



School of Electrical and Mechanical Engineering
Department of Mechanical, Energy and Industrial Engineering

**Failure Investigation and Techno-Economic Analysis of Remanufacturing Damaged
Drive Tumbler of a Diamond Mining Shovel**

by

GBENGA SAMSON OMOGBEHIN

Student ID number: 23019086

B.Eng. (Mechanical Engineering) (Federal University of Petroleum Resources Nigeria)

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Supervisor: Dr. Setswalo, Keagisitswe

Department of Mechanical, Energy and Industrial Engineering,

School of Electrical and Mechanical Engineering, BIUST

E-mail: setswalok@biust.ac.bw, Tel: (+267) 72814387

Co-Supervisor: Prof. E. O. Olakanmi

Department of Mechanical, Energy and Industrial Engineering,

School of Electrical and Mechanical Engineering, BIUST

E-mail: olakanmie@biust.ac.bw, Tel: (+267) 74276012

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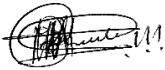
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CERTIFICATION

The undersigned certifies that he/she has read and hereby recommends for acceptance by the School of Electrical and Mechanical Engineering a dissertation/thesis titled: “*Experimental Failure Investigation and Techno-Economic Analysis of Remanufacturing Approach for Damaged Drive Tumbler of a Diamond Mining Shovel.*” in fulfilment of the requirements for the degree of Master of Engineering in (Industrial and Manufacturing Engineering) of the Botswana International University of Science & Technology (BIUST).



.....
Dr. K. Setswalo

(Supervisor)

Date: 15 August 2025



.....
Prof. E. O. Olakanmi

(Co-supervisor)

Date: 15 August 2025

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DEDICATION

I dedicate this work to the almighty God, my beautiful and loving wife, Mrs Blessing Ifeoluwa Omogbehin and to our incoming children, as well as my mother Mrs Olawunmi Omogbehin.

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LIST OF ABBREVIATIONS

EFA – Engineering failure analysis
SEM – Scanning electron microscope
EDS – Energy dispersive X-ray spectroscopy
XRD – X-ray diffraction
IC – Ion chromatography
ADI – Austempered ductile iron
GDP – Gross domestic products
GMAW- Gas metal arc welding
TIG – Tungsten inert gas
WAAM- Wire arc additive manufacturing
LC – Laser cladding
TEA – Techno-economic analysis
MH – Microhardness
MMC – Metal matrix composite
FEA – Finite element analysis
NDT - Non-destructive testing
HAZ – Heat affected zone
OEM – Original equipment manufacturer
LENS – Laser-engineered net shaping
CVD – Chemical vapor deposition
PVD – Physical vapor deposition
MTCs – Mechanical power transmission components

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Abstract

A critical but often overlooked stage in the remanufacturing of failed industrial components is failure investigation. Failure investigation involves the analysis of failure modes, mechanisms and root causes of failed components. In electric mining shovels, the drive tumbler is a critical component responsible for transmitting torque to the undercarriage system through continuous interaction of drive tumbler teeth with the crawler belt. However, this repeated engagement leads to high sliding-impact loading and frictional stresses, which result in premature failure of the drive tumbler in a diamond mine. The drive tumbler fails at approximately 5,000 running hours, below its expected service life of 25,000 hours. Despite the drive tumbler's critical role in propelling the undercarriage system of mining shovels, research on failure analysis, to uncover root causes of its premature failure remains limited. Understanding the failure modes, mechanisms, and root causes of the premature failure of is essential for developing sustainable mitigation and remanufacturing strategies to enhance its resistance to wear and fatigue failure. This research aims to address these challenges by conducting a comprehensive investigation that includes engineering failure analysis (EFA), development of a mitigation strategy through the selection of suitable wear-resistant materials and remanufacturing technique, and a techno-economic analysis (TEA) of remanufacturing options. The EFA involved detailed chemical, macroscopic and microscopic examinations to identify failure modes, mechanisms and root causes. Observed failure modes include severe surface wear, adhesive wear, plastic deformation, cracks, and fractures on the drive tumbler teeth. Microscopic analysis via optical microscope of the undamaged drive tumbler teeth revealed a tempered martensitic microstructure, while scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDS) revealed manufacturing defects such as voids as well as alumina and manganese sulphide inclusions with a total of 3.75 volume fraction. Additionally, ion chromatographic analysis of water samples from the mining site confirmed high concentrations of corrosive ions such as chlorine and sulphur, with distinct peaks of approximately 1973 ppm and 2423 ppm, respectively. These emphasized the chemically aggressive nature of the drive tumbler's operating environment. Fractography examination via SEM/EDS further uncovered multiple failure mechanisms including two-body sliding abrasion, adhesive-abrasive-fatigue wear, stress corrosion cracking, ductile-intergranular fatigue fracture, and sliding contact

fatigue. The surface microhardness of the drive tumbler teeth was found to be approximately 353 HV, significantly lower than that of the mating crawler belt by 48% which contributed to premature failure of the drive tumbler. Other root causes established from EFA are direct metal-to-metal sliding-impact contact, presence of corrosive media and abrasive kimberlite ore particles in the diamond mine, manufacturing defects, and inadequate maintenance practices. To mitigate these challenges, this study recommends the adoption of metal matrix composites (MMCs) due to their exceptional hardness, wear-corrosion resistance, and mechanical properties, through a detailed literature review and the findings from EFA. Laser cladding (LC) emerged as a highly suitable materials deposition technique for the remanufacturing of damaged drive tumbler teeth owing to its ability to enhance surface properties. Additionally, findings from the TEA demonstrate that a hybrid approach combining wire arc additive manufacturing (WAAM) with LC to remanufacture surfaces affected by severe wear and adhesive wear yielded an annual cost savings of up to 93.3%, while refurbishing the teeth of newly acquired drive tumbler with laser cladding alone offers up to 44.8% cost savings per year. This research provides a detailed technical and economic framework towards remanufacturing failed drive tumbler, by identifying failure causes and mitigation measures to prevent premature failure. The recommended strategy offers a potential sustainable and cost-effective solution with significant implications for operational efficiency and profitability in the diamond mining industry.

1. Chapter One: Introduction

1.0 Chapter Summary:

This chapter provides a comprehensive overview of this research, describing the shovel loader as an important mining equipment in the mining industry and establishing the uses, mode of operation. The importance of the drive tumbler as an essential component of the undercarriage system in electric mining shovels are also described. The problem of the drive tumbler due to the nature of its operating environment, operating condition, and its effects on the mine productivity are also discussed. The benefit failure analysis and techno-economic analysis offer as vital stages in remanufacturing of the drive tumbler are also elucidated. The general and specific objectives to solve the problem identified in this study are presented. Finally, the delimitations, particular themes to be investigated, and the significance of this research are highlighted.

1.1 Background to the study:

The diamond mining industry has contributed to the global economy through the extraction of economically valuable mineral resources which are used in manufacturing of machine tools (Adator Stephanie Worlanyo, 2021). According to Angeles, et al., (2020), three major important assets must be effectively monitored, evaluated, and maintained for optimum productivity in mining operations. They are, (i) the labor force, (ii) the environment, and (iii) the equipment. The mining industry particularly diamond mining, relies on heavy-duty equipment such as excavators and shovel loaders to ensure efficiency in mining operations. However, the reliability and availability of these equipment plays a major role in the productivity of the mining operations (Angeles & Kumral, 2020).

The electric rope shovel is a type of mining shovel loader that is operated electrically and is used in an open pit mine for excavation and loading of blasted rocks and extracted minerals into a nearby truck as shown in Figure 1.1a (Topno et al., 2021). The electric rope shovel consists of housing, mounting, propel system, crawler, or the drive components, dipper stick, hoist line and dipper bucket (Paulmakesh, 2020). It is designed with an undercarriage system that aids its movement around the operating environment making it possible for the shovel to dig and load at different positions and angles. The undercarriage system consists of an idler, drive shaft, and a drive

tumbler. Figure 1.1b shows the undercarriage system of an electric rope shovel and the different components (Ronald-mario-kupa-anticono, 2014; Dragan et al., 2019).

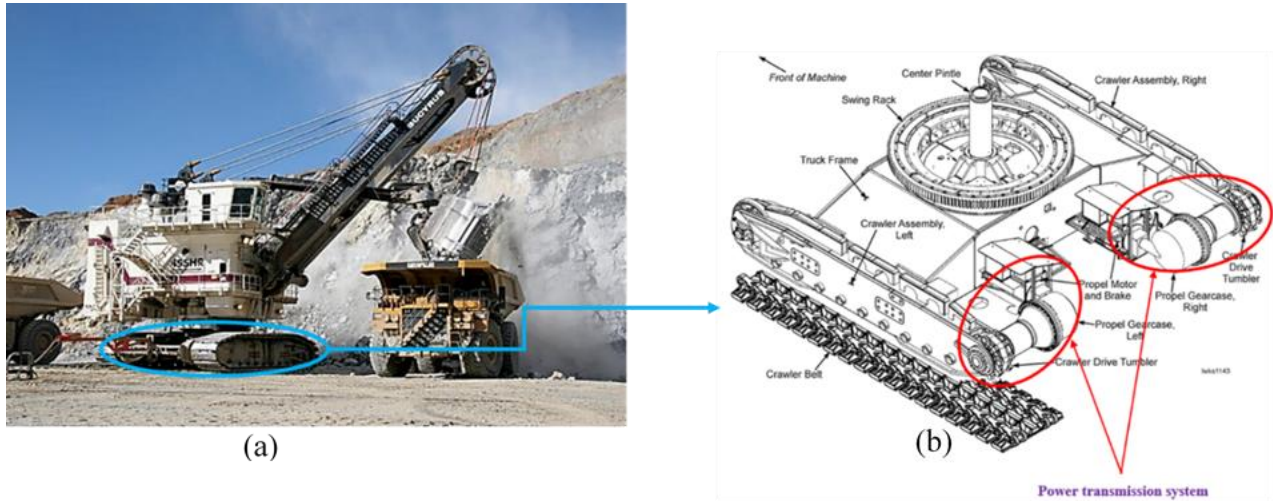


Figure 1.1: Shovel loader (a) entire machine (Topno et al., 2021) (b) undercarriage assembly (Ronald-mario-kupa-anticono, 2014; Dragan et al., 2019)

The drive tumbler as an essential component in the shovel loader, is a sprocket-type wheel made from large diameter steel castings of low alloy steels with induction hardening (Ronald-mario-kupa-anticono, 2014). It is designed with eighteen (18) teeth to engage with a chain or belt to transmit mechanical power between drive shafts made of forged alloy steel at about 0.44m/s (1.6 kph) to the continuous track/crawler belt weighing approximately 23,000 kg (Harnesswala & Jha, 2020). Additionally, the transmitted power propels the undercarriage system around the mining terrain and facilitates the easy movement of the electric mining shovel in the operating environment. This is done by the interaction of the crawler belt and continuous track with the mining terrain converting the rotational motion of the drive tumbler to linear motion (Ronald-mario-kupa-anticono, 2014; Dragan et al., 2019). Table 1.1 presents the operational condition of drive tumbler of the machine as observed during a site visit to the mine.

Drive tumblers manufactured from cast, induction-hardened low-alloy steels are commonly used in mining shovel loaders due to their balance of surface hardness and core toughness. However, several design-related challenges can compromise their performance in high-abrasion, high-impact environments. Induction hardening produces a hard, wear-resistant surface layer, but the case depth can vary significantly across complex tooth geometries, resulting in shallow hardened zones at critical areas such as the tooth roots or edges (Ronald-mario-kupa-anticono, 2014; Harnesswala

& Jha, 2020). Casting processes may also introduce defects such as shrinkage cavities, porosity, and inclusions, which act as preferential crack initiation sites under cyclic impact loading (Zhang & Thomas, 2002; Jung et al., 2008; Maciejewski, 2015; Zheng et al., 2015; Gorkusha et al., 2020).

The diamond mine environment consists of hard and abrasive kimberlite mineral containing diamonds, rocks, clay and sands causing continuous abrasive wear on metal surfaces (Sun et al., 2019; Nkgakile, 2023). Additionally, the presence of chemically reactive mine water, rich in dissolved salts and sulfates, accelerates corrosion, leading to severe material degradation and reduced equipment lifespan (Willison & Boyer, 2012; Peng et al., 2013). As a result, the diamond mining environment can be classified as both physically and chemically aggressive, posing substantial risks to component integrity and performance.

During operations in the harsh environmental conditions of diamond mining and under heavy loads application as summarized in Table 1.1, the drive tumbler was exposed to the operating environment during its service life (approximately 5000 running hours), and experienced wear, surface contact stress at the point of contact between the crawler belt as depicted in Figure 1.2. Frictional stress due to sliding motion and cyclic loading exerting fatigue stress causes a reduction in the structural integrity and mechanical performance of the drive tumbler teeth resulting in excessive wear and tooth breakage, a failure common to mechanical power transmission components like gears and sprocket (Aherwar, 2016; Sahoo, 2019; Guo et al., 2022). This type of failure, tooth fracture during operation is one of the most dangerous failure mode, because it can lead to sudden equipment breakdown, posing safety risks to personnel and resulting in significant operational downtime and financial loss (Xu et al., 2020), associated with improper design geometry, inappropriate materials and manufacturing processes (Xu et al., 2020).

Table 1.1: Operating conditions of the drive tumbler in the electric shovel loader operations

Operating conditions	Description
Frequent direction changes	The drive tumbler undergoes frequent directional changes to meet the dynamic demands of machinery operations, including rapid shaft rotation reversals.
Physical environment	Dust, moisture, and debris such as rocks and minerals, are present in the operating environment.
Sliding-Impact forces	The drive tumbler endures dynamic forces generated during the machinery operation.
Vibration	As the drive tumbler rotates, it causes intermittent changes in the trackpad's velocity and induces vibrations within the drive tumbler.
High loads	The drive tumbler bears heavy loads due to the weight of the undercarriage system and the materials being transported during digging and hoisting.
Mechanical stresses	The drive tumbler is prone to bending, torsion, and abrasion due to its continuous engagement with the crawler belt and the uneven terrain.

Additionally, information obtained from the diamond mine revealed that the drive tumbler is designed to operate for 25,000 running hours of the shovel loader. However, based on the experience of the maintenance engineer, the drive tumbler can barely operate at 20% of its design life. This occasionally leads to downtime of about 12 months (10, 000 running hours) and frequent replacement of at least three new drive tumbler within the supposed designed of the drive tumbler.

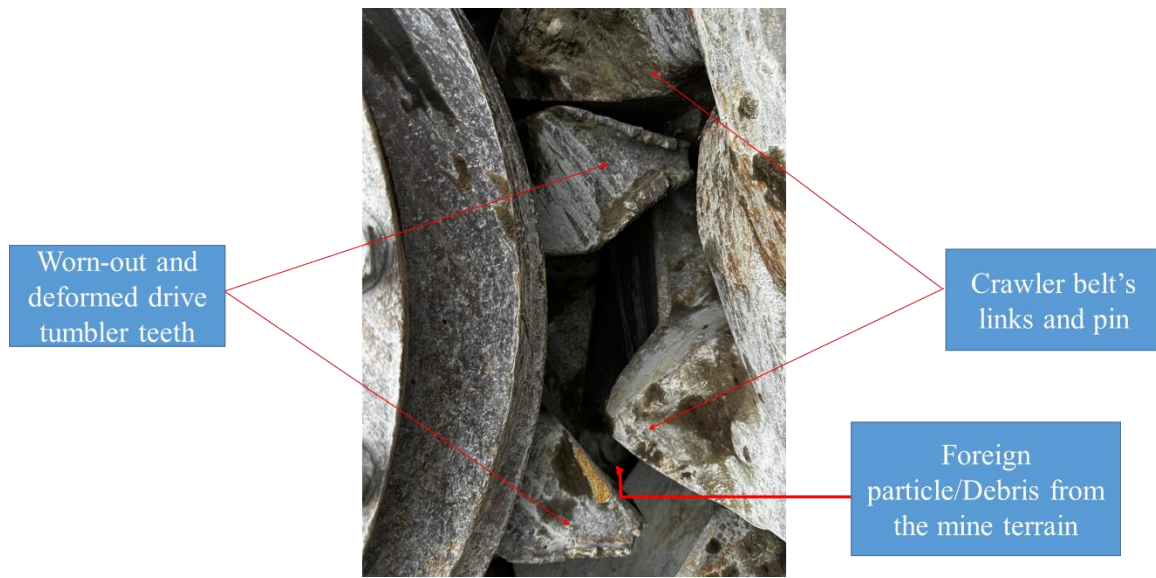


Figure 1.2: Image of drive tumbler in contact with crawler belt and entrapped foreign particle

Moreover, the reliability and efficiency of mining operations depend heavily on the heavy-duty mining equipment to extract, transport and process raw materials. The continuous premature failure in these equipment components presents the need for comprehensive failure analysis and the provision of mitigation strategies such as proper materials selection and suitable remanufacturing techniques to prevent unexpected failures by extending component service life (Wang et al., 2021). Remanufacturing is a sustainable development strategy, on the other hand is an essential strategy for extending the useful life of equipment components. This process involves the restoration of worn-out or damaged component to their original and/or improved state through various techniques, including surface modification that involves deposition of material through traditional techniques such as welding and machining, or advanced manufacturing process (Andrew-Munot et al., 2015; Cao et al., 2020). The mining industry can significantly reduce waste generation and financial expenses associated with the production or purchase of entirely new components by adopting appropriate remanufacturing techniques which generally contribute to environmental sustainability, including a decrease in carbon emissions, energy usage, and material consumption thereby ensuring long-term sustainability (Matsumoto et al., 2017; Krystofik et al., 2018; Kanazawa et al., 2022). The fact that remanufactured components consume 85% less energy compared to the energy required for manufacturing the same quantity with the lower quality of

new component highlights one of its significant technological and economic benefits (Hazen et al., 2017). Remanufactured items are typically priced significantly lower than new items, often at a cost that is around 60% of the price of a new component (Rathore et al., 2011).

