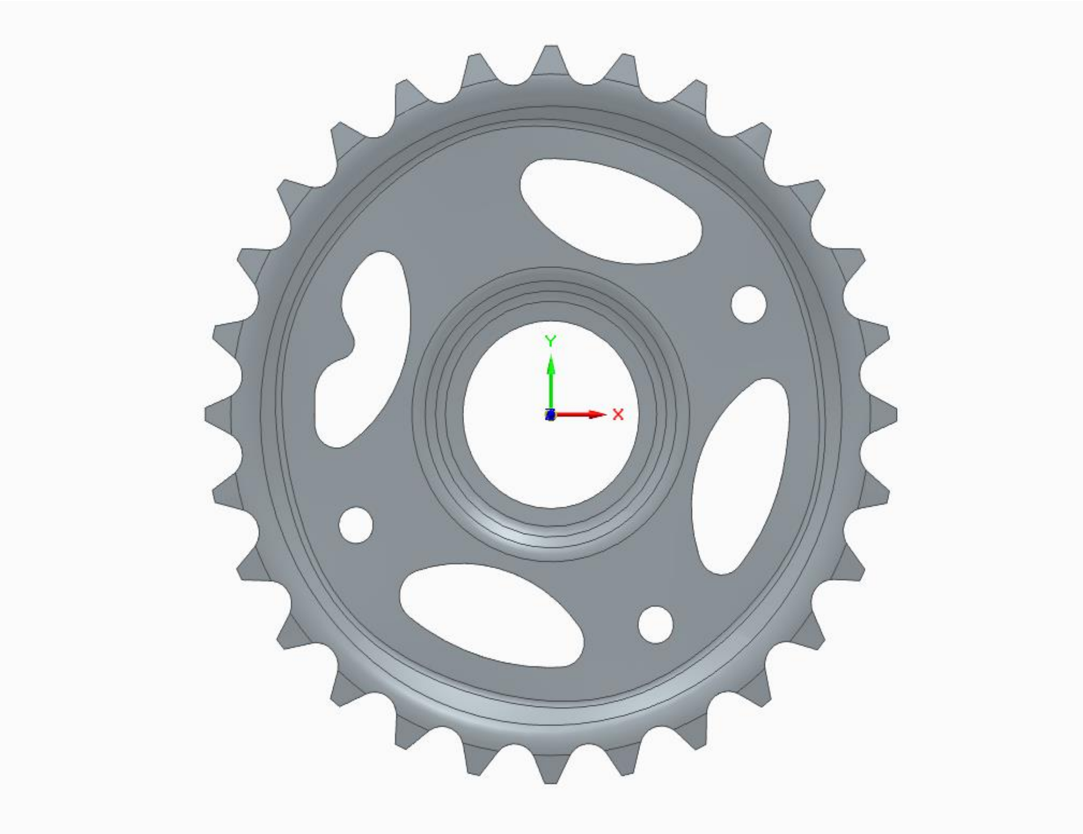


Figure 28: Small gear CAD Model (Restored)

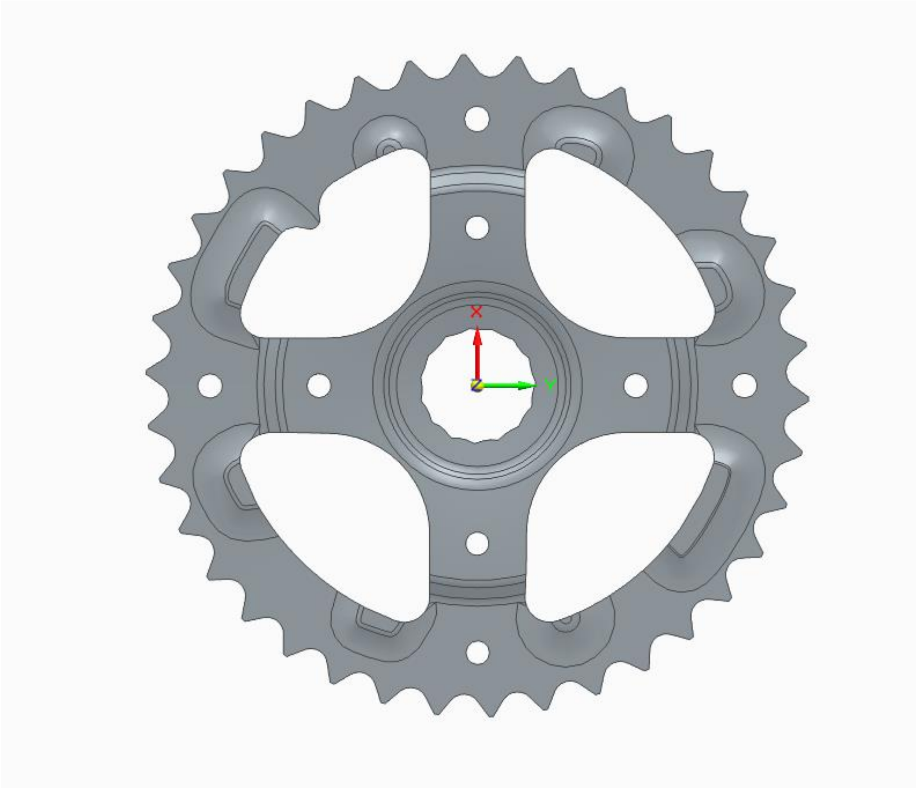


Figure 29: Medium gear CAD Model (Restored)