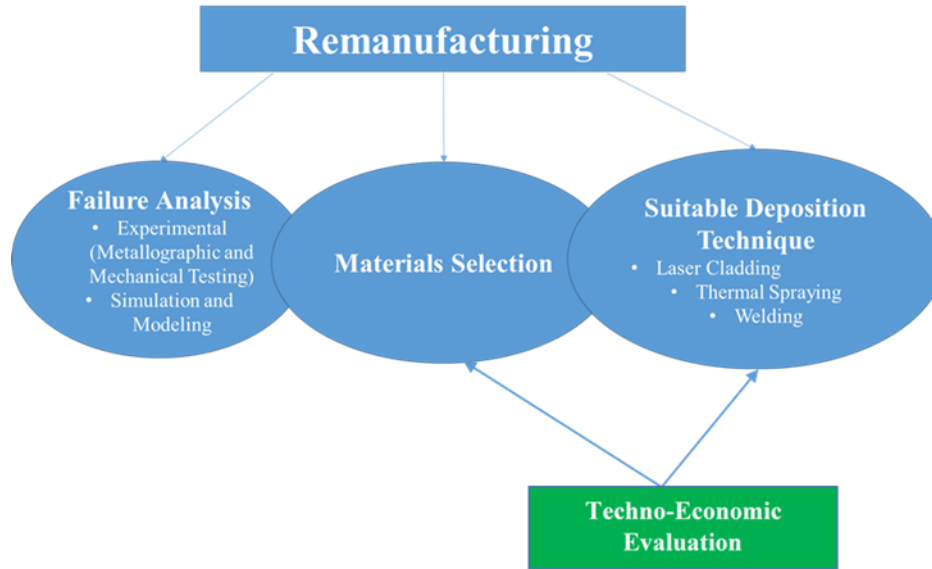


Figure 1.3: Systematic approach for successful remanufacturing of damaged components

Nevertheless effective remanufacturing of damaged components requires a systematic approach as depicted in Figure 1.3 including identifying the underlying causes of failure in engineering components through detailed failure investigation, selecting appropriate materials and suitable deposition techniques to restore functionality and extend service life of prematurely failed components (Lindsay, 2024), as well as cost-benefit evaluation to ensure profitability of the selected approach. Although other sectors like aerospace, healthcare, power generation has received huge attention in remanufacturing of their industrial tools and components, machine parts in the mining industry, particularly the drive tumbler in heavy-duty equipment received limited consideration in effective remanufacturing approach, especially in the investigation of causative factors contributing to premature failure and cost benefit evaluation of possible remanufacturing strategy. This study focuses on investigating the failure of damaged drive tumbler, select candidate materials and remanufacturing approach to mitigate failure and evaluate the cost-benefit of the selected approach. These are critical stages crucial before sustainable and profitable remanufacturing can take place.

According to Shipley et al., (2022), failure analysis is employed in machine systems and components to investigate the causes of their failures, identify the root cause and develop solutions in preventing recurrence. It involves the use of experimental approach such as visual inspection, non-destructive test (NDT), microscopic and metallographic examination and computational techniques such finite element methods (FEM) using simulation software. This is essential for identifying metallurgical deficiencies, stress-induced damage, and material degradation in failed components. By revealing hidden flaws such as microstructural anomalies, inclusions, and failure modes and mechanisms, it informs corrective actions during remanufacturing process to enhance material performance and prevent future failures (Boukharouba et al., 2009). For example, Eras et al., (2022), carried out a failure analysis on sprocket drivers in a clinker scraper conveyor using experimental characterization. It was discovered that the choice of a sprocket material with yield strength of 542 MPa, incapable of withstanding the operating conditions of the scraper conveyor in a cement plant and poor lubrication, were the main causes of the progressive surface shape loss of the sprocket teeth. Additionally, In the failure analysis carried out on a spiral bevel gear by Hein et al., (2017), the results obtained suggested that subsurface inclusions detected below gear surface, acted as points of crack initiation that led to fracture. Fracture in a girth gear of bucket wheel excavator used in an open pit mine, was also attributed to an initial crack from the gear's manufacturing process (Arsić et al., 2019). From the above studies, it was revealed that the combination of poor maintenance practices, poor materials selection, and inadequate manufacturing process were major factors that contributed to the damage of gears and sprockets in mining equipment.

Additionally, the cost of material degradation due to wear and fracture represents a significant portion of the total operational expenses of heavy-duty equipment components in a conventional mine (Cortie McEwan, JJ & Enright, DP, 1996). Because of this, appropriate materials selection is essential for the remanufacturing of damaged components, however this can be determined based on causative factors responsible for machine parts failures. Over the years, several materials including tool steels, low/medium carbon low alloy steels, and metal matrix composites (Manna et al., 2006; Zhang et al., 2007; Milanti et al., 2014; Braga et al., 2021; Xiao et al., 2021; Li et al., 2024), have been explored in the remanufacturing of damaged heavy-duty equipment components susceptible to wear. The selection of appropriate materials is vital to achieving components'

durability and effective performance for the intended application, thereby reducing operational and maintenance costs, and improving the overall profitability of the mining company.

Numerous techniques like thermal spraying, chemical vapor deposition (CVD), welding, and laser cladding can be adopted for depositing candidate wear-resistant materials towards the remanufacturing of damaged components in heavy-duty mining equipment. Nonetheless, the selection of the appropriate technique depends on the functional and materials requirement of the components to be remanufactured (Al-asadi & Al-tameemi, 2022). Other factors to consider in the selection of a suitable deposition technique include the overall cost associated with the equipment, the adaptability of the coating materials to the intended deposition technique, and the level of heat interaction in the form of heat-affected zone (HAZ) between the coating materials and substrate. Welding and thermal spraying are disadvantaged in remanufacturing because of the high heat affected zone, and distortion they exert on remanufactured components, causing their reduced lifespan, while CVD can only deposit few millimeters of coating thickness of about 0.05 μm to 20 μm which may not have the strength to withstand heavy load applications in the mining industry (Davis, 2005; Mohanty & Roy, 2012; Chmielewski & Golański, 2015; IRS-surfacing-echnologies, 2020; Hayden, n.d). To address these disadvantages, the laser-based remanufacturing techniques offer a sustainable solution because it provides superior techniques, an eco-friendly environment, and cleaner technology if properly explored. Among the laser-based remanufacturing technologies, LC is a very effective surface modification and repair technology that offers advantages like small HAZ, low dilution rate, thick coatings, and strong metallurgical bond between coating and substrate. It makes use of the laser beam and additive manufacturing principles to restore components to as new in performance whilst providing the following benefits to remanufacturing (Singh et al., 2020; Zhu et al., 2021; Liu et al., 2021; Ehsan et al., 2021):

-  It presents an advantage of minimal dilution ratio and special performance characteristics.
-  Can be used on different materials.
-  Prevent materials waste, supporting reuse of materials.
-  Can remanufacture complex and near-net shape components.
-  The HAZ can be controlled to optimum due to the ability to focus on the intended work area allowing remanufacture of a selected area with minimal thermal deformation to the whole part.

🔥 Produces high-quality coating with excellent metallurgical bonds and superior mechanical properties.

Based on the benefits listed, and its unique ability to create thick coatings that improve the wear resistance and corrosion resistance of substrates, different researchers have reported the adoption of laser cladding to remanufacture damaged components, particularly mechanical transmission components like gears and sprockets in heavy-duty mining equipment as shown in Figure 1.4 (a & b), (Liu et al., 2017; Zhu et al., 2020; Li et al., 2021; Guo et al., 2022; Niu et al., 2023; Guan et al., 2023). However, the evaluation of cost associated with the adoption of laser cladding to deposit materials towards repair or remanufacturing of industrial equipment parts is an untapped area of study.

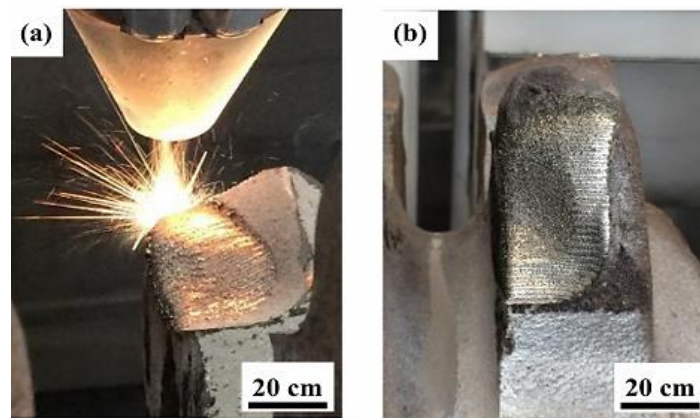


Figure 1.4: Image of the sprocket remanufacturing process using laser cladding and its final repair result (Liu et al., 2017).

Techno-economic analysis (TEA) serves as a critical decision-making framework that supports the evaluation and justification of manufacturing systems at scale. It combines both technological and economic perspectives to assess the viability and efficiency of a given process (Lauer, 2008; Oyesola et al., 2019; Di & Yang, 2020). From the technological standpoint, TEA considers the current capabilities, limitations, and readiness of available fabrication techniques. Economically, it requires careful analysis of production costs, material usage, process duration, and other performance indicators relevant to system optimization. Ultimately, TEA enables stakeholders to determine the economic soundness and long-term value of implementing a particular technology by weighing its associated costs against the expected benefits (Lauer, 2008; Oyesola et al., 2019; Di & Yang, 2020).

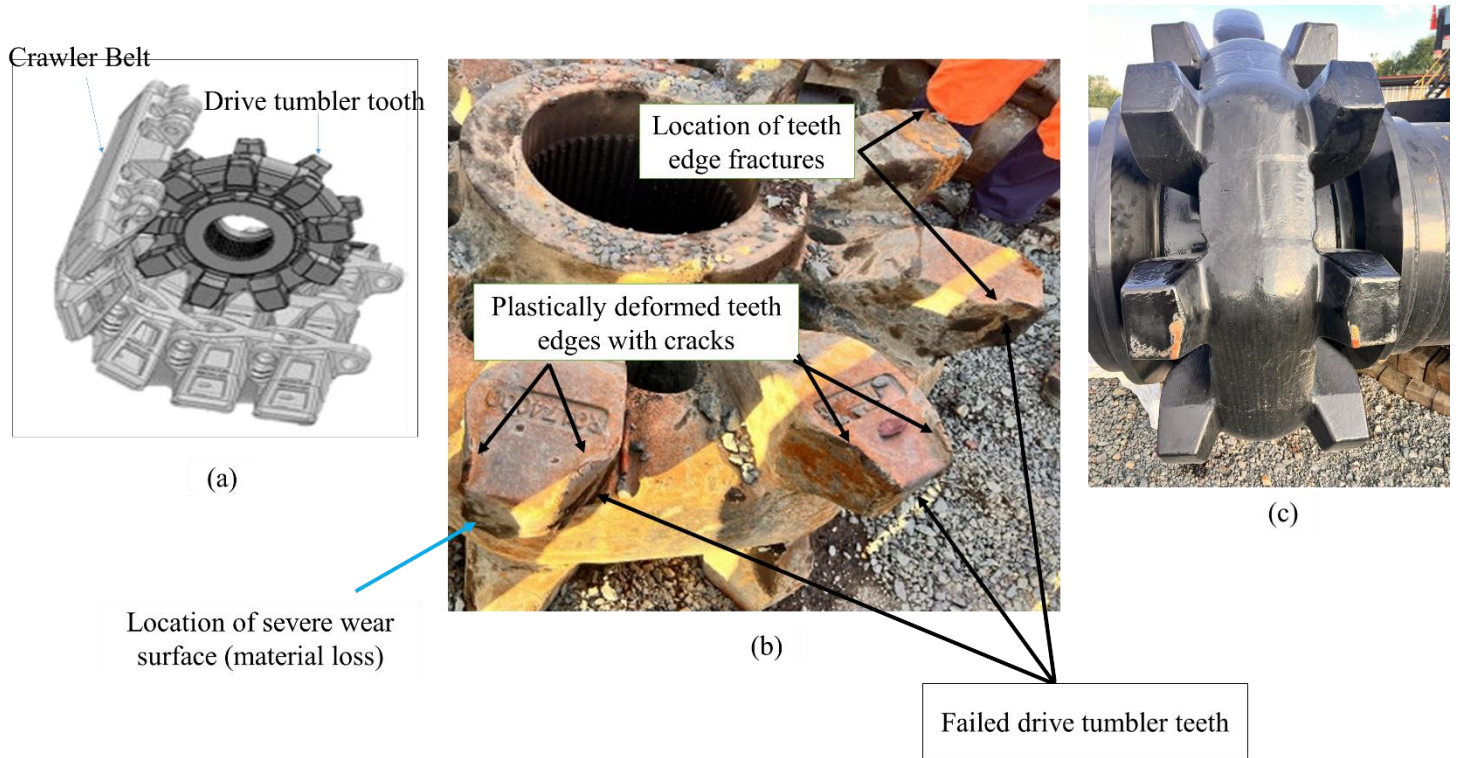
Hence, this research focuses on carrying out engineering failure analysis to reveal the failure modes and mechanisms, and the root causes of the drive tumbler's premature failure, to help identify candidate wear-resistant materials and deposition techniques from the literature and to evaluate the cost-benefit of adopting selected materials and deposition technique towards the remanufacturing of the damaged drive tumbler teeth to at least new in performance. One benefit of failure analysis is achieving better results. Whether creating or refining a product or service, failure analysis can improve it with each new version, model, or variation. Failure analysis can also be a source of information to prevent failures in future projects such as remanufacturing of damaged components, as it often uncovers conditions or mechanical components causing problems or weaknesses that were previously unknown. Failure analysis is an ideal method for improving the planning of new remanufacturing projects before committing time and materials to their completion. Hence, this research focuses on carrying out engineering failure analysis to reveal the root cause of the drive tumbler's premature failure in a diamond mine, propose suitable candidate wear resistance materials and remanufacturing approach from the literature, and evaluate the cost-benefit of remanufacturing based on level and failure mechanisms of the failed drive tumbler.

1.2 Problem Statement

Botswana known as a diamond mining country is the world's leading producer of high-quality diamonds, contributing to 30% of her Gross Domestic product (GDP), 70% of the country's foreign exchange earnings and 30% of the world's output by value from four mines (Debswana Report, 2020). A prominent diamond mine in Botswana, which contributes about 60-70% of a diamond company's total revenue from its annual production of 12 million carats (International, 2022), experiences losses in production because of the prolong downtime due to the damage of high-value drive tumbler in the electric rope shovel.

The drive tumbler which contribute to the optimum performance of the shovel under harsh working environment and operating condition of bending, sliding contact, fatigue and wear stress, experiences premature failure with several failure modes such as plastic deformation, surface wear, gouging, cracks and fractures, at 5,000 running hours instead of 25,000 running hours, resulting in unplanned downtime spanning through 12 months and about 30% increase in cost of maintenance of the electric shovel.

The drive tumbler teeth are subjected to severe continuous engagement with an induction-hardened links of the crawler belt as shown in Figure 1.5a (Dragan et al., 2019). The sliding friction,



combined with the impact of possible abrasive particle trapped between the drive tumbler and crawler belt, imposes excessive fatigue stresses on the surface of the drive tumbler teeth.

Figure 1.5: (a) Drive tumbler engaging with crawler tracks. (Dragan et al., 2019), (b) Drive tumbler with critical damage & plastically deformed teeth, (c) Typical new sprocket-type drive tumbler installed on the crawler assembly of the shovel or belt, Source: (Debswana mine, 2024).

Consequently, this leads to pronounced material loss particularly at the contact interfaces of the drive tumbler teeth. These degradation mechanisms critically affect the functionality and lifespan of the drive tumbler, contributing to the complete fracture of the drive tumbler teeth edges before its expected life cycle. Figure 1.5b shows the damages experienced by the drive tumbler during operations while Figure 1.5c shows the drive tumbler when it has not been subjected to use. Annually, the mine is subjected to replacing the drive tumbler twice costing about \$100,000 (Ronald-mario-kupa-anticono, 2014; Dragan et al., 2019; Boundary Equipment 2024).

Furthermore, the company's practice of discarding damaged drive tumblers as scrap significantly increases maintenance and downtime costs. These added expenses raise the overall operational cost and negatively impact the productivity of the diamond mine. The root causes of the premature failure of this critical component remain unclear due to limited research study and report on the failure and mitigation strategies of the drive tumbler of mining shovels. Additionally, while existing literature have effectively adopted laser cladding technique for the remanufacturing and repair of damaged industrial components, its application has not been linked to solving specific type of failure in mining industry and the techno-economic analysis of this unique method before remanufacturing has not been effectively studied.

Therefore, it is essential to perform a comprehensive experimental failure investigation to understand the root cause of the failure and provide a sustainable solution that can mitigate the recurrent premature failure of the drive tumbler. The goal of this research is to investigate several components including material and mechanical characteristics, manufacturing processes, operational circumstances, and environmental factors that are involved in the premature failure of the drive tumbler teeth. The study aims to identify critical failure mechanisms through macroscopic, chemical, and microscopic analysis, analyze their impact on the performance of the drive tumbler teeth, and propose a practical solution to enhance the durability and dependability of this crucial part in the electric mining shovel. This will be done by conducting a detailed engineering failure analysis (EFA), selection appropriate wear-resistant materials and deposition technique from compressive literature review. Additionally, to investigate the profitability of selected candidate materials and the remanufacturing approach, the study evaluates the cost-benefits of remanufacturing the drive tumbler teeth, based on the mechanism and degree of failure, cost associated with the selected materials and the laser cladding technique.