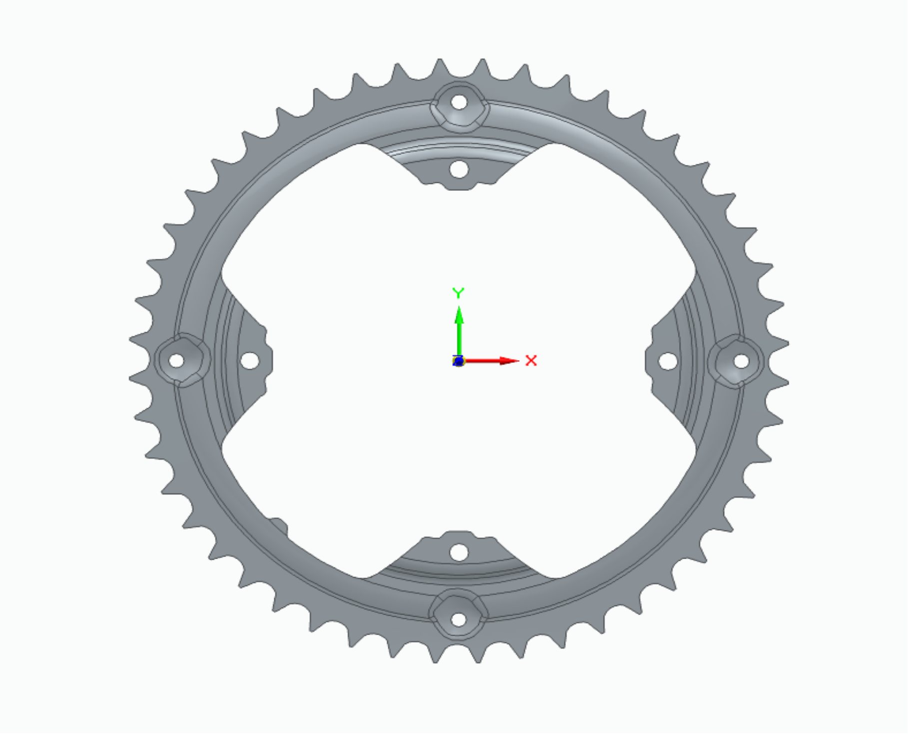


Figure 30: Large Gear CAD Model (Restored)

4 Comparison of the Models

In this chapter, after the restored CAD models had been made, the next step of this study will be comparing them with the worn sprocket models. The purpose of the task is to evaluate and understand the geometric differences between the two models of each gear respectively and to also identify where the greatest change happened during its service life. The comparison was done separately for the small, medium and the large gears, also two views were used for each, a front view and a back view which will allow a complete geometric analysis to be done for both faces of the gears. Primary focus will be given to the tooth region since the teeth of the gears are the primary contact surfaces between the sprocket and the chain, alongside the teeth of the gears, the body of the sprocket was examined as well because the deviation maps show that there was geometric changes not only to the tooth profile or outer perimeter of the gear. Which will give us a better understanding and a bigger view of the deformation of the sprocket system and help understand possible wear mechanisms and operating effects.

The comparison was done by overlapping the original worn model and the restored unworn model on top of each other for each gear. After allignment, the software then generated a colour deviation map that therefore showed the difference in the geometries between the two models. The areas that are close to zero deviation are shown in green. The positive deviation is shown by yellow,orange and red colours, and the negative deviation is shown by cyan and blue colours. In other words the green area indicated that the worn and restored models remained close to each other, and the warmer and cooler colours indicated that the regions where greater geometric change happened.

Figure 31 and 32 show the front and back view of the small gear, the overall pattern of the small gear is relatively balanced, a big portion of the surface remains within the green to yellow range which indicates that much of the sprocket body remained close to the restored reference geometry. The most noticeable difference is the appearance along the perimeter of the outer tooth, where warm colours form a consistent pattern along the tooth perimeter of the gear. This pattern suggest that most of the geometric change occurred at the tooth region, which makes sense considering the fact that the teeth of the gear are the active contact points during chain engagement, this result is consistent with operational wear, the repeated warm coloured zones around the perimeter are consistent with gradual material loss from the tooth profile. This kind of change suggests abrasive wear in which repeated contact and the presence of contaminants between the points of contact between the teeth and the chain cause removal of small amounts of material from the tooth surface, it also agrees with adhesive wear in which case the potential lack of lubrication leads to surface damage and change in the tooth profile over time.

As for the body of the small gear, it shows several blue and cyan areas, mainly near the cut out opening and also the central mounting region. These areas are more localized than the perimeter of the gear which suggests the body of the gear did not deteriorate or deform uniformly but instead it maintained most of its original geometry, while these zones experiences a more local deviation, this may be related to a number of factors, for example, minor deformation during service, local contact stresses, or deformation caused during assembly or disassembly. Since the strongest or more severe pattern is concentrated on the outer perimeter of the gear, the teeth therefore represent the main area exposed to wear. The front and back views of the small gear are consistent for the most part, this is important because it suggests that the deviation pattern is not limited to only one side, additionally, the small gear therefore appears to have gone though mainly moderate and distributed tooth wear with local changes in the internal body region, compared to the other gears, it seems to be one of the more stable patterns.

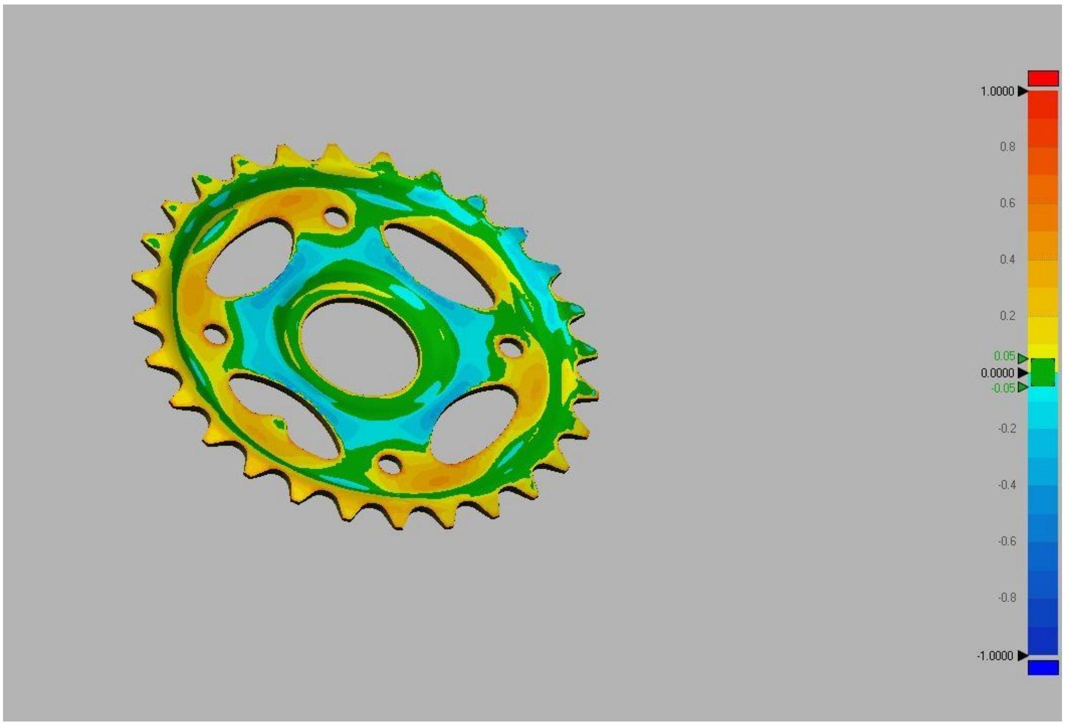


Figure 31: Small Gear Deviation Map (Front View)

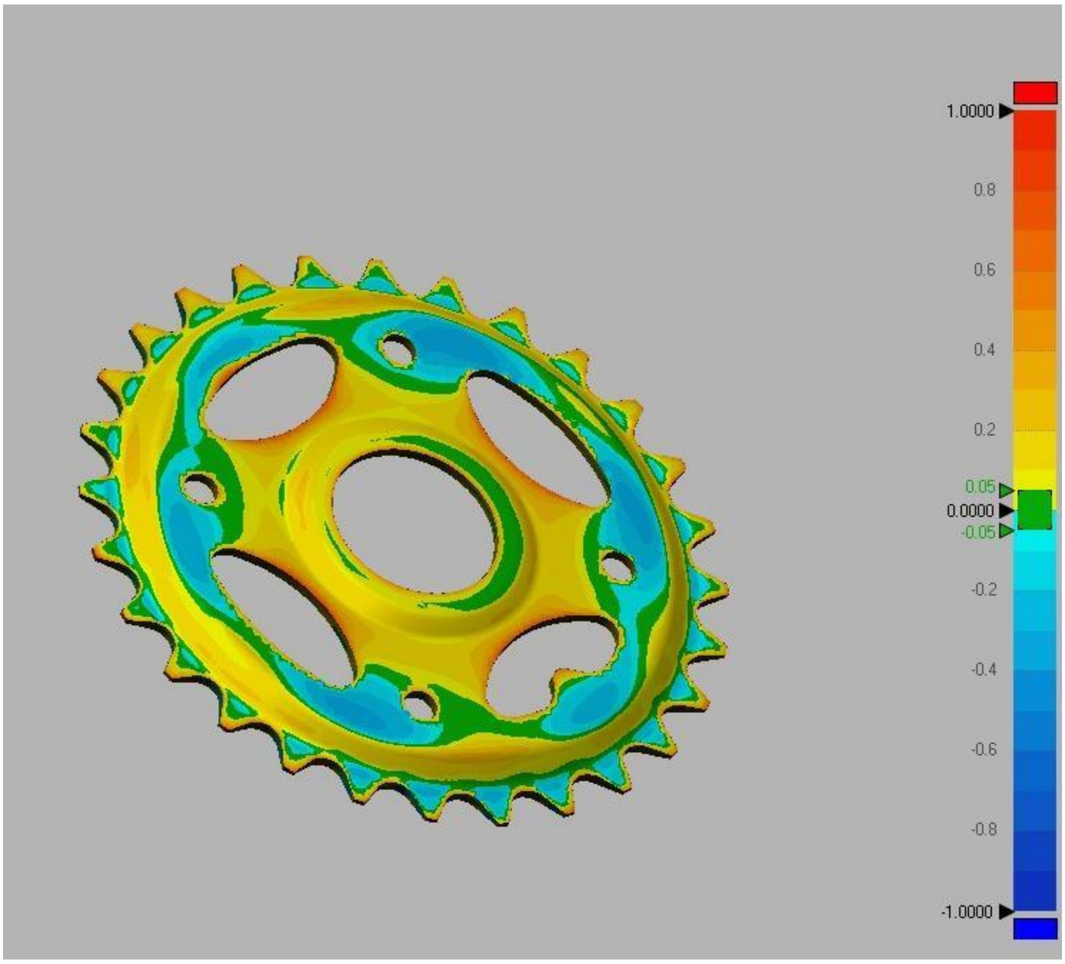


Figure 32: Small Gear Deviation Map (Back View)

Regarding the large gear, figures 33 and 34 show the front view and the back view of the large sprocket, in these images, the outer ring of gear shows the most visible or clearest deviation pattern. As broad yellow and orange regions appear around most of the tooth perimeter, and multiple localized red areas appear at the outer edge and the tips of the tooth of the gear. This indicates that the largest geometric deformation are concentrated at the tooth ring rather than in the central body of the gear. This result strongly suggests wear driven by repeated chain contact during operation, also the tooth tips and flanks are the zones that received the highest or most amount of operational interaction during the meshing of the tooth with the chain. This broad perimeter deviation pattern is consistent with progressive tooth profile loss. The likely cause or contributor to this is the abrasive wear, especially dirt or metallic particles that were present between the meshing area of the tooth of the gear and the chain, along with contaminated lubricant that has impurities present in it, or lack of lubrication of the drive system it self. Fatigue related wear is also another potential contributor due to the fact that because the repeated loading at the tooth flank can slowly but gradually change the local profile and increase the difference between the worn and restored geometries. In comparison to the small gear, the large gear shows a stronger signature on the colour map, and this signature is not only isolated to certain points but instead it is speak around the perimeter, This suggests that wear on the large gear developed more continuously around the ring, a possible reason for this may have been that the large gear experiences longer and more consistent contact with the gear, in other words, it suggests that the large gear was used up and utilized much more than the small gear. Also another possible explanation is that the large diameter of the large sprocket created a wider active wear path over time. The internal body of the large gear shows mixed results, some of the regions are remaining near zero deviation, while other regions around the arms of the mounting holes show moderate change and deviation. The deviations are definitely weaker than those that are in the outer perimeter, which confirms that the body of the gear was less affected that the teeth, this results is seen in both the front view and also the back view of the large gear, basically the tooth ring is the area where most wear occurred, while the body shows secondary and local differences, for this reason, the large gear presents the clearest case of perimeter dominated deterioration and geometric deviation or deformation.