1.3 General Objectives

The primary objective of this study is to conduct failure investigation of drive tumbler teeth of an electric mining shovel using experimental methods and provide mitigation strategies that can prevent future failure in the drive tumbler. The aim of the study will be accomplished via the following specific objectives:

- 1) To investigate the operating environment and material properties of the drive tumbler and analyse the failure modes and mechanisms in the damaged drive tumbler teeth, to identify the root causes of the premature failure.
- 2) Propose mitigation measures that can prevent future failures of drive tumbler teeth through selection of candidate wear-resistant materials and suitable remanufacturing approach from the literature and findings from objective one (1).
- 3) Investigate the profitability of remanufacturing drive tumbler teeth by evaluating the cost-benefits of adopting selected materials and remanufacturing approach.

1.4 Delimitation of the Scope of the Study:

This study focuses on the failure analysis of the drive tumbler teeth of an electric mining shovel for diamond mining application, primarily using experimental characterisation. While the mechanical properties of crawler belt as a mating component against the drive tumbler is considered through literature review and data collections from the mine, detailed experimental investigations are limited to the drive tumbler teeth. The study also includes analysis of mine water from the mine using ion chromatography (IC) and an assessment of the geological formation from existing literature to establish the conditions of the drive tumbler's operating environment. Although the research begins with a site visit to collect operational data, field testing and in-service monitoring are not conducted. Computational simulations and performance predictions beyond the laboratory environment are also excluded. The techno-economic analysis presented in this work is a preliminary evaluation based on identify failure mode, assumptions and literature-sourced data. The estimated cost of laser cladding is calculated using assumed process parameters and surface area of the failure mode to be remanufactured. While no experimental laser cladding was performed, the study provides a comparative insight into the material cost and processing feasibility of selected candidate materials (MMC: H13 and WC-12Co) and deposition technique (laser cladding process) for remanufacturing drive tumbler teeth.

1.5 Significant of the Study:

The recurrent premature failure of drive tumbler in the electric mining shovel has serious implications on safety, profitability and overall productivity of the diamond mining operations. Figuring out the underlying causes of the failure, the performance, reliability and durability of the

drive tumbler can be greatly improved which will enhance the efficiency of the shovel by reducing maintenance cost and downtime, thereby increasing the diamond mining productivity and profitability.

Remanufacturing often results in lower cost than replacing entire components. Hence the results from this study will serve as a guide and a decision-making model for the remanufacturing of the failed drive tumbler teeth in terms of selecting suitable wear-resistant materials and manufacturing strategies, which will help prolong the service life of the drive tumbler and reduce the overall cost of replacement. Furthermore, due to limited relevant studies on the failure of the drive tumbler, this research will contribute to the body of knowledge in engineering failure analysis of the drive tumbler, material science and sustainable development through the publication of the findings from this study. Also, the experimental results from analyzing the various failure modes could be applied to other similar mining equipment component that operates under combined condition of bending, sliding-impact contact, fatigue and wear stress and harsh operating environment.

1.6 Thesis Outline

This thesis consists of six (6) chapters covering the three objectives of the study. The references cited in the research work are listed at the end of the thesis followed by the other materials in the appendices that are important to the research but could not be included in the thesis. The thesis is organized as follows:

-  Chapter 1 is an introduction to the research background which brings out the problem leading to this study and the objectives of the research. The delimitation of the scope of this study, specific themes of the thesis as well as the significance of this study are presented in Chapter one of this thesis.
-  Chapter 2 is the literature review on the nature of failure of mechanical power transmission component (the gears and sprockets) which operates similarly to the drive tumbler in heavy-duty equipment, materials selection and suitable remanufacturing to provide guide during recommendation of mitigation strategies.
-  Chapter 3 outlines the materials and experimental methods used in this study. It provides a detailed procedure for carrying out engineering failure analysis (EFA) of failed drive tumbler teeth from the shovel loader used in a diamond mine and TEA of selected materials and remanufacturing approach.

- 📖 Chapter 4 presents the results and discussion of the failure analysis carried out on the drive tumbler. The results from visual examination, chemical analysis, microstructural and fractographical analysis are presented.
- 📖 Chapter 5 discusses the techno-economic analysis of selected materials and remanufacturing approach.
- 📖 Chapter 6 gives a detailed summary and conclusion drawn from the research finding and provides recommendations for future studies.

1.7 Conclusion

The necessary information on the background of this research, including the problem statement, aim and specific objectives, delimitation scope of work, specific themes of the research as well as the thesis outline are presented in this chapter. The background to this study highlighted the importance of the electric mining shovel in diamond mining operations. It further explained how drive tumbler serves as a major component in the shovel, and its contribution to the shovel efficiency in digging and loading operations in diamond open-pit mine. The importance of failure analysis and techno-economic analysis as a critical stage before remanufacturing has also been discussed. The problem statement is identified, as premature failure of the drive tumbler which has posed an increase in operational cost of the mine due to prolong downtime, high cost of maintaining the shovel and cost of buying a new drive tumbler and limited study on the failure of drive tumbler in diamond mining applications. The aim of this study is however stated to investigate the root cause of damaged drive tumbler teeth and provide mitigation strategies to prevent future failure and extend the service life of the drive tumbler teeth.

2 Chapter Two: Literature Review

2.0 Chapter Summary:

Due to limited research on failure analysis of drive tumblers, common failure modes experienced by similar mechanical components such as gears, and sprockets, are briefly discussed in this chapter. These components work in a similar way as mechanical transmission components like the drive tumbler. This is to provide adequate information to understand the possible similar failure modes the drive tumbler experiences in operations. Additionally, the impact of the mechanical properties of working environment's geological formation, and crawler belt as interacting component on the drive tumbler teeth are briefly discussed. Different materials and deposition techniques for remanufacturing are also presented.

2.1 Operational Environment and Conditions of Drive Tumbler in Heavy-duty Mining Equipment

The diamond mine extracts a diamond-bearing kimberlite complex of three main pipes known as the D/K2 kimberlite. South (S), Center (C), and North (N) pipes are the names of the three main pipes (McKechnie, 2019). Kimberlite pipes are a major geological formation that is enriched in diamonds. They are vertical, pipe-like igneous rocks that play a crucial role in the formation and transformation of diamonds (GeologyScience, 2024). According to Nkgakile, (2023), the three kimberlite pipes exhibit geological heterogeneity in terms of their rock content and texture. The kimberlites are laid out in abundance layers of rocks such as quartz, sandstone, dolomites and shales in different proportion as shown in Figure 2.1a (Nkgakile, 2023). The quartz, sandstones, dolomites and shales have distinct mechanical properties ranging from about 1000 HV – 1200 HV hardness value making them more abrasive (Chang et al., 2006). During operations, the intense and abrasive nature of a diamond mine as shown in Figure 2.1(a & b) can put significant stresses on mining equipment, where particles and mineral ore debris are entrapped in between the surface of the drive tumbler teeth and crawler belt. This leads to a higher rate of equipment failure such as a severe wear and surface contact fatigue (Hisan et al., 2019).

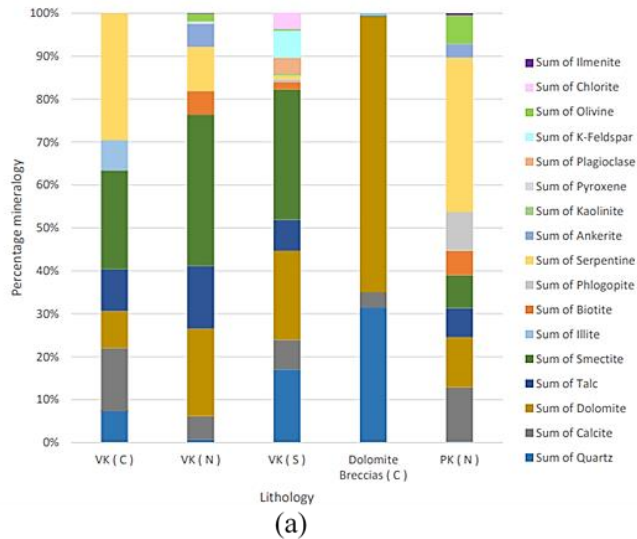


Figure 2.1: A typical diamond open pit mine showing (a) Geological formation and lithology (b) Physical view with hard minerals (mining.com, 2021)

The operation of the drive tumbler is demonstrated through its connection and continuous engagement with the crawler belt (Figure 1.5a). The crawler belt, with its interlinked plates, loops around the drive tumbler, and creates a track system that distributes the machine's weight and stabilizes movement (Ronald-mario-kupa-anticono, 2014; Dragan et al., 2019; Topno et al., 2021). Meanwhile, the drive tumbler which is located at the rear of the undercarriage assembly, engages directly with the crawler belt. As the drive tumbler rotates, the teeth of the tumbler insert into the spaces between the links of the crawler belt, transmitting torques that propel the entire equipment forward (Ronald-mario-kupa-anticono, 2014; Dragan et al., 2019; Topno et al., 2021). However, this engagement is highly dependent on proper alignment and synchronization between the drive tumbler teeth and the crawler belt links' (valuetrackparts, 2018). Misalignment in the belt's links can cause uneven engagement and increase stress concentrations on the surface of the drive tumbler's teeth. This is because, this misalignment forces the drive tumbler to work harder to maintain traction, resulting in accelerated wear and potential damage, especially on the edges of the drive tumbler's teeth (valuetrackparts, 2018). This may further be aggravated depending on the type of material the crawler belt is made of (valuetrackparts, 2018; Bortnowski et al., 2022). In the literature, crawler belts used in heavy-duty mining equipment are typically manufactured from high-strength low-alloy (HSLA) steel such as 30CrMnMoV, austempered ductile iron (ADI), and manganese steel (Yu et al., 2010; Bošnjak et al., 2013). These materials are known for their

extremely high tensile strength, impact resistance, and wear resistance under high impact or abrasion (Yu et al., 2010; Bošnjak et al., 2013). In addition to this, information gathered from the mine and original equipment manufacturer (Walkson, n.d.), indicated that the crawler belt is induction hardened with approximately 700 HV microhardness. The effective interaction between the drive tumbler as the driver mechanism, and the crawler belt as the driven mechanism, in terms of proper engagement and suitable materials that can withstand this interaction in the presence of foreign abrasive minerals, is critical for the durability of the drive tumbler and efficient operation of the mining shovel loader in the abrasive mining environment. However, to further understand contributory factors in the failure of the drive tumbler, there is a need for a detailed failure analysis. The next section revealed the failure analysis of mechanical transmission components that have been explored in the literature.

2.2 Failure Analysis of Drive Tumbler

Despite the limited research on the failure analysis of drive tumblers, that of shafts, gears, and sprockets has been investigated by some researchers using a range of techniques such as visual inspection, macrographic analysis, optical microscopy, microhardness measurement, quantitative chemical analysis and finite element analysis (FEA) (Zhao et al., 2019; Sales et al., 2020; Eras et al., 2022; Bian et al., 2022). For example, Zhao et al., (2019) utilized fracture analysis, mechanical testing, metallography examination and FEA to identify fatigue failure in a drive shaft, related to improper design due to stress concentration from small fillet radius at the spline of the shaft, resulting in a high stress at the root fillet. Also, Eras et al., (2022), carried out a failure analysis on sprocket drivers in a clinker scraper conveyor using experimental characterization. It was discovered that the choice of a sprocket material with yield strength of 542 MPa, was incapable of withstanding the operating condition of the scraper conveyor in a cement plant. Poor lubrication, was amongst the main causes of the progressive surface shape loss of the sprocket teeth. These techniques have effectively identified the root cause of early failure, such as unsuitable material composition and flaws in manufacturing approaches (Bian et al., 2022). These studies revealed that experimental and numeral approaches of failure analysis provide insights into identifying various failure modes and mechanisms such as wear, fatigue, and tooth fracture as discussed in the next section of this study.

2.2.1 Nature of failures in similar components with drive tumbler; Gears and Sprocket

Comprehensive knowledge of the failure modes in similar components such as gears and sprockets are essential to enhance the drive tumbler's reliability, performance, and design. Generally, the failure of these mechanical transmission components is mostly attributed to wear, fatigue, and fracture. Wear is described as a process of losing materials from a solid surface of machine components resulting in the material's deformation, separation, and peeling in a particular area as a result of physical and mechanical contacts between different parts and abrasive particles (Gromyka & Kremcheev, 2020). However, wear which can be an abrasive, adhesive, fatigue, or corrosion wear can occur from different factors ranging from the nature of components' manufacturing technique and materials, size of abrasive particle, working conditions such as speed of component, nature of materials these components are in contact with, and operating environment (Hong & Hu, 2022). The different types of wear as depicted in Figure 2.2, can be experienced by the drive tumbler due to its operating conditions as discussed in chapter 1, and the environmental condition of the diamond mine. Table 2.1 summarizes the major types of wear in Figure 2.2 (a-d) and mechanisms by which they occur in engineering components.

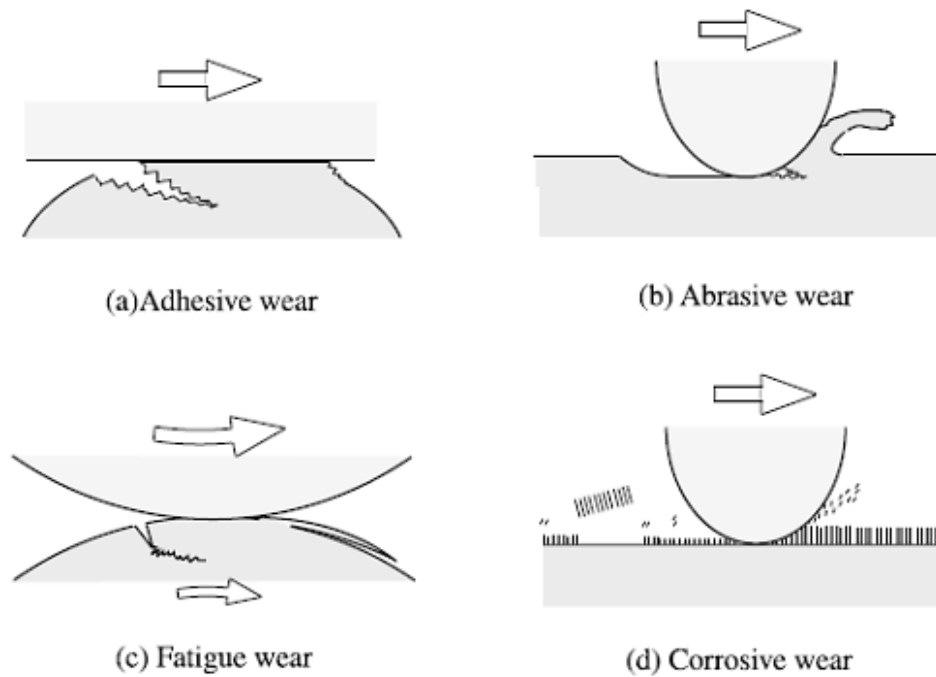


Figure 2.2: Types of wear (Kato & Adachi, 2000)

Table 2.1: Major types of wear mechanism, surface damage, and occurrence in machine component (Stachowiak & Batchelor, 2013).

Failure modes	Definition	Mechanisms	Machine components mostly occurred
Abrasive wear	Material removal by abrasive particles (three body) or strong protuberances on the opposing surface (two body)	Micro cracks, Microfatigue, Cutting, Ploughing, Wedge formation.	Machinery in mining, mineral processing, earth moving, and agriculture industry, valves, piston/cylinders
Adhesive wear	Localized bonding between contacting surfaces leads to material transfer and subsequent detachment	Shear fracture, Tearing, Galling, Scuffing.	Dry sliding, e.g., chain-link conveyor belt, Fasteners, sliding parts in valve lubrication failure e.g., journal bearings, engines, and gears.
Fatigue wear	Removal of material by fracture due to material fatigue caused by cyclic loading and stresses	Spalling, Delamination, Microcracking, Pitting.	Gear teeth, wheel-rail contacts, Rolling-element bearings, etc.
Corrosion wear	Material loss as result of chemical/electrochemical reactions at the interface of components	Pitting, Rusting, Polishing	Pipelines, mining machinery, pipelines, marine industries.

Nonetheless, in mining equipment components, particularly, in mechanical power transmission parts, abrasion, adhesion, and fatigue are the most prevalent wear mechanism, which promotes friction between two contacting surfaces, surface contact fatigue, and the sudden fracture of the mechanical components (Sun et al., 2019; Xu et al., 2020; Vukelic et al., 2020; Liu et al., 2020; Goswami & Nandan Rai, 2023). According to Bob Errichello, & Jane Muller, (2024), there are three states of wear namely: low, mild, and severe wear state. The state at which catastrophes

mostly occur is the severe state, emanating from both low and mild wear states. In the severe state, wear mechanisms act as stress raisers, initiating cracks at the surface and propagating into the subsurface, with macroscopic fractures and larger wear debris that can be found on damaged surfaces (Bob Errichello, & Jane Muller, 2024). These are further discussed as failure modes and mechanisms in the next section.