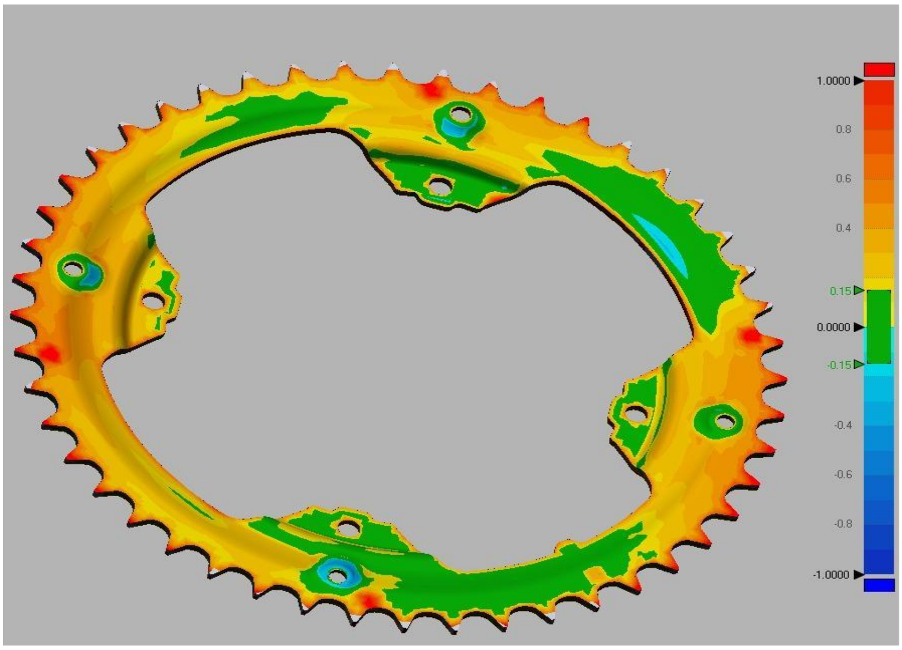


Figure 33: Large Gear Deviation Map (Front View)

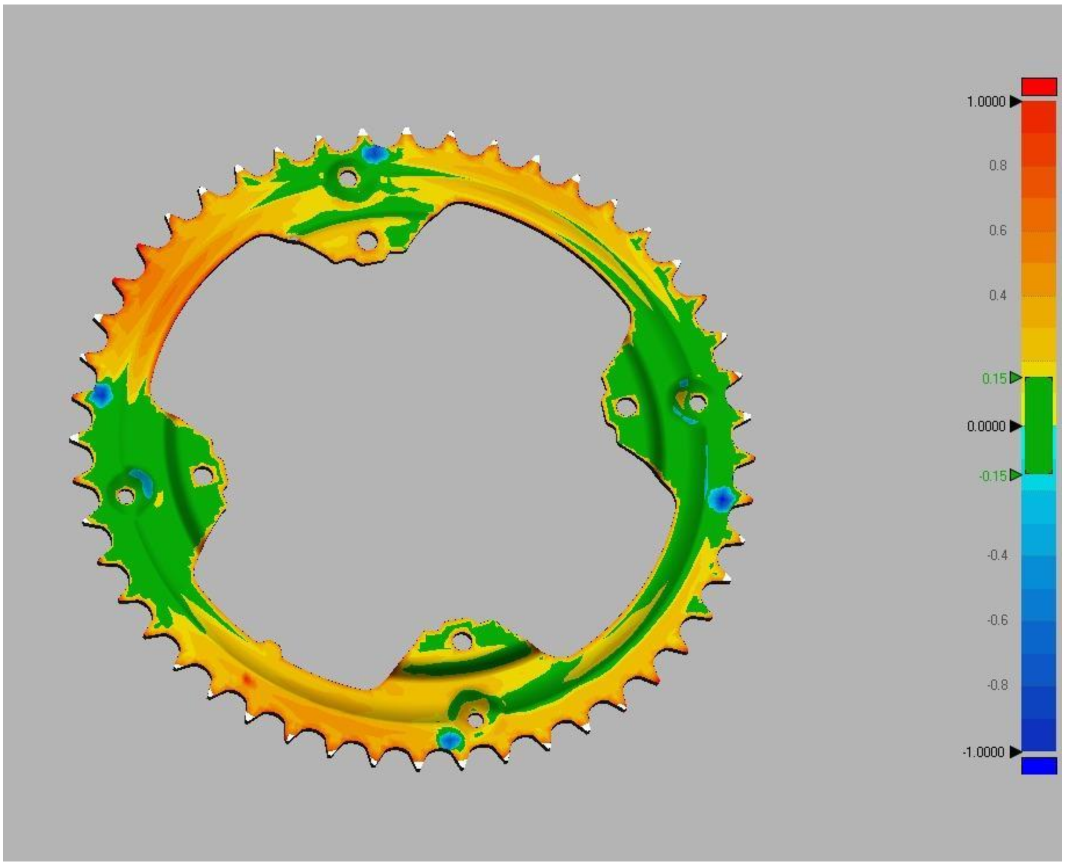


Figure 34: Large Gear Deviation Map (Back View)

Figure 35 and 36 shows the front and back view of the medium gear, in the deviation map, this gear shows the most irregular pattern compared to the other gears, the reason to that is because the deviation is spread across both the outer tooth region and also the main body of the gear. Blue, cyan, green, yellow and also red zones are all visible across the gear, which basically means the geometric difference and deviation is not concentrated on only one part of the gear. Just as seen in the large and small gears, the medium gear also contains alot of variation and change in the tooth perimeter. The body of the medium gear shows change around the cut-out openings, arms and also the central region. This kind of wider spread of the deviation suggests that the medium gear experienced a more complex and different service life than that of the large and small gears. The pattern is consistent with a mix of wear and also local structural change, rather than just tooth profile deformation. One of the possible explanations to this is that the medium gear was under uneven loading, since because the medium gear was part of the same sprocket system, and had its own contact and force distribution, that means that some areas of the gear may have been exposed to more local stress which can lead to a non-uniform wear that develops. Another reason is misalignment or a fluctuating contact of the chain which can explain the lack of symmetry between certain areas. Another potential reason for this uneven or not symmetrical deformation pattern could be the disassembly process which caused local deformation to the body of the gear, and not only the tooth themselves. As for the difference of the two sides or faces of the medium gear, it was not like the small and large gears, rather it was more noticeable. One side of the medium gear contains bigger areas of negative deviation which resulted in cooler colours, while the other side shows more positive deviation and therefore warmer colours on the deviation map, specifically near the cut-out opening and edges. This further shows and indicates that the two faces of the medium gear did not experience fully symmetric geometric change, which explains and solidifies the claim that the medium gear was under non–uniform operating conditions, and that the load was more one sided, or that local stiffness differences was present across the component.

Thats why for these reasons, the medium gear shows the more complex deterioration pattern. Naturally, it still also shows tooth wear since the tooth of the gear are the main contact point of the component, but the body region was also needed to be taken into consideration and analyzed.