2.2.2 Failure Modes and Mechanism of Mechanical Power Transmission Components (MTCs)

MTCs such as gears, sprockets, and drive tumblers used in mining equipment are susceptible to frictional wear, abrasive wear, plastic deformation, sliding-rolling contact fatigue, and fracture mostly in the area of contact between mating components (Davis, 2005). While these components ensure efficient and reliable torque transmission, they usually encounter wear and fracture related failure.

Gears, sprockets, and drive tumblers are integral mechanical components that masterfully transmit rotational motion and power within various systems. By leveraging positive engagement with their mating parts, these components ensure efficient and reliable torque transmission. Gears, distinguished by their toothed wheels, seamlessly mesh with other gears, enabling precise torque transmission (Davis, 2005). Sprockets, equipped with teeth that interlock with chain links, perform optimally in chain-driven systems by effectively conveying rotational motion and torque (Harnesswala & Jha, 2020; JLC, 2025). In the same manner, drive tumblers, with their strategically placed teeth, fit perfectly into the holes or pockets of a crawler belt or assembly, facilitating smooth mechanical power transmission to the entire machine (Ronald-mario-kupa-anticono, 2014; Dragan et al., 2019). This robust engagement mechanism ensures that gears, sprockets, and drive tumblers can adeptly transmit torque from the driving component to their respective driven component, thereby enhancing the performance and reliability of mechanical systems (Davis, 2005; Ronald-mario-kupa-anticono, 2014; Hein et al., 2017; Dragan, et al., 2019; Harnesswala & Jha, 2020).

Although the failure modes and mechanisms of the heavy-duty gears and sprockets have been studied, the same cannot be said of the drive tumbler despite its uniqueness and importance in the overall performance of the electric shovel loader. As discussed in section 1.2, the drive tumbler which is designed to operate for about 25,000 running hours was able to perform 20% of its service

life. The limited study on failure analysis of the drive tumblers has facilitated the analysis of failure modes and mechanisms of other mechanical power transmission components such as the gears and sprockets. This is due to the similarity in their modes of operations, which increases the likelihood that these components exhibiting comparable failure modes and mechanisms. As a result, analyzing their failure modes can offer valuable insights into the possible failure modes that may occur in the drive tumbler.

2.2.2.1 Gears

Gear failures are mostly attributed to wear and damage of the gear teeth, often caused by factors not limited to excessive loading, insufficient lubrication, and misalignment of the gear shafts (Goswami & Nandan Rai, 2023). Some major failure modes experienced as shown in Figure 2.3 by gears include (1) wear, (2) surface contact fatigue (Guagliano et al., 2002), and (3) tooth flank fracture. These failures which have been attributed to factors such as the use of inferior materials (Shukla et al., 2013), defects in manufacturing processes, and the operating environment will be discussed in the next subsection.

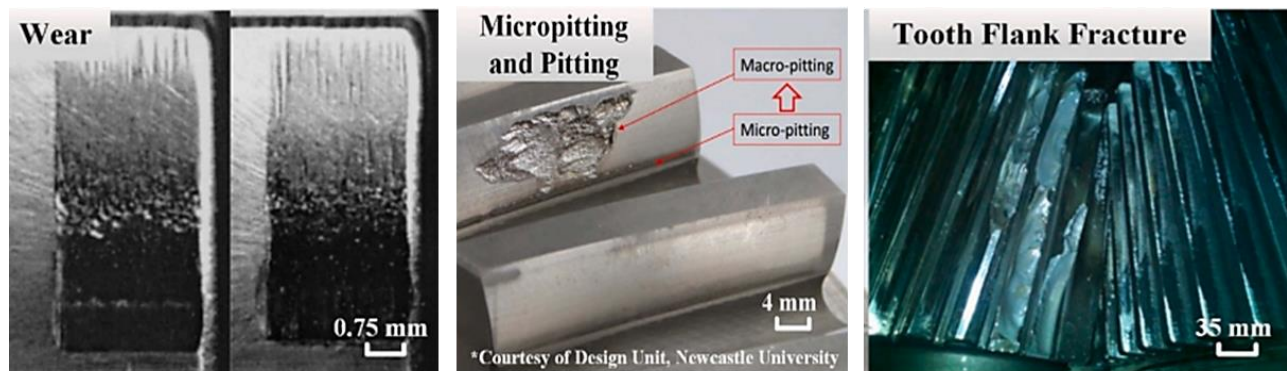


Figure 2.3: Types of failure modes in gears (Liu et al., 2020)

2.2.2.1.1 Wear

Wear in gears occurs because of the constant sliding and rolling contact between the gear teeth. The various type of wear in gears are depicted in Figure 2.3 and Figure 2.5 with their wear mechanism.

Scoring: As shown in Figure 2.4a, this is a form of abrasive and adhesive wear that occurs as a result of starved lubrication, combined with a poor surface finish of gear teeth, causing a breakdown of the oil film and eventually leading to direct metal-to-metal contact maximum (Flodin & Andersson, 1999; Kahraman & Ding, 2013; Goswami & Nandan Rai, 2023). It also promotes the generation of frictional heat, which can overheat the mating teeth. As rapid welding and shearing takes place between the contacting surface, wear rate increases, as large fragment of materials breaks off from one gear tooth and adhere to the opposing tooth (Flodin & Andersson, 1999).

Scuffing: Just like scoring, scuffing is also a form of adhesive wear that occurs when there is a breakdown of lubrication under high load conditions. As, shown in Figure 2.4b. It is characterized by rough edges and is usually found at extreme edges of the tooth face, where the sliding forces are maximum (Flodin & Andersson, 1999; Kahraman & Ding, 2013; Goswami & Nandan Rai, 2023).

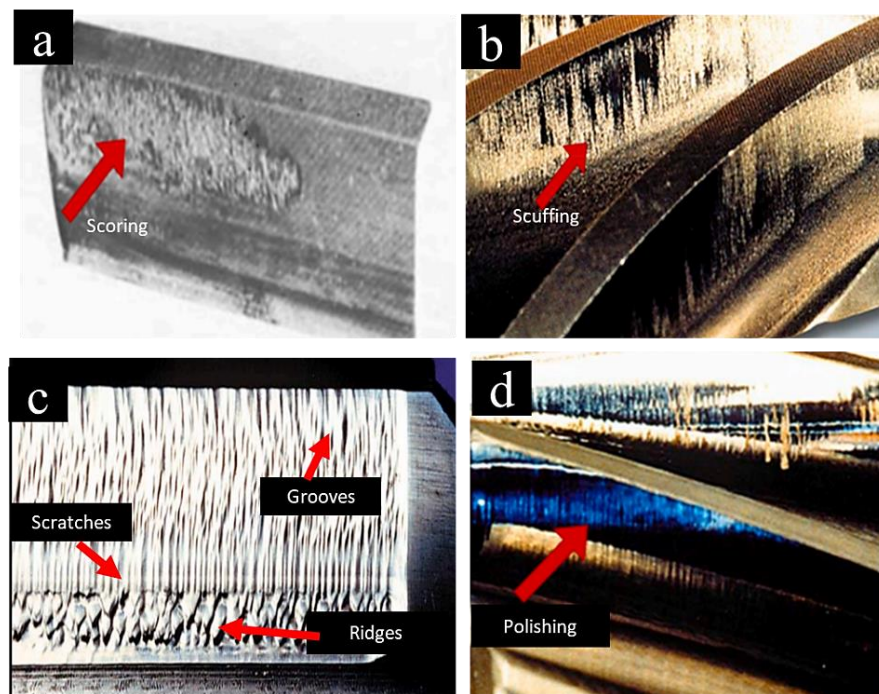


Figure 2.4: Various wear mechanism in gears (a) Abrasive and adhesive wear, (b) Adhesive wear, (c) Abrasive wear, (d) Polishing wear (Flodin & Andersson, 1999; Kahraman & Ding, 2013; Goswami & Nandan Rai, 2023).

Scratches: This is a form of abrasive wear and is characterized by short scratch-like lines as depicted in Figure 2.4c in the direction of tooth sliding, resulting from abrasive actions or impacts. This can also be caused by foreign particles entering the gear maximum (Flodin & Andersson, 1999; Kahraman & Ding, 2013; Goswami & Nandan Rai, 2023).

Grooves: As depicted in Figure 2.4c grooves are elongated depressions formed on the surface of gear teeth due to continuous rubbing and abrasion. They arise from abrasive wear processes where hard particles are trapped between meshing gears or from misalignment causing uneven contact along the tooth surface maximum (Flodin & Andersson, 1999; Kahraman & Ding, 2013; Goswami & Nandan Rai, 2023).

Ridges: As shown in the Figure 2.4c, ridges are raised areas on the surface of gear teeth that develop because of material displacement. This can wear mechanism increases friction between meshing gears leading to additional wear and overheating (Kahraman & Ding, 2013).

Polishing wear: Figure 2.4d show a polishing wear characterized by a shiny surface, which is an initial removal of mild surface layer from the gear tooth flank (Abdelbary & Chang, 2023).

These failure mechanisms are as well suspected in the drive tumbler teeth due to the abrasive minerals present in the mine and possibly, the design deficiency in shovel loader undercarriage system, which does not incorporate proper lubrication plan between the drive tumbler and the crawler belt.

2.2.2.1.2 Surface contact fatigue

Surface fatigue develops as cracks grow under cyclic loading, resulting in the detachment of debris particles, from both the main materials and mating materials. This phenomenon is influenced by the repeated stresses that promote crack formation and materials degradation (Zhang et al., 2020). Usually, these stresses result from a combination of impact, rolling and sliding loading conditions (Kovaříková et al., 2009). As shown in Figure 2.5, when sliding is superimposed on rolling, tangential forces and thermal gradients caused by friction alter stress distribution in and below the contact area. The alternating shear stress intensifies and moves closer to the surface due to sliding forces.

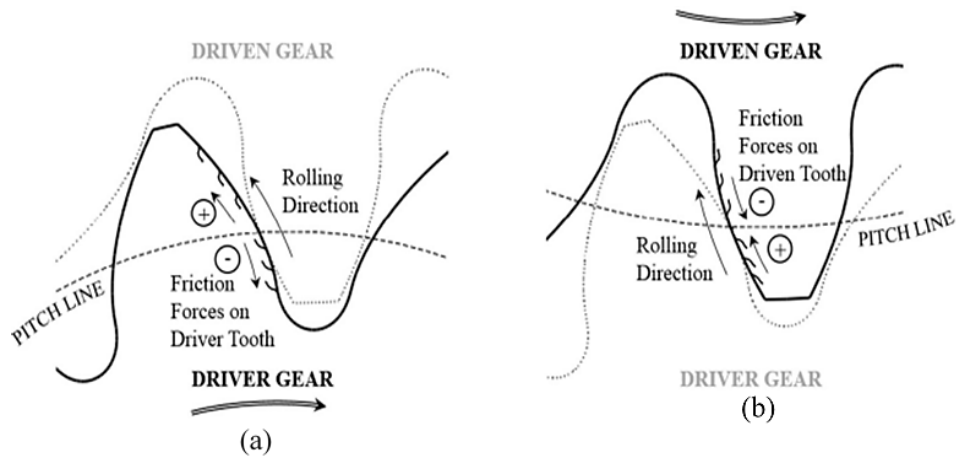


Figure 2.5: Schematic representation of sliding and frictional forces in (a) driver gear meshing, (b) driven gear meshing (Terrin et al., 2017)

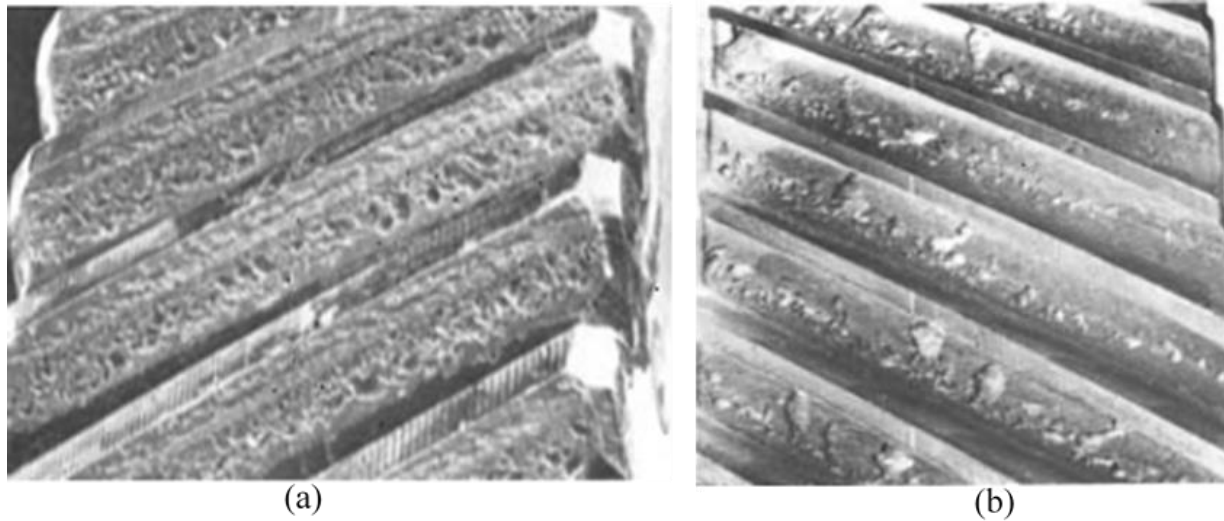


Figure 2.6a Pitting, (b) spalling (Rexnord Industries, 1978)

Surface contact fatigue which is mostly characterized by spalling and pitting is a prevalent failure mode in gears as shown in Figure 2.6. Figure 2.6a revealed pitting which generally appears as small, shallow craters on the surface of the gear tooth, with depths of less than 0.01mm (Ding & Rieger, 2003) and diameters ranging from 0.01mm to 0.8 mm (Luo et al., 2019). On the other hand, spalling as depicted in Figure 2.6b is characterized by cavities with depths ranging from 20 to 100 μm and diameters significantly larger than those of tooth pitting (Ding & Rieger 2003; Luo et al., 2019). According to Wang et al., (2018), pitting and spalling are facilitated by manufacturing

defects and fatigue-induced flaws that is initiated on and below the surface leading to final failure (Wang et al., 2018). While this assertion is correct, other researchers have also attributed the occurrence of pitting and spalling to repetitive cyclic loading. Pitting and spalling initiate when cyclic contact stresses exceed the subsurface fatigue limit, leading to crack formation below the surface along stress-affected microstructural boundaries (Ding & Rieger 2003; Wang et al., 2018; Luo et al., 2019). These cracks propagate toward the surface, causing small pits or larger spalled areas. In the drive tumbler analysis, scanning electron microscopy (SEM) was used to detect subsurface cracks, crack branching, and fractured interfaces features consistent with sliding contact fatigue in abrasive environments (Sun et al., 2019).

The mechanical damaged of a spiral bevel gear was reported by Vukelic et al., (2020) as shown in Figure 2.7a.

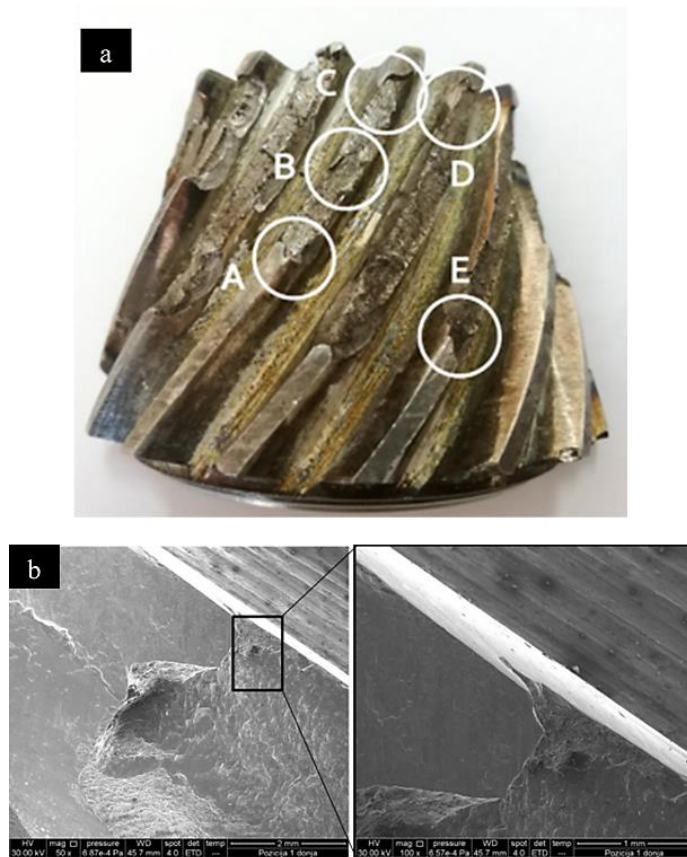


Figure 2.7: Damage crane gear with (a) spalled areas encircled with broken lines (b) SEM micrograph of point B in (a) (Vukelic et al., 2020)

It is evident from the scanning electron microscopy analysis as shown in Figure 2.7b, that the gear made of 28NiCrMoV8-5 materials contained inclusions, which are impurities trapped within the

steel during the manufacturing process. According to the report of Vukelic et al., (2020), these inclusions, located near the case/core transition zone of each tooth-damaged area as labeled in Figure 2.7a, acted as weak points where stress is concentrated. Under repeated loading and misaligned shaft of the gear, these inclusions became initiation sites for cracks and worsened the damage as the contact pressure between the gear teeth increased due to misalignment (Vukelic et al., 2020).