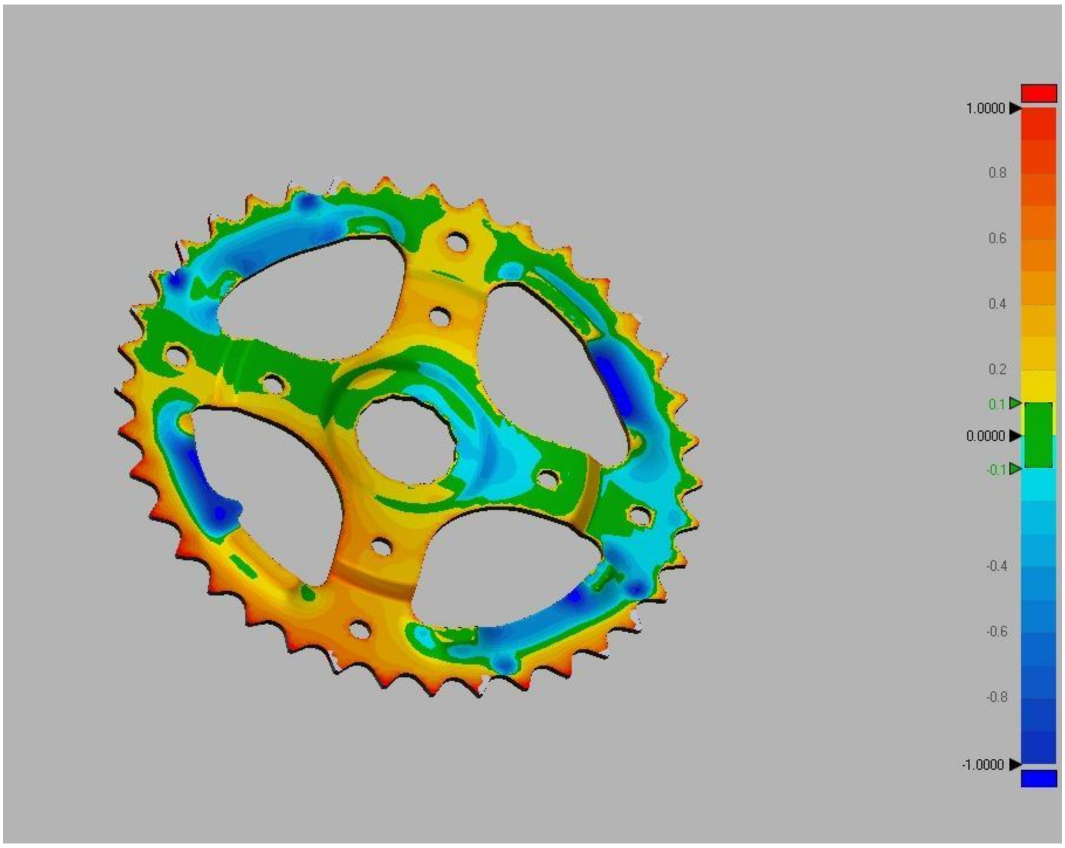


Figure 35: Medium Gear Deviation Map (Front View)

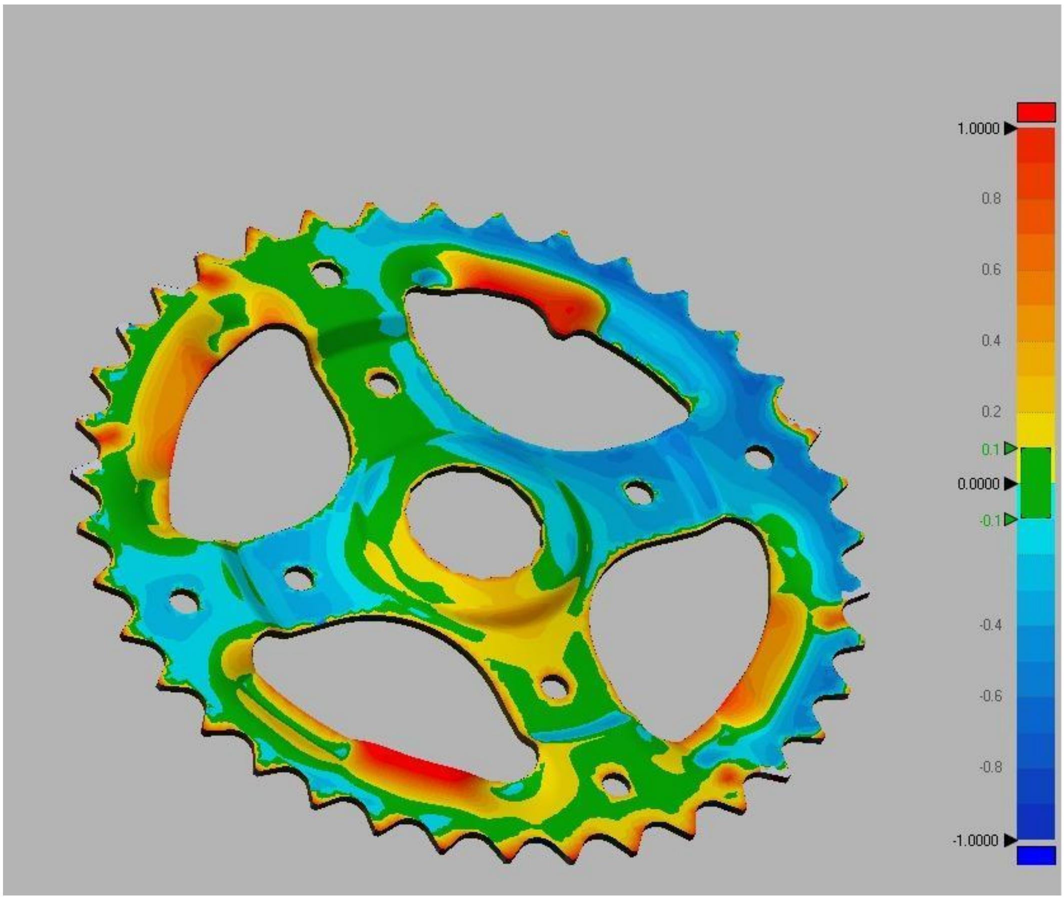


Figure 36: Medium Gear Deviation Map (Back View)

When all these three gears are examined, one common results appears, the main change or deviation that happened to the geometries of the gears happened mainly at the tooth region and this is expected due to the fact that because the tooths of the gears are the main point of contact in the functionality of the gear, for example in power transmission and the chain engagement, these figures of the deviation maps supports and confirms that the primary zone of wear of the gears is the outer perimeter and the tooth profiles and surfaces of the gears. Although with that being said, the deviation is not completely exactly uniform as certain zones around the outer perimeter in one gear shows more change or stronger deviation in comparison to other gears, which basically means, that the wear did not occur evenly on every tooth of every gear and every region. This kind of unevenness in the deformation could be explained by, natural operating conditions and operating environment, inconsistent loading, chain tension, allignment, lubrication, and also contamination.

Regarding a wear point of view, the figures are most consistent or indicate predominantly abrasive wear and fatigue wear at the tooth region of all three gears.

Abrasive wear arises as a result of the slow yet gradual loss of material due to repeated contact, a phenomenon intensified by the current trajectory of technology advancements.

As machines in various industries are continuously optimized for performance, the encounters between gear tooth surfaces can become more frequent and intense, magnifying the impact of wear over time. On the other hand, fatigue wear is characterized by the repeated stress that occurs systematically over extended periods at the tooth flank and root.

The stresses involved can introduce micro-fractures, which not only impair functionality but can also lead to premature failure of the gear systems. As we look toward the future of technology, the understanding of fatigue wear becomes increasingly critical, particularly in the development of materials that can better withstand these stresses while improving overall gear longevity.

Additionally, adhesive wear may also be occurring due to inadequate lubrication, as this type of wear transpires when there is persistent metal-to-metal contact. The implications of this wear mechanism highlight the necessity for advanced lubrication solutions that adapt to different operating conditions, thereby mitigating adverse effects and enhancing performance.

As technology evolves, innovations in lubrication technology could revolutionize how we approach gear maintenance and performance assurance. Another wear type that warrants attention is corrosive wear.

If the sprocket system operates in humid or contaminated conditions, corrosive wear could exacerbate the other forms of wear mentioned, leading to a more aggressive degradation of the material.

This underscores the significance of environmental factors on wear patterns, prompting a need for development in protective coatings or treatments that can mitigate corrosion.

In summary, as we navigate the complex landscape of mechanical engineering and its future, understanding the multifaceted types of wear— and their impact on gear systems— becomes essential. Embracing advancements in technology will not only enhance our comprehension of these wear mechanisms but also inform strategies for creating more resilient and efficient mechanical systems. Ultimately, integrating a holistic approach to wear reduction technologies can lead to more sustainable practices, ensuring longevity and reliability in our gear systems for years to come.

5 Determination and Analysis of the Maintenance Operations

The results of chapter 4 showed that the three sprockets did not deteriorate in a uniform manner. The strongest geometric changes that were observed appeared at the tooth region, naturally it is the point of contact in the drive mechanism, and also local deviation across parts of the body of the sprocket as well. This shows that there is damage from repeated contact, alongside non-uniform loading and also operating conditions that promoted wear. For this reason this chapter will be about prescribing maintenance operations that are relevant and practical to prevent these kinds of deteriorations as much as possible and to improve the service life of the drivetrain system.

Literature regarding maintenance usually distinguished breakdown maintenance, preventive maintenance and also condition based maintenance and predictive maintenance. Jardin et al. describe breakdown maintenance as an action that is done to the component only after it has stopped working or has reached failure, while the time-based or preventive maintenance is carried out at certain fixed intervals that are based regardless of the condition of the component. Also it defines condition-based maintenance as a way that recommends the decisions for maintenance from monitoring the conditions of the system and monitoring the information that it provides, and then after that, it organizes the information into 3 main stages, data acquisition, data processing, and then lastly, maintenance decision [11].

Predictive maintenance is a kind of maintenance that is data-driven approach that is meant to avoid unplanned downtimes, increase the equipment service life, and support maintenance decision through the analysis of data, prognostics [12]. While preventive maintenance is a type of maintenance that is planned action which is intended to replace sudden or unexpected downtime with organized downtimes instead, through regular check and replacement and other standardized procedures [13].

In this study these kinds of maintenance are relevant and also important because they are relatable and applicable to a bicycle sprocket system which is a kind of drivetrain that is wear driven and has a constantly or gradually changing condition of components during its service. Preventive maintenance is the main starting point for bicycle sprocket maintenance, because the drivetrain is exposed to constant repeated contact, contaminations from its surrounding working environment and also the loss of lubrication during use.

The primary purpose of maintenance is to keep equipment operational and reduce downtime through the process of checking the functionality of the components, repair, replacement and related technical actions, also proper maintenance should replace anomalies within the system [13].

In terms that are applicable to the bicycle sprocket, this would be routine cleaning, proper lubrication, tightening check of any loose parts that should not be loose, inspection of chain and sprocket conditions rather than waiting for a visible change or unnatural behaviour to occur in the system.

A useful practical concept is the TLC sequence of tightening, lubrication and cleaning [13]. This sequence is well fitting to the bicycle sprocket system, tightening is important because a loose crank connection or loose fastening, or poor alignment can disturb the chain engagement and increase the local loading. Lubrication is important also because the chain and sprocket operate together under repeated contact and friction, lubrication will minimize friction and therefore minimize wear. Cleaning is important because of dirt, which is usually common in the working environment and conditions of a bicycle sprocket, dirt can strongly increase or accelerate the rate of wear. Preventive maintenance requires interval planning, Hardt et al. describe maintenance frequencies are assigned by equipment priority, with weekly, biweekly, monthly and annual cycles depending on the load and importance [13]. For a bicycle sprocket system, the same logic can be applied according to the riding intensity and frequency, and also environment of its operation, for example, a bicycle used in dusty off-road riding, or frequent hill climbing, or high-load use, will require shorter maintenance intervals in comparison to a bicycle used in dry and urban commuting. This is consistent with the drivetrain review by Liew et al., which states that the lubricant of choice and the drivetrain performance an related and depend on the riding type and location, use in dry and dusty requires lubricant types that are low-dirt attracting lubricants, while wet environments require more persistent lubrication as well as types of lubricants that are more water resistant, also visual inspection of the tooth flanks of the sprocket and chain conditions should be a part of this routine [14].

Condition based maintenance is another kind of maintenance that can be applied to bicycle sprocket systems.

Jardine et al. define condition based maintenance as a form of maintenance which is based on information and data that is attained when condition monitoring, and which this data will decide what specific maintenance procedure will be carried out, the relevance of condition based maintenance for bicycle sprocket systems is due to the fact that wear does not progress the same for every user as there is difference in terrain, climate and the state of lubrication, a time-based maintenance schedule can ignore these difference [11].

For the bicycle sprocket system studied in this thesis, condition based maintenance should focus on observable wear indicators, Liew et al. state that chain elongation is a good indicator of roller chain wear, chain elongation that exceeds 0.5 - 0.75 percent in a chain checker tool, then the chain should be replaced before it starts to damage other components of the drivetrain system [14]. They also state that sprocket wear occurs mainly the gear tooth region, and that worn out tooth surfaces and profiles will fit poorly, and also increase chain wear and cause it to deteriorate faster, also will make the transmission and power output inefficient [14].