As a result, cracks begin to propagate from the subsurface towards the surface, resulting to surface flaking (spalling) and eventually fracture of the gear teeth as seen in points A-E in Figure 2.7a (Vukelic et al., 2020). Literature has however proven that spalling is not considered an initial mode of failure (Davis, 2005). The transition of wear into surface fatigue was investigated by (Liu et al., 2020), they investigated the interaction between micro pitting and pitting under cyclic loading, it was reported that localized stress concentration due to poor lubrication at the gear tooth contact area caused the surface contact fatigue mode of failure. However, as wear progresses on the surface of the gear tooth, the most likely failure mode shifts from surface-initiated such as micro pitting as shown in Figure 2.8a to subsurface initiated (pitting) and cracking as shown in Figure 2.8b.

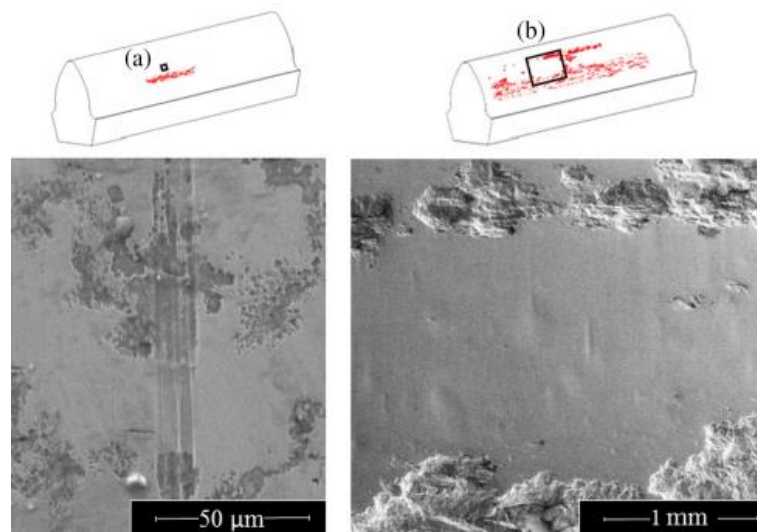


Figure 2.8: Debris dent, (a) micropitting and (b) macropitting on a sun gear surface meshing (Terrin et al., 2017)

Micropitting and macropitting damage of a sun gear was reported by Terrin et al., (2017). As it can be seen in Figure 2.8 the pitting morphology characterized by micro-pitting and macro-pitting

may be caused by the initial abrasive wear generated on the gear surface during operation, defects such as debris and dents which occur in areas with significant geometric deviation, leading to a localized high stress and pressure. Also, the pitting was found to be more severe at the dedendum of the gear tooth. It was reported that this area is mostly affected by the pitting damage because of high sliding speeds and unfavorable slide-to-roll ratios (SRR). Further, as depicted in Figure 2.9a, the sliding and frictional force between the drive and the driven gear under poor lubrication led to the formation of the white etch layer as shown in Figure 2.9b

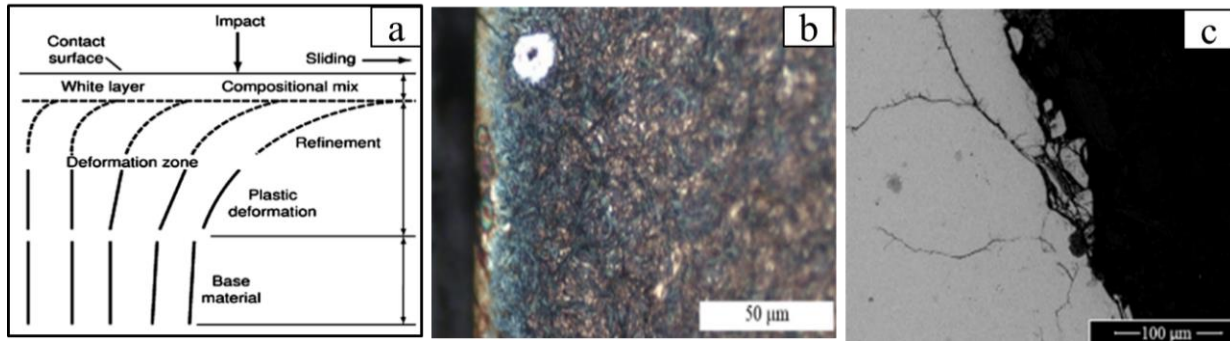


Figure 2.9 (a) The behavior of materials under sliding contact fatigue failure (Gourab Saha, 2017) (b) white etching layer of gear and (c) crack propagating into the interior of the gear material meshing (Terrin et al., 2017).

This white layer area is a region where the microstructure of the materials is altered, due to frictional heat generated on the surface of the gear when not properly lubricated, and subjected to severe plastic deformation during contact fatigue (Rice, 1978; Österle et al., 2001; Gourab Saha, 2017). Again, the combination of friction, and impact between the contacting surface as illustrated in the Figure 2.9a can contribute to this failure, causing severe deformation beneath the surface of the gear, and martensitic transformation (Gourab Saha, 2017; Österle et al., 2001; Rice, 1978). It can then be concluded that the deformation of mechanical components before failure is influenced by the surface contact pressure of abrasive particles which also introduce microcracks on the surface of the component (Myszka et al., 2023). Cracks in gears can be initiated by a combination of tension-compression fatigue which are mostly initiated on or near the surface of gears and then with time propagate and branch into the interior of the component under repeated loading as shown in Figure 2.9c (Li et al., 2019).

According to (Yan et al., 2022), the wearing of the tooth surface under the combined effect of tooth roughness, heavy load condition, frictional, and rolling contact between gears impacts the rate of crack growth and level of deformation, which has the possibility of reducing the lifespan and can alter the way failures occur. In addition to the literature review, mechanical failure of other types of gears in mining equipment has been reported. For instance, in the failure analysis carried out on a spiral bevel gear by Hein et al., (2017), the results obtained suggest that subsurface inclusions detected below the gear surface, acted as points of crack initiation that led to fracture. Further, a fracture in the girth gear of a bucket wheel excavator used in an open pit mine was also attributed to an initial crack from the gear's manufacturing process (Arsić et al., 2019).

2.2.2.2 Heavy Duty Sprocket

Sprockets play a crucial role in the power transmission systems of mining machinery. However, they also encounter challenges similar to those faced by gears. Heavy-duty sprockets in mining operations can experience various failure modes and mechanisms, largely due to their operating conditions. The main failure modes for sprockets include fracture, wear, deformation, and cracks which have been reported to often arise from operational stresses (Sun et al., 2019; Sobota, 2013). Sprockets make direct contact with chains or belts as shown in Figure 2.10, leading to friction that causes wear. Excessive wear is the primary form of sprocket failure and a major contributor to downtime in crawler bulldozer used in mining industry (Sobota, 2013). Poor alignment of the sprocket with the shafts can aggravate this issue by generating heat and bending the shafts, which accelerates premature failure of sprocket. Additionally, high compressive and tensile stresses on the sprocket-tooth surface can result in plastic flow failure and further excessive wear (Jose et al., 2022).



Figure 2.10: Sprocket wheel in contact with crawler Bulldozer chain (Sun et al., 2019; Sobota, 2013)

Sun et al., (2019) reported the abrasive wear characteristics of a sprocket wheel of an excavator under simulation conditions. The identified failure mechanisms and characteristics under different conditions of the mining environment are presented in Figure 2.11. As shown in Figure 2.11 (a & b), the main failure mechanisms of the sprocket wheel under simulated working conditions are surface fatigue, spalling, scratching, chiseling, and plastic deformation. It was reported that abrasive wear which is accomplished by both adhesion and surface fatigue is the dominant wear mechanism. The authors established that the wear rate is influenced by the content of the hard and abrasive particles in the mine (soil, coal, and sand). The subsurface of the sprocket wheel materials is also affected due to the contact and sliding friction between the abrasive particles and the surface of the sprocket material as shown in Figure 2.11(c & d). This correlates with the behavior of materials under sliding contact fatigue discussed in the section of gear failure in this study (Figure 2.9). Over time, due to repeated rotation and contact with the chain or belt this failure can progress and cause a more catastrophic failure of the sprocket like breakage and fracture.

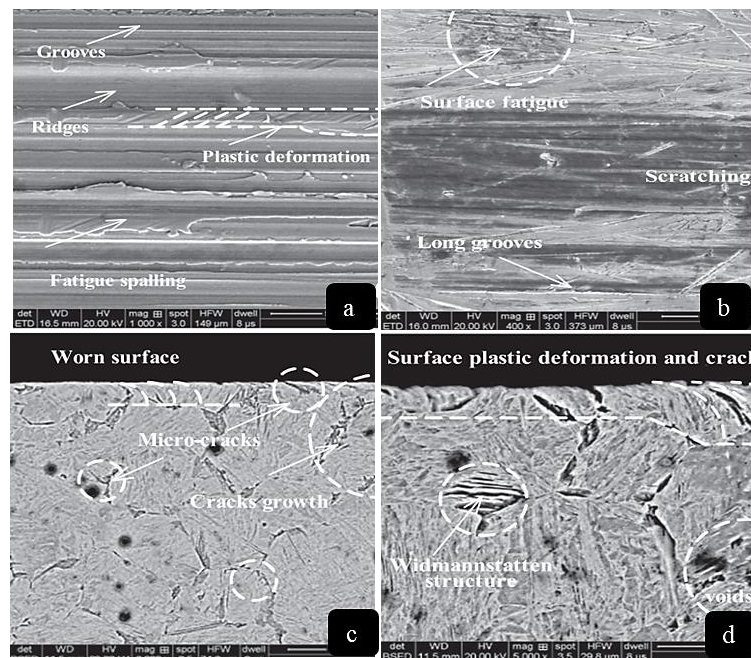


Figure 2.11: Wear morphology of sprocket teeth under simulation condition of mining environment showing (a), (b) abrasive and adhesive wear mechanism (c), (d) subsurface damage in a and b (Sun et al., 2019)

Sprocket tooth fracture is the breaking or cracking of the teeth into two separate parts due to the mechanical stress that exceed the material's yield strength. These fractures can occur suddenly or develop in three stages as depicted in Figure 2.12. Over time, due to repeated cyclic loading, the first stage is characterized with crack initiation at the point of high stress concentration on the surface of the teeth. Once the crack is initiated, it propagates through the material with each loading cycle. At the point of each cycle, the cracks grow little by little. The growth rates depend on several factors like, the magnitude of loading, material properties, and environmental factors. When the remaining cross sectional area of the materials are insufficient to withstand the applied load, the final stage occurs which is the sudden breakage (Doquet et al., 2019).

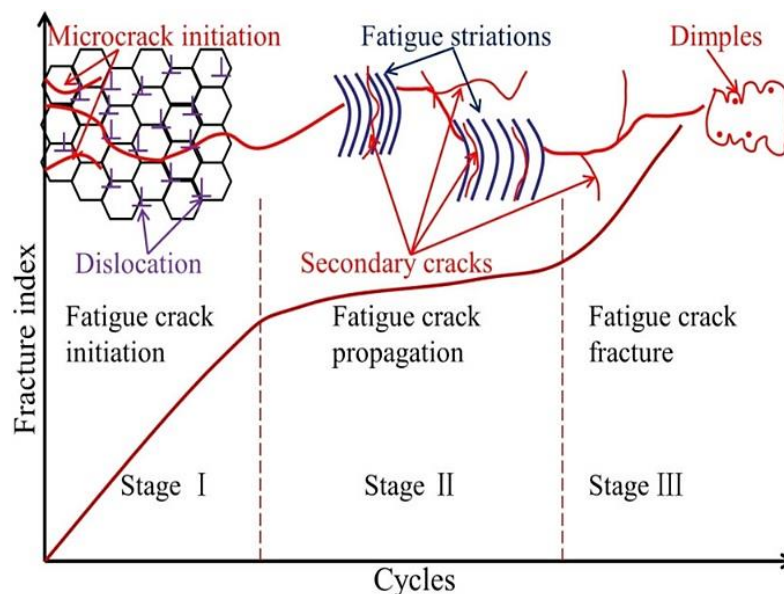


Figure 2.12: Stages of fatigue fracture failure (Graspengineering, 2021)

This type of fracture is called fatigue fracture failure. The most notable failure characteristics that can be identified while examining fatigue fracture through macro-fractography or visual inspection are:

- i. Beach Marks: these are semi-circular or elliptical-shaped markings that indicate a change in the location of fatigue cracks due to load interruption and development of compressive stress at the crack tip when the component are still operating (Garcia et al., 2016).
- ii. Ratchet Marks: These are shear ridges like lines which indicate the presence high stress concentration conditions and multiple fracture starting locations (Crack initiation sites) (Pantazopoulos, Zormalia & Vazdirvanidis., 2010).

They are created, when the cracks initiated at different locations are combined together, creating layers on fracture surface (Pantazopoulos, Zormalia & Vazdirvanidis., 2010). The final fracture zone patterns of fatigue fracture correspond to either ductile or brittle failure.

Ductile fracture encompasses failure by cavitation or plastic instability. In this mechanism of failure, significant plastic deformation occurs and this can be seen macroscopically as shape-geometry or cross-section warping (necking) (François, Pineau, & Zaoui, 2012). Under the microscope, voids appear around the center of the neck, where triaxial stress is prevalent around inclusion interfaces and hydrostatic stress is maximum. In the development of fracture, void nucleation, growth, and joining which is also known as coalescence, occurs. The density of the inclusions contributes to the rate at which microvoids nucleate, resulting to a number of nucleation sites (Figure 2.13) (Pineau, Benzerga, & Pardoen, 2016). Microvoids are small voids or cavities within a material that often form during plastic deformation or fracture, and they play a role in ductile failure mechanisms (Pineau, Benzerga, & Pardoen, 2016)

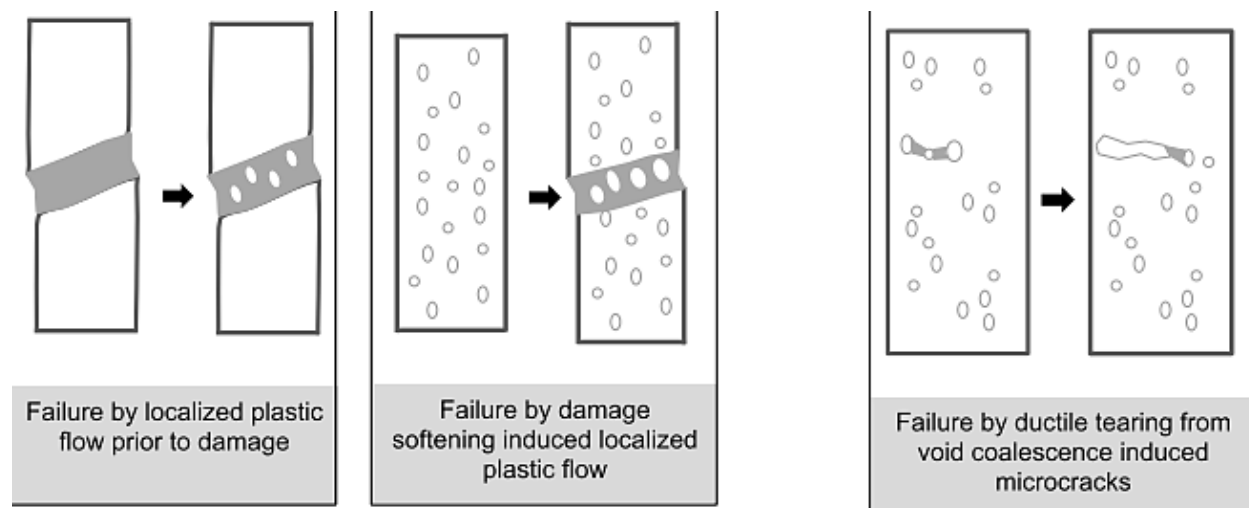


Figure 2.13: Description of the mode of ductile failure (Pineau et al., 2016)

This results in a high void distribution density and smaller dimples, which signify reduction in the entire plasticity (Viswanathan, Yadav, & Sagapuram, 2020). The relative position of the dimples correspond the type of loads applied on the component (shear, tear, or axial). Shear dimples are a sign of high stress tria-axial condition, which prevent large number of voids. Slip band formation is limited to inclusions in shear ductile fracture, which lead to a localized strain expansion and the initiation of voids (Wulpi, 2013; Abbasi, Esmailian & Ahangarani, 2018).

On the other hand, brittle fracture is a type of failure in materials that happens by rapid crack propagation with little or no plastic deformation. Once crack is initiated, the crack spread quickly in the materials. This kind of fracture can occur quickly and catastrophically, mostly without warning. Unlike ductile fracture, brittle fracture absorbs minimal energy, resulting in flat, clean fracture surface with features like cleavage planes and river patterns (Berto & Lazzarin, 2014). For example, Xu et al., (2020) investigated the fracture failure of the teeth of sprocket wheel in mineral conveying equipment. The findings from the study suggested that failure of the sprocket was a brittle fracture caused by the quick propagation of cracks from the region where defects are in the interior of the materials to the outside (Figure 2.15 a & b). This is because of a combination of bending stress and residual stress that existed within the material during the short-term operation.