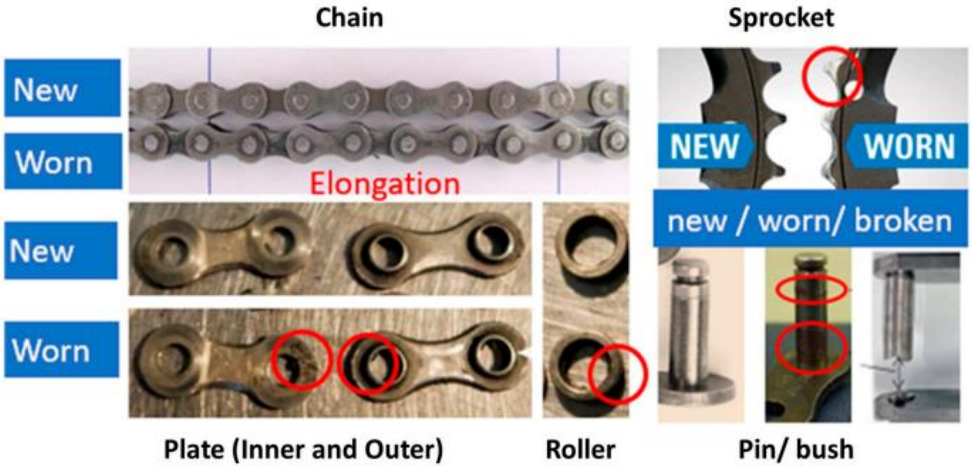


Figure 37 : Wear phenomenon in roller chain components and sprocket, including elongation of chain due to wear, The red circles indicate noticeable worn locations present in the chain drive components [14]

These points are important in this thesis because it correlates well to chapter 4, were it was shown that the strongest geometric changes were concentrated at the perimeter or the tooth region of all three gears. Condition based maintenance helps support decisions on replacement, Jardine et al. state that a proper application of condition based maintenance helps reduce unexpected downtime [11]. For a bicycle drivetrain this means that for example a chain or sprocket should not be replaced too early when the wear is still low, but also it should not be kept for too long after visible deformation or damage has occurred in which it would affect or change the engagement quality.

Predictive maintenance is another kind of maintenance operation that would be fitting for a bicycle sprocket system. Achouch et al. describes predictive maintenance as an accurate workflow that starts by first understanding the working mechanism of the system, collecting data, and then lastly decision making, they also state that predictive maintenance is important for lower downtime, cost saving, extending service life of components [12]. In relation to a bicycle sprocket, the same logic can be applied in a simpler form, for example, the condition of the sprocket system must be monitored, and then the future need for maintenance should be estimated from the current condition, plus, expected use [12].

The Woldman et al. study deals directly with abrasive wear and also directly uses sprockets as a case study, they show that maintenance in sandy operating conditions should depend on the current conditions of both the component and also the environment it is working in, wear can also be linked to parameters such as the terrain the system is being used on and also the driving distance, these parameters combined can help decide on maintenance intervals [9]. This is highly related to a bicycle sprocket system since bicycle sprocket system are exposed to the environment around them and will affect the severity of the wear and the rate of wear. A drive train used on paved urban roads is not exposed to the same wear condition of a drive train working in dry dust, mud, gravel or mixed terrain [9].
This interpretation is also related to what was stated by Liew et al. which state that dry and dusty areas require lubricants that attract less contaminants, while wet environments will require a more constant lubrication of the system, and that the amount of contamination and also the temperature affect the friction and therefore the rate of wear [14].

A maintenance prescription for the studied bicycle sprocket system in this study can be separated into three different levels of action.

The first level will be the preventive maintenance operation, in which this includes the regular cleaning of the sprocket and chain, or the drivetrain in general, routine lubrication, also meanwhile checking for looseness or misalignment of the chain or any rivets, and also a planned visual inspection of the teeth of the gears and also the inspection of the chain. This process of maintenance has the objective of reducing dirt present in the system, constant preservation of proper lubrication, and also to prevent accidental deterioration.

The second level will be the condition based maintenance, in which this will include visible and measurable indicators that will help decide if action is required. For a bicycle sprocket system, the most practical indicators are the visibility of the chain elongation or the visibility of it, poor engagement between the chain and the teeth of the sprocket, and also rough tooth surface or tooth surfaces that are chipped.
Another factor can be drivetrain noise, and a clear elongation of the chain which is beyond 0.5 to 0.75 percent, which should trigger a replacement before further damage in the drivetrain system starts to happen and develop, based on Liew et al. report, the procedure of chain inspection should be treated as a core maintenance operation [14].

The third level is the predictive maintenance which includes adjusting the time between maintenance operations based on the expected wear severity of the environment the system will be operating in, basically, a bicycle used in dusty, muddy, or high-load conditions should not follow the same maintenance intervals of a bicycle used in clean and more calm conditions.

Woldman et al. show that predictive maintenance becomes more efficient and produces more results when usage conditions and wear mechanisms are linked directly to the timing of the maintenance operations [9].

In relation to this study, this means that riding environment should influence the decision of the intervals or frequency between cleaning, lubrication and also inspection.

In addition to the maintenance approaches discussed earlier, the use of special maintenance and diagnostic tools can improve the reliability of the bicycle sprocket system and help with making maintenance decisions more accurate. Two useful examples are a chain wear measurement tool and also surface roughness measurement tools. These tools are valuable because they help detect deterioration before failure occurs, also, since some wear or deformation can not be easily spotted by visual inspection, these tools help provide information that is measureable about the progression and extent of the wear, this makes them suitable for maintenance prescriptions in a drive train system which can be affected by wear [15].

One important tool for drivetrain maintenance is the chain wear measurement tool. Down et al. presented a high precision in-situ tool which had the purpose of measuring chain wear directly on the bicycle without the need of disassembly of the chain from the bicycle, the main purpose of the tool is to detect elongation of the chain with much more precision than some commonly used gauges found in workshops, since chain elongation is one of the most important indicators of drivetrain wear, this tool allows for the inspection and monitoring of chain wear before any catastrophic damage occurs or until wear starts to appear on the sprocket teeth [15].

This tool is closely relevant to the bicycle sprocket system studied in this thesis because chain condition is directly linked to sprocket wear, as the chain elongates, the fit between the chain and the sprocket teeth becomes worse, which results in an increase in local contact stress, also changes the engagement pattern and therefore accelerates at the tooth flanks and tips.

The chain wear measurement tool is also suitable for condition-based maintenance, since this approach will depend on measurable parameters and not only fixed time intervals, in this case, chain elongation becomes the measurable parameter, if the chain has reached a critical wear state, then maintenance should be performed immediately, on the other hand if chain wear is still low, then the chain can stay in service [15].

Since this study showed that the tooth region of the sprocket is the main area of deterioration, measuring chain wear regularly would help reduce tooth damage caused by a worn chain that is continuing to engage with the sprocket.

Figure 38: Chain wear checker in-situ operation [15]

Another kind of useful maintenance tools is surface roughness measurement equipment, Wagner et al. compared different methods for measuring the surface roughness of gear tooth working surfaces, including contact stylus profilometers and optical interferometry methods, their work showed that roughness measurement can provide important information about the condition of the tooth surface [16].

Although their study was carried out on gears, the same maintenance logic is relevant and can be applied to sprocket teeth because both are working tooth surfaces that are under constant and repeated mechanical contact.

A roughness measurement tool can help identify if the tooth flank is still in a healthy operating condition or whether the surface has already been damaged by repeated friction, abrasion, or other wear mechanisms, a smoother and more regular tooth surface usually indicates better contact conditions, meanwhile rougher tooth surfaces that contain scratches or irregular peaks, suggest deterioration and can affect the efficiency and reliability of contact, surface roughness measurement tools provide a way of assessing the condition of the teeth, specifically before large visible deformation starts to show [16].

This kind of tool is especially valuable for condition-based maintenance because it helps provide measureable information on the surface of the tooth profile, since visual inspection alone may only show wear that is already severe or large, and that has already taken effect into the sprocket system.

Roughness measurement can detect earlier changes in the contact surface, if repeated measurements show an increase in roughness over time, that trend could mean a growing in the severity of the wear, even if the overall tooth shape appears to be acceptable, this could also indicate lubrication problems or contamination in the lubrication, early abrasive wear can be detected sooner and therefore maintenance actions such as cleaning, relubrication can be carried out before the wear becomes more destructive [16].

Surface roughness measurement also helps with predictive maintenance, if the surface condition of the tooth of the sprocket is measure at repeated intervals, the maintenance planner can observe whether the roughness is still at a stable or acceptable condition, or if it is increasing rapidly, stable surface condition suggests that the lubrication and operating condition are good, on the other hand a rapid increase in the roughness of the tooth profile suggests that the system is moving towards a more severe state in the wear, such information can help in estimating the future maintenance needed [16].

Figure 39: Profilometer (“Shop Floor” Model) [16]

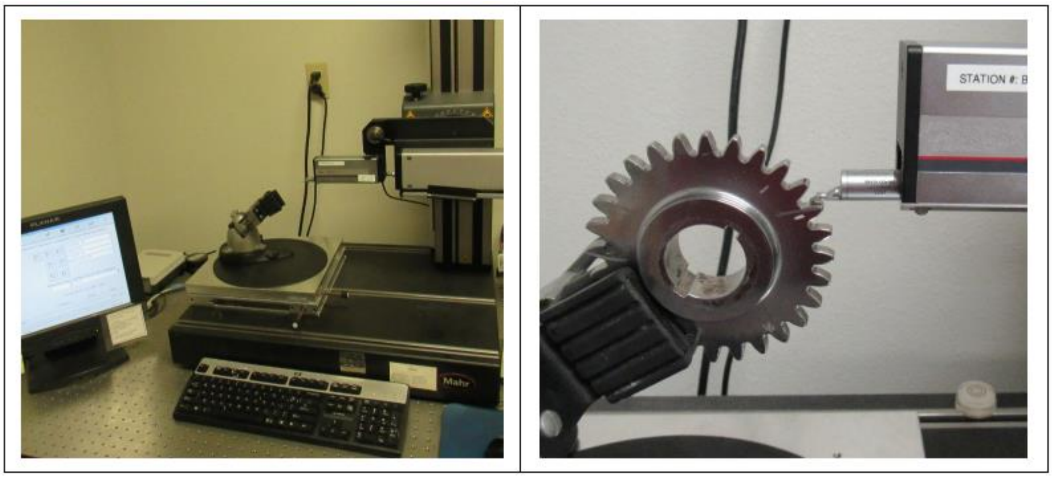


Figure 40: Profilometer (“Metrology Lab” Model) [16]

Figure 41: Gear Tooth (Left) and Hard Epoxy Replica (Right) in Interferometer [16]

6 Summary

This thesis studied the geometric deterioration of a bicycle sprocket system which is made up of three gears, with 28, 38, and 48 teeth respectively, and then based on the observed wear to the gears, a maintenance prescription was developed. The goal of this study was also to compare the worn conditions of the gears with an estimated unworn condition and then after that, relate the results to what kinds of wear may have caused these specific kinds of deformation and deterioration, and then relate this data to practical maintenance operations.

The study began with a literature review on sprocket manufacturing, 3D scanning, and the different types of wear sprocket systems are in danger to. This helped give the technical understanding of how sprockets are manufactured and also how their geometry could be digitized to help analyze it, and also how different wear mechanisms and types can affect their service life.

After the literature review came the practical work of this study, which was the disassembly of the original sprocket assembly into its three separate gears, After preparing the surface with a thin layer of white paint, each gear was scanned individually from both sides using the Shining 3D FreeScan Combo, which helped produce the STL files which were the mesh models of the worn sprockets, these scanned models formed as the base of the rest of the thesis.

The STL meshes were then converted into solid CAD models through reverse engineering tools, After that, the tooth profiles were modified by adding 0.1 mm to the tooth surface profiles to approximate the unworn state. This created two CAD models of each gear, one for the worn state and one for the unworn state.

These worn and restored models were compared, and deviation maps produced. The results in these deviation maps showed that the main changes in the geometric shape of the gears were more concentrated at the area of the tooth perimeter of the three gears. Small gear showed a kind of moderate and also balanced wear, while the large gear showed a kind of wear that was clearly and heavily concentrated across the perimeter of the gear, and lastly the medium gear showed a very irregular pattern, with deformation appearing in different parts of the gears body.

The final part of this thesis study was focused on maintenance and maintenance prescription. The three kinds were, preventive maintenance, condition based maintenance and also predictive maintenance. These maintenance approaches were related to the bicycle sprocket system and provided practical action plans to help reduce the rate of wear and deterioration and also extending service life of the sprocket system, while also improving the drivetrain reliability and functionality.

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