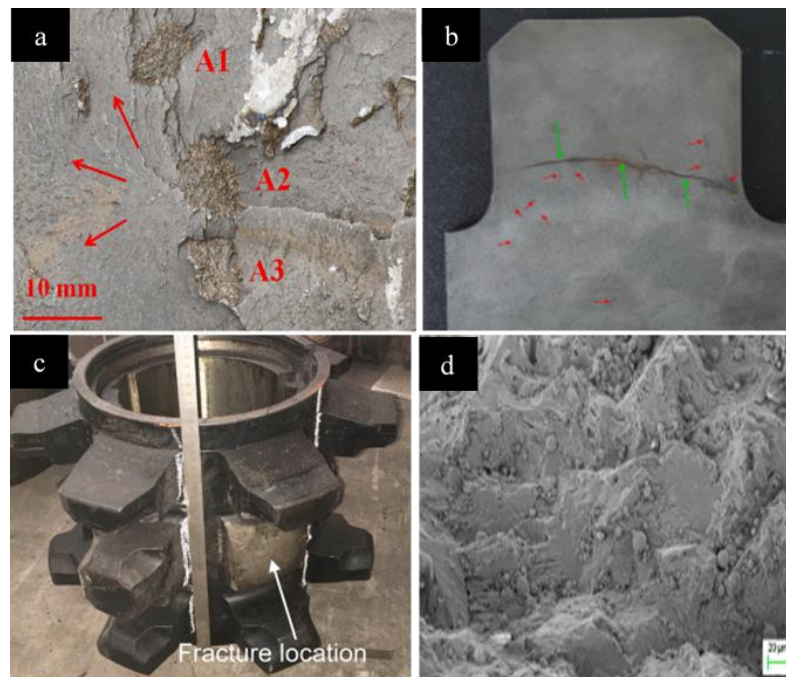


Figure 2.14: (a) Defects in the initial region of failure (b) Crack propagating from defective regions (c) Sprocket wheel with fractured tooth (d) SEM micrograph of fractured surface revealing quasi-cleavage (Xu et al., 2020)

According to the report of Xu et al., (2020), the primary cause of the fracture of the sprocket of the presence of hydrogen flakes in the internal part located in the regions A1, A2, and A3 of the sprocket as shown in Figure 2.14a, which serves as a high-stress concentration area and crack initiation sites. This cracks under the combined action of residual stress in the materials from

quenching and bending stress, rapidly propagate from the defective areas to the exterior part of the sprocket as depicted Figure 2.14(b & c). Additionally, the SEM analysis as shown in Figure 2.14d revealed a quasi-cleavage feature which confirms that the failure of the sprocket is hydrogen-induced. The formation of hydrogen flakes in materials can be attributed to the high hydrogen content in the conventional smelting and pouring methods of forging (Xu et al., (2020). However, while the presence of hydrogen flakes is a challenge, additional factors which may have contributed to the failure like environmental conditions during operation was not studied.

While drive tumblers and gears/sprockets share fundamental tribological mechanisms such as sliding contact, cyclic loading, and surface fatigue phenomena, directly applying gear failure modes to tumblers has clear metallurgical limitations. For example, gears and sprockets are typically forged or precision-machined and carburized, resulting in uniform case depth, and controlled microstructure (Davis 2005; Terrin et al., 2017). In contrast, drive tumblers are often cast and induction-hardened, producing more variable case depths, higher inclusion content, and residual stresses that influence crack initiation and propagation differently (Zhang & Thomas, 2002; Jung et al., 2008; Ronald-mario-kupa-anticona, 2014; Maciejewski, 2015; Zheng et al., 2015; Gorkusha et al., 2020; Harnesswala & Jha, 2020).

Moreover, the operating environment differs significantly. Gears usually operate in lubricated, and dust free conditions, whereas tumblers engage with crawler belts' links in abrasive, and debris prone mining environments. This increases three-body abrasion, impact-sliding loading, and localized stress concentrations, which are not typically captured in gear failure models. Therefore, while the failure modes of gears and sprockets provide a useful conceptual framework, they cannot be directly applied to drive tumblers without accounting for these differences in material processing, microstructural features, and service conditions. This limitation underscores the need for dedicated experimental and metallurgical investigation of drive tumbler failures.

It is established from the literature that there is no peer-reviewed literature on the experimental failure analysis of drive tumblers of the electric mining shovel loader or similar equipment in the diamond mining sites, that report their failure modes and mechanisms and causative factors. Also, the current approaches adopted in the failure analysis of damaged gears and sprockets in mining equipment do not consider the other necessary factors like the properties of geological formation

in mining environment and interacting materials of sprockets. Furthermore, failure analysis of similar components did not consider material properties of an undamaged or new one, to identify any microstructural and metallurgical changes that could be responsible for failures.

From the above studies, it has been established that the different failure modes and mechanisms in gears and sprockets is as a result of combined stresses during operations, lack of proper maintenance practices, flaws in the manufacturing process, and unsuitable materials for specific operating conditions. It is expected that these attributes may also have some influence on the failure of the drive tumbler under discussion. The drive tumbler has some similarities with gear and sprocket in their mode of operations. Nonetheless, this section has demonstrated the significance of manufacturing quality and appropriate material selection in averting premature failure. Therefore, section 2.3 will go over the potential materials that could be adopted in the enhancement of the drive tumbler teeth surface to withstand high contact stress and heavy load applications.

2.3 Materials Selection

In the design and manufacturing of machinery, another important factor that leads to component failure in the mining industry is the type of material selected. According to Zhai et al., (2021), wear in mining equipment components such as heavy-duty gears, and sprocket, is inevitable as a result of the harsh environment, and heavy loads applications, and the uniqueness in the modes of operations. The cost of material degradation due to wear represents a significant portion of the total operational expenses of a conventional mine (Cortie McEwan, JJ & Enright, DP, 1996). Nonetheless, this can be reduced or mitigated through the introduction of advanced wear-resistant materials. The wear resistance ability of a material includes factors such as the microstructure of the materials, impact energy, tribological properties, and its ability to withstand harsh environments like contaminated moisture and high temperature (Holmberg et al., 2017). The selection of appropriate wear-resistant material and its deposition techniques is crucial for the successful remanufacturing of damaged mining equipment such as drive tumbler. Hence, to address and prevent a particular type of failure mode and mechanisms being encountered in the mechanical transmission components in mining equipment such as the drive tumbler of a mining shovel loader from reoccurring, while ensuring cost savings and increase in their service life, the process of selecting suitable wear-resistant material towards remanufacturing damaged drive

tumbler must be carefully implemented (Ratia et al., 2014). One major factor that contributes to the effective cost saving in material selection for damaged equipment is understanding the mechanism by which existing material of the damaged component failed (Cortie McEwan, JJ & Enright, DP, 1996). This is done by conducting a detailed failure analysis to give adequate information on the underlying causes of the damage experienced by the component which is the main focus of this research. This however helps in the proper selection of appropriate materials before replacing existing materials of the damaged component.

In this section, a proper materials selection process like the one developed by (Foroulis, 1984) and (Phelps, 2002) will be applied, to identify suitable candidate wear-resistant materials for the remanufacturing of damaged drive tumblers to at least new in performance. This process includes the following criteria:

-  The operating conditions of the drive tumbler and mechanical properties of the mine's geological formation and that of the crawler belt.
-  The analysis of the candidate wear-resistance materials that can withstand the harsh operating conditions of the mine and the mechanical properties of the mating materials (crawler belt).
-  Metallurgical compatibility of the selected substrate materials of the drive tumbler considering Rume-Ruthery rules.
-  The material's availability and cost. These two are interrelated criteria often considered together when selecting wear-resistance materials.

On the account of the above criteria, the different candidate wear-resistant materials will be compared to identify the suitable wear-resistant materials for the drive tumbler, ensuring enhanced mechanical performance and longevity, and increasing the sustainability and profitability of diamond mining.

2.3.1 Selection of candidate wear-resistant materials toward the remanufacturing of drive tumbler.

Generally, low carbon and medium carbon low-alloy steel such as AISI 4140, 4340, 1039, 42CrMo, 32CrMo, 35CrMoA and AISI 1039, are common materials used by original equipment manufacturers (OEM) in the manufacturing of mechanical power transmission components such as gears, heavy-duty sprockets, and drive tumblers, which can either be manufactured through

rolling, forging or casting processes (Accorsi Gans et al., 2015; Wavelet, 2017; Liu et al., 2017; Xu et al., 2020; Sarvestani et al., 2020; Wang et al., 2021; Li et al., 2021; Guo et al., 2022). These materials are well known for their excellent combination of strength, toughness, and hardenability and are used where high strength, resistance to wear, and fatigue are essential such as gears, heavy-duty sprockets, shafts, and crankshafts. Their mechanical properties and hardness vary depending on the heat treatment and tempering applied (Rao, 2021). Nonetheless, they are prone to excessive wear and fatigue failure under high stress and harsh operating environments when exposed to high cyclic loads because of their low fracture toughness and low wear resistance (Terrin et al., 2017; Vukelic et al., 2020; Xu et al., 2020).

In mining machinery, it is important to look critically into the working environment where these machineries are utilized. The presence of hard and abrasive like quartz, plagioclase, olivine, and limenite in the geological formation of the mine with hardness values ranging between 400-1200 HV (Singh et al., 2014; Röttger et al., 2015) exert a high level of abrasion on mining equipment component which is accelerated by the continuous rotation, impact and sliding contact between the mechanical power transmission component particularly sprockets, and their mating components, inducing surface contact fatigue on the surface of these components (Chang et al., 2006; Hisan et al., 2019; Nkgakile, 2023). It is however worthy of note that to fight and mitigate frequent premature failure, wear-resistant materials with better mechanical properties such as high strength, toughness, and good corrosion resistance must be considered for the remanufacturing of drive tumblers.

In recent times, some different coating materials with excellent mechanical properties have been designed by different researchers (Li et al., 2021; Luo et al., 2022; Zhang et al., 2024), to serve as a protective layer to reduce friction and prevent different wearing mechanism of engineering equipment parts used in harsh environments such as mining environment with heavy loads applications, cyclic stress, and high temperature (Luo et al., 2022). For instance, Li et al., (2021), identified iron-based alloy to be an excellent wear-resistance material with improved nanohardness and elastic modulus when deposited on low-carbon steel through ultrasonic impact. In a report by Zhang et al., (2024), cobalt-based alloy, iron-based alloy, and reinforced composite coatings are commonly used as remanufacturing materials that possess wear and corrosion resistance characteristics with improved mechanical properties suitable for the operations of mechanical

power transmission components like the drive tumbler, with the ability to withstand the abrasive nature of the mining terrain. Hence, the discussion in this section is limited to cobalt-based alloy, iron-based alloys, and metallic metal composites. These materials will be discussed, focusing on their cost, mechanical and tribological properties, and how these properties affect their performance characteristics, after which suitable materials for the remanufacturing of the drive tumbler will be identified and selected.

2.3.1.1 Cobalt-based Alloys

Cobalt-based super-alloys are materials that have several applications in harsh environments because of their excellent mechanical properties, high hardness, good corrosion resistance, and superior wear characteristics, especially sliding and rolling under elevated contact pressure (Yawei et al., 2021). Their heterogeneous microstructure of the cobalt matrix and refractory carbide particles have contributed to its wide use in materials machining and mining machinery (Bagci & Aykut, 2006; Birol, 2011; Chandrashekar & Sreenivasa Prasad, 2018). Also, they have high hardness raging between 500 HV to 600 HV, contributing to their wear resistance ability (Motallebzadeh et al., 2019). The properties of these alloys are largely attributed to the crystallographic characteristics of cobalt, particularly its behavior under stress, the solid-solution strengthening effects of elements like chromium, tungsten, and molybdenum, the formation of metal carbides, and the corrosion resistance provided by chromium (Total-material, 2002). An example of a cobalt-based alloy is stellite 6.

Subramaniam Nellian & Hock Lye Pang, (2022) confirmed the applicability of stellite 6 in repairing damaged component by investigating the wear resistance, hardness, shear stress in rail application using laser metal deposition technique. The result demonstrated a strong bonding between the rail steel substrates (R350HT and R260) and the stellite 6 layer, with a variation in level of hardness, between the stellite 6 clad and HAZ region. The HAZ region showed highest hardness value of 763 HB compared to the stellite 6 clad surface of 420 HB. However, the stellite 6 experience a 34% and 52% decrease in wear volume, compared to the substrate materials R350HT and R260 respectively as shown in Table 2.2, which indicates a better wear resistant feature of the stellite 6B coating. However, a combination of heat input, dilution, microstructural changes, alloy composition, process parameters and substrate materials could be responsible for

the observed hardness difference between the HAZ and stellite 6B clad surface (Subramaniam Nellian & Hock Lye Pang, 2022).

Table 2.2: Comparison of wear volume of rail substrate and stellite 6 (Subramaniam Nellian & Hock Lye Pang, 2022).

Steel Grade	Wear track width (μm)	Wear volume (mm ³) – ASTM G99
Stellite 6 (on R350HT)	342	10.95×10^{-3}
R350HT	393	15.93×10^{-3}
Stellite 6 (on R260)	355	11.7×10^{-3}
R260	455	24.7×10^{-3}

Durejko & Łazińska, (2021) reported the microstructure and mechanical properties evaluation of a Stellite 6 (Co-6) alloy deposited on X22CrMoV12-1 substrate by laser-engineered net shaping (LENS). Figure 2.15 presents the microstructure and phase distribution within the deposited stellite 6 clad. Figure 2.15a shows the SEM image revealing three microstructural regions; cobalt-rich dendrites, chromium enriched-interdendritic regions and areas containing tungsten-rich carbides, formed due to rapid cooling of the LENS process. The Electron Backscatter diffraction image depicted in Figure 2.15 (b & c) provide a detailed map of the grain boundaries and phase distribution within the stellite 6 coating, this distribution map highlights the presence of cobalt austenite (red) and chromium-cobalt with tungsten carbides (green).

The confirmation of the multi-phase structure of the stellite 6 coating is presented in Figure 2.15d, revealing the peaks corresponding to the phases identified. The sharpness and intensity of the peaks suggest that the stellite 6 coating has low internal stress, which is beneficial to the mechanical performance and durability of the deposited layer. Their results are consistent with the typical hypoeutectic microstructure of cobalt alloy, where cobalt dendrites are interspersed with hard particles that contribute to the high wear resistance of the coating.

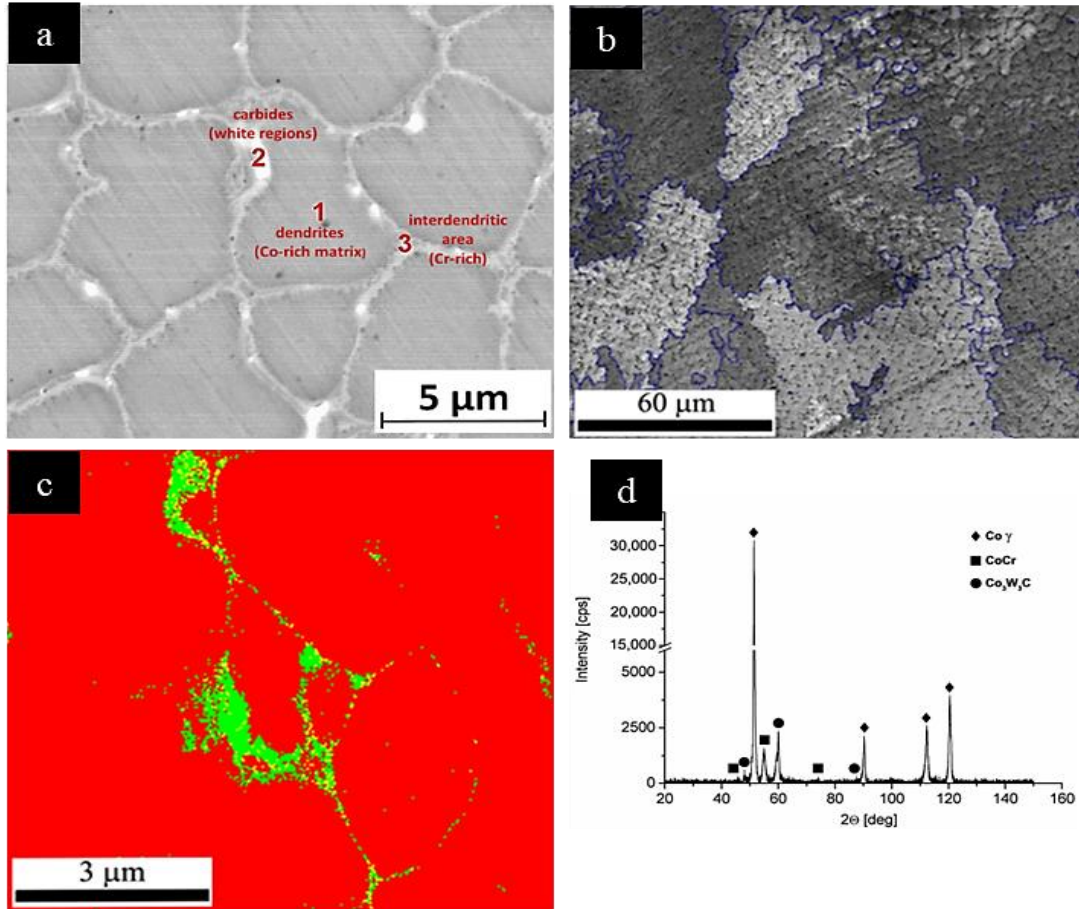


Figure 2.15 (a) SEM image micrograph of Stellite 6 deposited through LENS, (b),(c) EBSD maps of phase distribution in deposited layer (d) XRD patterns confirming the identified phases in (a) (Durejko & Łazińska, 2021)

Furthermore, the result revealed the highest microhardness value of 550 HV near the substrate and gradually decreased towards the surface with microhardness value of 450 HV. This gradient in hardness can be attributed to the presence of hard carbides near the substrate which provide strength, and softer cobalt-rich matrix closer to the surface. Nonetheless, while the presence of these hard carbides offers significant wear resistance, the softer upper layers are less resistant to abrasion. The drive tumbler operates in a highly abrasive environment, where it is in constant contact with the crawler belt and chains made of high strength low alloy steel, and abrasive particles like quartz with a hardness value of 1200 HV (Xiao et al., 2009; Bosnjak et al., 2013; Nkgakile, 2023). The softer surface layer of the coating could lead to more rapid surface wear compared to the harder inner layers. Over time, this might result in surface degradation, reducing

the component's overall lifespan. In addition, the cobalt content in this alloy makes it a relatively expensive material (Chandrashekar & Sreenivasa Prasad, 2018). While stellite 6 provide good wear resistance, the mismatch in hardness and the high cost makes it less considered for the remanufacturing of the drive tumbler teeth.

2.3.1.2 Fe-Based Alloys

These are materials that are mainly made of iron with different amounts of other elements added to enhance specific properties. Because of their mechanical properties, economic viability and versatility, these alloys are essential to many industrial applications particularly, in a demanding and harsh environment like the mining industry where equipment are prone to excessive wear. Due to the versatility of Fe-based alloy, several studies have investigated its functionality via different applications and remanufacturing strategies (Manna et al., 2006; Zhang et al., 2007; Milanti et al., 2014; Braga et al., 2021; Li et al., 2024). Manna et al., (2006) developed a coated surface on an AISI 1010 steel substrate with varying composition of Fe-B-Si, Fe-B-C and Fe-B-C-Si-Al-C. Based on their findings, the various coatings were found to improve wear resistance of the substrate materials. Zhang et al., (2007) studied the characteristics of Fe-based coating. The study focuses on a plasma process to produce the Fe-based alloy coating on a low carbon steel. The coating's microstructure is austenite and hypoeutectic, with main phase consisting of interdendritic carbides and borides which contributes to its strong wear resistance and hardness of 780 HV. The microstructural characteristics, sliding, abrasive and cavitation behavior of thermally-sprayed Fe-based coating was investigated by Milanti et al., (2014). The study reference conventional Ni-based (Ni-Cr-Fe-Si-B-C) coatings. It was elucidated that the Fe-based coatings have a dense microstructure with less than 1% porosity and retain some of the powder structural attributes. The report by Milanti and co-investigators revealed that the coatings have high nano-hardness, comparable to the Ni-Cr-Fe-Si-B-C alloys. Furthermore, their result revealed that the sliding wear rate of HVOF-sprayed Fe-based metal alloy coatings has a lower sliding wear rate than the conventional Ni-based coatings due to the lower coefficient of friction and Mo-containing oxide scale formation in the coatings, which reduces adhesion and as well reduces friction. However, thermally sprayed Fe-based coatings possess lower bonding strength which is 54% lower than the conventional Ni-based coating.

Other notable Fe-based alloys are Rockit, 316L and H13 steel. 316L powder is a Fe-based alloy with a high corrosion resistance, toughness and good ductility which makes it a good choice in many industries including construction, energy, and automotive (Kim et al., 2004; Baddoo, 2008). The chemical composition is presented in Table 2.3

Table 2.3: Chemical composition of 316L

Elements		C	Mn	P	Si	S	Cr	Ni	Mo	Fe
316L	Min	-	-	-	-	-	16.0	10	2.0	Bal
	Max	0.030	2.0	2.0	0.75	0.030	18.0	14	3.0	

The 316L stainless steel, an austenitic alloy characterised by 16% - 18% chromium provides corrosion resistance due to the formation of chromium oxides layer on the surface of the material in corrosive environment. Coupled with the presence of hard kimberlite mineral in the diamond open-pit mine, the diamond mine is characterised by highly corrosive moisture due to the presence of sulphur and chlorine ion which are in abundance in the tailing dams (Willison & Boyer, 2012; Peng et al., 2013). The contaminated moisture usually exacerbate corrosion pitting on the worn surface caused by 2-body abrasion wear which contributes to stress corrosion cracking and inter-granular fracture of components. The formation of these oxides in 316L, which are compact and non-soluble can however provide a good adhesion with the materials surface, ensuring a corrosion resistance in many corrosive operating environments. In addition to its corrosion resistance, the microstructure consists of a homogeneous austenitic phase which enhances toughness and ductility. The austenitic matrix of 316L stainless steel exhibits a face-centered cubic (FCC) structure, formed through the incorporation of austenitizing elements such as Ni and Mn making it suitable for absorbing high impact energy. Nevertheless, the low carbon content of 316L has resist its application in abrasion-prone terrain due to its low microhardness between 150 HV – 200 HV and consequently low wear resistance. Meanwhile during laser processing e.g. laser cladding and laser alloying, the microstructure of 316L usually consist of columnar dendrites, equiaxed dendrites, austenite dendrites and interdendritic network carbides , improving its microhardnes between 300 HV – 600 HV and impacting it wear resistance properties, especially when reinforced with cemented carbides (Song et al., 2016; Ding et al., 2023; Fan et al., 2023). Song et al., 2016,

investigated the repair of 304 stainless steel substrate with 316L via laser cladding followed by laser surface alloying with WC. The microstructure evolved from columnar dendrites in the clad zone to austenite dendrites and interdendritic networked carbides in the laser alloyed layer. This microstructural evolution caused an increase in the hardness of 316L coating up to 550 HV, which is 2.55 and 3 times higher than the substrate and pure 316L respectively. Consequently, the improved hardness reduced wear loss from 11.9 mg to 0.7 mg which can be attributed to the presence of un-melted WC particles contributing to grain refinement strengthening and second phase strengthening (Song et al., 2016). Similar findings were reported by Ding et al., 2023, who investigated the deposition and optimization of 316L wear behaviour on U71Mn rail steel materials. However, the study lacks a detailed hardness analysis from clad surface to the HAZ and substrate. It was reported that at the laser power of 1500 W and scanning speed of 10 mm/s, the clad layer exhibited significant low hardness of 250 HV and heat affected zone with 900 HV. This can however impact its wear resistance and makes the coating more susceptible to sliding contact fatigue and abrasive wear. The study shows the potential of 316L for wear resistance application when laser power and scanning speed are altered, producing an average microhardness of 600 HV between 2000 – 2500 W laser power and 15 – 20 mm/s scanning speed. Overall, 316L proves to be a good coating for wear-corrosive application. Since the drive tumbler teeth requires surface hardness between 800 HV to 1000 HV to operate optimally without premature failure, 316L might require hybrid reinforcement such as TiC, WC, and WC-12-Co for application in an extreme wear-corrosive environment.

H13 is a tool steel used in application that requires high wear, high strength and high temperature environments like tooling and forming industries (Podgornik et al., 2020). H13 tool steel is attractive for its hardness which can range between 720 HV to 800 HV. It is also well known for its good wear resistance under high thermal and impact loading (Leskovšek et al., 2006; Podgornik et al., 2020; McClements, 2022). H13 sometimes can be regarded as a semi-stainless steel because of its high chromium content. This classification is largely because of its ability to resist corrosion at high temperature, due to the presence of dissolved carbides. However, at lower temperature, the precipitation of chromium and carbon as carbides significantly reduces its corrosion resistance (Paulo, 2018; Podgornik et al., 2020). Despite this limitation, its exceptional dimensional stability and the balance of properties it offers make it well-suited for application involving high-impact and wear-intensive conditions.

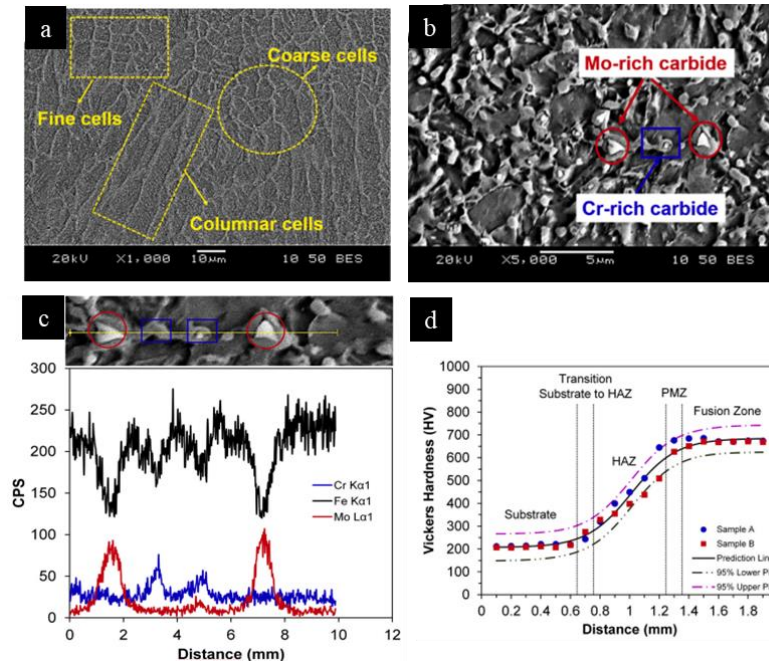


Figure 2.16: Microstructure, phase mapping and the hardness profile of H13 clad (Braga et al., 2021)

Braga et al., (2021) reported the microstructural and mechanical properties of H13 powder deposited on a hot work tool steel substrate via laser cladding. Figure 2.16 presents the microstructure, phase mapping and the hardness profile of the H13 laser clad surface. Figure 2.17 (a) shows the SEM-BES (back electron scattering image, (b) SEM-BES micrograph of the Mo and Cr-rich carbides in the deposition region (c) line scan analysis of the Cr and Mo elements across the track in the PMZ, showing peaks corresponding to the presence of the carbides. As shown in Figure 2.16a, the cellular structure of the H13 powder consists of quasi-equiaxial grains that were solidified during the laser cladding process as well as coarse and columnar grains formed due to the directional heat flow and cooling effects. Additionally, the presence of martensite and Cr-rich and Mo-rich carbides in the deposition layer shown in Figure 2.16b, and with the elemental mapping in Figure 2.16c confirming their presence, contributes significantly to its high hardness value of about 700 HV as depicted in the hardness profile in Figure 2.16d. Further, the study also reported that these carbides formed MC, M₇C₃, M₂₃C₆, M₂C, and M₆C precipitates on the substrate between the precipitation temperature of 675°C and 700°C, which play a key role in enhancing the wear resistance of the materials of the substrate by 83.89%.

Notwithstanding, the abrasive nature of the mining environment with average hardness of 1200 HV (Singh et al., 2014; Röttger et al., 2015), in collaboration with high mechanical properties particularly hardness of heavy cast steel used in the manufacturing of crawler belts and links in heavy-duty equipment (Ronald, 2014), might still post some challenges in combating premature failure with a pure H13 steel powder due to the mismatch in their hardness value. According to Viana et al., (2020), excessive wear is less likely to occur when the hardness ratio of two contacting surfaces is less than 1, conversely, wear occurs when the hardness ratio is greater than 1.2. Hence, there would be need to reinforce the H13 powder with a reinforcement material to produce coating with good wear-resistant properties that can withstand the extreme condition of the diamond mine and resist corrosion at high temperature and the abrasive wear exerted by the crawler belt and links which work simultaneously with the drive tumbler teeth.

If the damaged drive tumbler teeth which is suspected to be made from low carbon low alloy steels (Li et al., 2021), like ASTM A514, 35CrMoA, ASIS 4140, and AISI 1039, are to be remanufactured with either H13 or 316L powder material, there would be well-defined interface with good metallurgical bonding since they have the same composition. One of the reasons associated with increasing demand for Fe-based alloys such as H13 is because of their low initial cost. The cost of Fe-based alloy materials such as H13 tool steel powder is largely influenced by its availability, which is determined by how commonly it is used.

To increase the reliability and performance of the Fe-based alloys, particularly the H13 tool steel in the application of the drive tumbler teeth, Further works are required to improve the quality and performance of Fe-based coatings. Hence the H13 steel powder is recommended to be reinforced with ceramic materials to produce metallic matrix composites (MMCs). This is because MMCs can adopt different alloy powders to withstand surface degradation like sliding and impact wear, surface contact fatigue and corrosion experienced in gears, heavy-duty sprockets, and possibly, the drive tumbler.

2.3.1.3 Metallic matrix composite (MMCs)

The use of alloy powders and different carbides in metal matrix composite (MMC) coatings has increased in popularity because of their improved wear resistance and greater hardness (Kotarska et al., 2021). Metal-based composite materials, or MMCs, have properties that go beyond those of their constituent parts. MMCs are typically made up of different hard phases and a metal matrix.

It is important to note that the performance of MMCs is influenced the type, volume fraction, size, and distribution of the reinforcement particles (Haghshenas, 2016). Generally, most of these reinforcement particles are ceramic materials (Naoum, 2023). Ceramic materials have higher hardness than the highest abrasive particle in the mining terrain, and can be used to optimize the hardness of Fe-based alloy to meet up the crawler belt hardness (Naoum, 2023). Their high hardness and good wear resistance properties provide improved performance in sliding contact, abrasive and corrosive environments (Naoum, 2023). As shown in Table 2.4, in this study, tungsten carbide (WC) and Tungsten carbide cobalt (WC-Co) are recognized as prominent ceramic materials for reinforcement due to their exceptional properties. Their high melting points, strong adhesion to Fe-based alloys and ease of dispersion with the Fe-matrix phase make them particularly advantageous in composite applications. These characteristics improve the mechanical integrity of the resulting materials, making WC and WC-Co suitable for several applications, including wear-resistant components (Emamian et al., 2010).

Table 2.4: Properties of WC and WC-Co

	Density g/cm ³	Thermal Conductivity W/m	Electrical resistivity Ohms-cm	Hardness HV	Tensile Strength MPa	Compres sive Strength MPa	Elastic Modulus GPa	Reference
WC	15	100	0.2	3000	-	3360	600	Jiang et al., (2003)
WC- Co	14.5	-	-	2000	-	3000 - 4000	500	Zhao et al (2022)

2.3.1.3.1 Tungsten carbide

(WC) has demonstrated significant potential among a wide range of existing wear-resistance materials because of its outstanding mechanical characteristics and high hardness (Micallef et al., 2019). Scientific investigation into the utilization of WC as a material for surface modification to extend the lifespan in operation and performance of components was spurred by industrial demand in the 1950s and 1960s (Kurlov & Gusev, 2013). Since then, several kinds of coating deposition procedures have been developed and employed in different technical applications to reinforce and

modify bulk material surfaces primarily to improve their resistance to wear and corrosion. According to Jiang et al., (2003)., WC is the pinnacle of hard, stiff, and wear-resistant technical ceramics, its wear rate can be less than $7 \times 10^{-7} \text{ mm}^3/\text{Nm}$, its hardness level can exceed 3000HV, its elastic modulus can exceed 600Gpa, and its compressive strength can reach 3360Mpa. The Young's modulus and hardness of WC are compared with those of other materials in Figure 2.17.

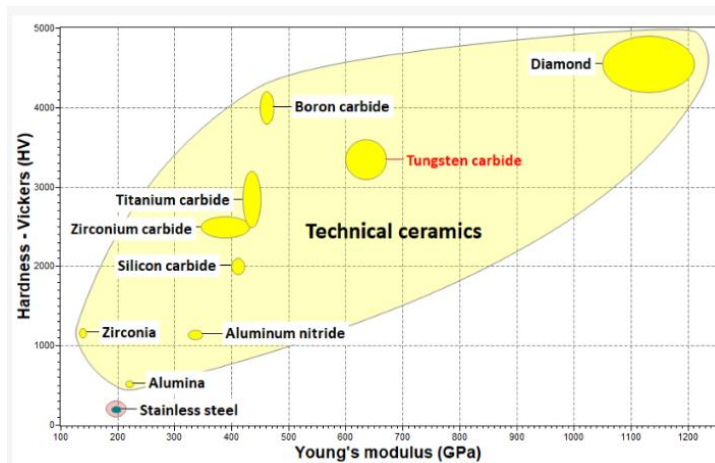


Figure 2.17: Ashby diagram of Hardness (HV) versus Young's Modulus (Gpa) for other hard coatings (Ashby, 2009)

WC coatings are widely applied to parts that are employed in harsh environments that require resistance to wear, erosion, and corrosion because of their high hardness, fracture toughness, and oxidation resistance (Micallef et al., 2020). However, due to its allergy to deposition techniques that require high surface finishing which results into cracks and other defects, WC has found its application mostly in laser cladding (Yao et al., 2022). For instance, Xiao et al., (2021) developed Fe-WC composite coatings with varying WC content (0-60 wt%) on 15CrNiMo steel using laser cladding. The coatings' properties, including phase composition, microstructure, microhardness, friction, and wear, were analyzed, focusing on WC particles' thermal damage and its effects. It was discovered that most WC particles retained their structure, although some melted, leading to dissolution and re-precipitation. The coatings featured equiaxed, cellular, and some short columnar crystals. Microhardness increased with WC content, ranging from $729.9 \text{ HV}_{0.2}$ to $1029.2 \text{ HV}_{0.2}$, compared to the Fe-based coating's $621.7 \text{ HV}_{0.2}$. Improved wear resistance was observed due to phases like $\text{Fe}_3\text{W}_3\text{C}$ and M_{23}C_6 . Clad with increased WC content shifted wear from adhesive to

abrasive, enhancing the coatings' overall performance. Bartels et al., (2023), investigated the utilization of tungsten carbide to create wear-resistant coatings through L-DED, the study reported that adding WC in their application significantly increases the hardness and enhances the wear resistance. In addition, WC led to a fine microstructure with high hardness and the combined addition of carbon and WC resulted in the highest hardness in the materials. However, the study is limited as a result of transition zone weakness between weld tracks, and instability in scratch test due to surface roughness of the specimen affecting adequate evaluation wear resistance. This was attributed could to uneven distribution of elements like tungsten and molybdenum with depletion in the transition zone, potentially resulting in weakness in the materials (Bartels et al., 2023). Additionally, Tungsten carbide (WC) faces challenges like brittleness because of its high hardness, high cost, machining difficulty, density, and limited thermal conductivity. To address these, WC is often combined with cobalt (Co) to create WC-Co (cemented carbide), which enhances toughness, machinability, and thermal management. The cobalt binder absorbs impact, resists cracking, and facilitates shaping, making WC-Co more versatile and cost-effective.

2.3.1.3.2 Tungsten carbide cobalt

WC-Co is widely used in cutting tools, mining equipment, wear-resistant parts, and automotive components due to its superior hardness and improved toughness (Tepperneegg et al., 2016). This combination effectively broadens the applications of tungsten carbide, overcoming the limitations of pure WC. WC-Co can be manufactured using conventional molding techniques such as powder metallurgy, extrusion molding, and injection molding. Components produced by injection molding exhibit minimal shrinkage but are prone to forming undesirable η phases (such as $\text{Co}_3\text{W}_3\text{C}$ and $\text{Co}_6\text{W}_6\text{C}$) (Baojun et al., 2002; Lin et al., 2015). While extrusion and powder metallurgy can achieve low porosity, they are limited in producing components with complex geometries (Wang et al., 2019). Furthermore, these traditional processes are inefficient and expensive (Su et al., 2014). Recent techniques like laser cladding, offer significant improvement over conventional methods for developing WC-Co components, addressing issues of geometrical complexity and efficiency. For Instance, Hu et al., (2020) examined the phase composition, microstructural evolution, microhardness, and wear performance of WC–12Co composite coatings created by laser cladding with a coaxial powder-feed mode. They elucidated that high scan speeds and laser energy densities caused partial melting of WC on the edges of WC–12Co composite powders in a

liquid Co and 304 stainless steel matrix. This led to the formation of new carbides, such as lamellar WC and herringbone M₃W₃C (M=Fe, Co). The WC–12Co composite coatings achieved high densification and robust metallurgical bonding with the substrate, avoiding issues like porosity, cracks, and decarburization. The coatings exhibited impressive properties, including high microhardness of 1600 HV, a low coefficient of friction of 0.55, and a low wear rate of $2.15 \pm 0.31 \times 10^{-7} \text{ mm}^3/(\text{N} \cdot \text{m})$, attributed to the excellent metallurgical bonding and fine microstructures at a laser power of 1500 W. Jiang et al., (2022) established the process-structure-properties of laser clad WC-Co composites. This came through by investigating the effects of laser power on the quality of the WC-Co coating on the Ti-6Al-4V substrate. The experimental results indicated strong metallurgical bonding between WC-Co composite coatings and the substrate. In fact, a microhardness of up to 1536 HV and a wear rate of 1.5 g/h were achieved. The main phases in the composite coatings are WC, W₂C, W, and η -Co, which indicate decarbonization and formation of new eutectic carbides.

These studies revealed the potential of WC-Co in enhancing component mechanical properties when produced with laser cladding. Hence, H13 and WC-12Co are selected as candidate wear resistance materials that can be used to remanufacture damaged drive tumbler teeth. While restoring the damaged drive tumbler and any engineering component to at least as new in performance, its improved mechanical properties, performance, and sustainability are influenced by the combination of suitable materials and a reliable material deposition technique. Therefore, the following section will explore suitable and sustainable remanufacturing techniques to identify the appropriate technique for the deposition of selected candidate wear-resistant materials on the drive tumbler substrate.

2.4 Remanufacturing Approach.

The world recently has taken energy sustainability as one of the core aspects of life in creating an environment suitable for mankind. For a sustainable society, it is important to look critically into the manufacturing sector and develop lasting solutions in the ways and modes of reducing waste (Van Nes, 2016). Hence researchers are working effortlessly to see how used and damaged products can be remanufactured. Remanufacturing has key characteristics in producing a green environment (accuracy research, 2024). It is a process of transforming used or worn-out products into as new in performance which can either have same or greater performance characteristics

(accuracy research, 2024). Andrew-Munot et al., (2015) examine the main motivation and benefits of remanufacturing such as environmental regulations, awareness of the importance of green environment, and economic advantages. In their report, remanufacturing has gained influence in different sectors especially, automotive, mining, and aerospace, having a large share in the US market, with an estimated size of two billion USD. According to Liu et al., (2018), the impact of remanufacturing and direct reuse of end-of-life vehicles and automobile parts on the resource productivity of automotive production in China, affects resource productivity of automotive production positively. In a report by Diener et al., 2019, an estimate of \$1.8 trillion as the potential economic benefits of remanufacturing in Europe by 2030 was recorded which aims to achieve zero waste through complete reuse, recycling or restoration of damaged products particularly in heavy industry settings (Diener et al., 2019). One of the benefits of remanufacturing is its contribution to the global circular economy consequently reducing waste and pollution by restoring used or damaged products to at least as-new in performance (Duberg et al., 2020). It is important to note, that when shifting towards remanufacturing, factors such as core acquisition, labor skills, facilities, and process technology are essential factors to be considered by the OEMs and end-users (Duberg et al., 2020). Figure 2.18 illustrates the remanufacturing process which involves a series of steps, including disassembly, cleaning, inspection, repair or replacement of components, reassembly, and quality testing, to restore used and damaged products to like-new condition before reintroducing them to the market (Singhal et al., 2020).

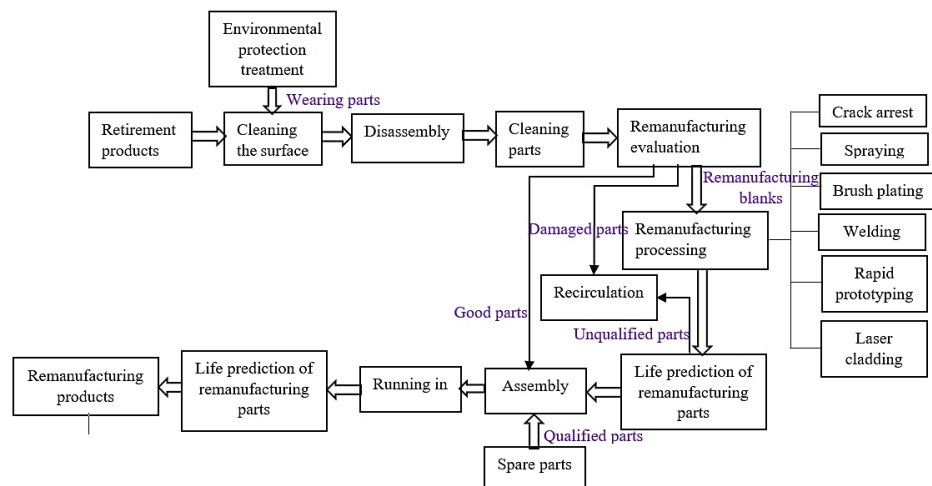


Figure 2.18: A general flow chart of a remanufacturing process (Zhang et al., 2013).

Remanufacturing, in the repair and replacement stage, involves restoring worn-out or damaged components to their original or improved state through various techniques, including surface modification such as welding, thermal spraying, chemical vapor deposition (CVD), physical vapor deposition (PVD) and laser cladding (LC). The following section provides a detailed analysis of these surface modification techniques.

2.4.1 Evaluation of Surface modification techniques for the remanufacturing of drive tumbler.

Surface modification is applied to increase the performance or structural integrity of materials with inadequate functionalities, whereby a material with better functional performance is coated through a deposition technology on another material with less mechanical performance in terms of its resistance to fatigue, wear, and corrosion. Different techniques as shown in Figure 2.19 (a-d), to achieve this include thermal spray, manual arc welding, physical vapor deposition, and chemical vapour deposition (Al-asadi & Al-tameemi, 2022).

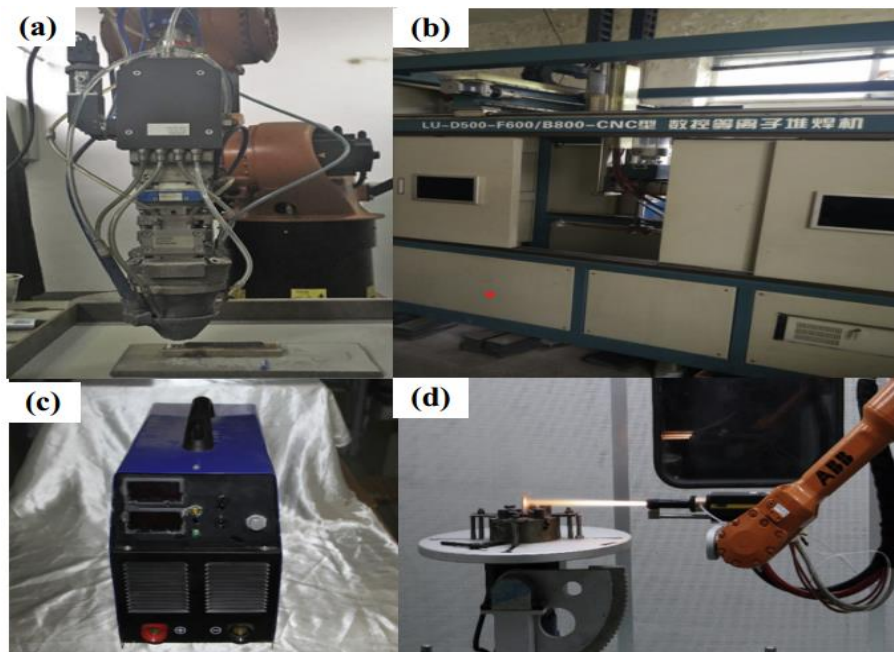


Figure 2.19: Different technologies in surface modification technique: (a) laser cladding, (b) Plasma arc surfacing, (c) Brushing electroplating, (d) Plasma spray (Peng et al., 2019).

The goal of this section is to analyze these surface modification techniques to identify and select the appropriate deposition strategy for the remanufacturing of the drive tumbler to at least as-new

in performance. Factors such as the ability to fabricate functional clad, improvement of mechanical properties of the component, the little requirement for post processing, and good metallurgical bonding between the substrate and the coated surface will be critically considered. These factors when successfully implemented contribute to the following benefits to the mining industry.

- 🔧 Improved service life of the drive tumbler to prevent premature failure
- 🔧 Reduced costs of replacing the drive tumbler.
- 🔧 The downtime associated with the drive tumbler's frequent damage is avoided, hence productivity in the mining operations.
- 🔧 Improved efficiency of the shovel loader and overall mining operations
- 🔧 Reduced time for breakdowns.

Table 2.5: Overview of surface modification techniques for remanufacturing drive tumbler

	Working Principles	Process Features	References
Welding	Joining metals by heating and melting through Arc Welding, Gas Welding, Resistance Welding, etc.	- Can facilitate the fabrication of high-strength joints. - Can be suitable for a diverse thickness and array of materials. - Produces medium heat input and high heat affected zone (HAZ) - Induces thermal distortion and phase changes. - Prone to defects such as porosity and cracking.	(Davis 2005; Chmielewski & Golański, 2015).
Thermal Spraying	Deposition of molten or semi-molten particles on a surface through Plasma spraying, flame spraying, HVOF and cold spraying.	- Can delivers exceptional protection against corrosion. - Can restore worn parts. - Often exhibits lower bonding strength. - May necessitate post-treatment for specific application. - Induces defects like porosity	(Mohanty & Roy, 2012: IRS-surfacing-technologies, 2020)

CVD	Deposition of thin films by chemical reactions of gaseous reactant	- Generates coatings of exceptional purity and uniformity. - Well-suited for wide range of materials. - Necessitates elevated temperatures. - Equipment often entails significant financial investment. - Toxic byproducts	(Hayden, n.d.; IRS-surfacing-echnologies, 2020)
PVD	Deposition of thin films in a vacuum by sputtering, evaporation, and ion plating.	- High-purity coating - Can operate at lower processing temperatures compared to Chemical Vapor Deposition (CVD). - Limited to the production of thin coatings. - Poor bonding with the substrate. - Often necessitates sophisticated and expensive equipment.	(Hayden, n.d.; IRS-surfacing-echnologies, 2020)
Laser Cladding	Deposition and melting of additional material onto a substrate using a laser beam to create a new surface layer.	- Enhances wear and corrosion resistance. - Suitable for repairing and building up worn parts with intricate shapes. - Can produce excellent metallurgical bonding between the coating material and the substrate. - Can be automated to achieve high productivity levels. - Low dilution, low porosity, and small HAZ - Minimal distortion - Involves high initial equipment investment. - The high-energy laser utilized in this process can be dangerous, creating potential safety risks for personnel.	(Liu et al., 2021; Ehsan et al., 2021)
WAAM	Involves the deposition of metal wire using an arc welding process to create	- Cost-effective for large components. - Versatile in material options.	(Li et al., 2022; Kanishka & Acherjee, 2023;

three-dimensional
structures

- Can build damaged parts with the deposited weld forming the whole parts
- Rate of deposition is high up to 9.5kg/h
- Reduced material waste.
- Surface finish may require additional processing.

Shah et al.,
2023)

Table 2.6: Summary of process characteristics of various remanufacturing techniques

Remanufacturing Techniques	Feedstock Materials	HAZ	Bonding Strength	Coating thickness	Dilution	Cost	Post-processing requirement
Welding	Only Metals	Very high	High	1 mm to about 12 mm	High	Low	Highly required
Thermal Spraying	Metals and Ceramics	High	Low	50 μm to several mm	No dilution	Moderate	Heat treatment required
CVD	Metals and Ceramics	Very low	Low	0.05 μm to 20 μm	No dilution	High	Highly required
PVD	Metals and Ceramics	Very low	Low	0.05 μm to 10 μm	No dilution	High	Highly required
Laser Cladding	Metals, Ceramics and composites	Low	High	50 μm to several millimeters	Low	High initial cost	Moderately required
WAAM	Only Metals	Moderately high	High	1 mm to several millimeters	High	low initial cost	Highly required

From the overview of the surface modification techniques that are used in the remanufacturing of heavy-duty mining equipment, some of these techniques still require some improvements to address the recurrent failure of mechanical power transmission components like the drive tumbler in mining equipment. While welding can facilitate the fabrication of high-strength joints with moderate bonding strength with parent materials, its high heat input leads to an increase in HAZ and makes it prone to defects such as cracks and porosity. Power transmission components in heavy-duty mining equipment especially the drive tumbler which are mostly manufactured from low carbon low-alloy steels experience high impact and sliding contact fatigue making them susceptible to rapid crack propagation from inherent defects like porosity and cracks (Li et al., 2019). Surfaces fabricated with manual welding process are susceptible to defects due to high heat inputs, hence are not good for the drive tumbler as they will experience further failure due to sliding contact fatigue. However, welding techniques have experienced a positive shift in recent years. This is due to the emergence of the Wire Arc Additive Manufacturing (WAAM) process. Figure 2.20 depicts the WAAM process, where wire and arc welding tools are utilized to build the parts with the deposited weld forming the whole parts (Nagamatsu et al., 2020).

According to Chaturvedi et al., (2021), in comparison to the conventional welding process and other additive manufacturing innovations, the directed energy deposition-arc (DED-arc) method is advantageous and economical, given that it produces large and complex parts with solid structure due to high deposition rates of about 9.5 kg/h, reduced materials garbage, and low energy consumption. Depending on the particular type of arc-based welding technology used to melt the feed wire and create a structure layer by layer, the WAAM process can be split into three main categories; plasma arc welding (PAW), gas tungsten arc welding (GTAW) also known as tungsten inert gas (TIG), and gas metal arc welding (GMAW) which can either be metal inert gas (MIG) or metal active gas (MAG) (Xiong & Zhang, 2014). This technique is often effective when rebuilding a completely fractured part or excessively worn surface. However, WAAM alone can introduce coarse columnar grains, higher residual stresses, which can be detrimental to the wear resistance performance and fatigue life of the as-built part (Nagamatsu et al., 2020; Chaturvedi et al., 2021).

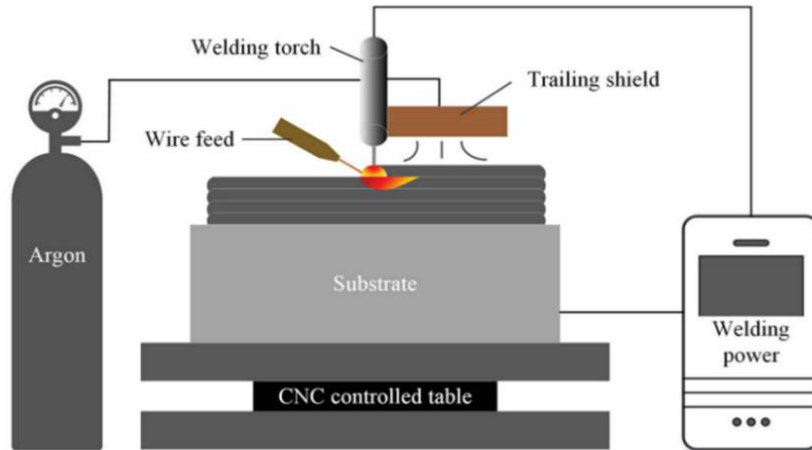


Figure 2.20: Wire additive arc manufacturing process (WAAM) (Zhuo et al., 2021)

The analysis in Table 2.6 suggests that the low bonding strength, and irregularities in the heat-affected zone (HAZ), from thermal spraying, CVD and PVD may not be suitable for remanufacturing parts that work under extreme impact stress and sliding contact stress. While thermal spraying, CVD, and PVD can be used in varieties of metals and ceramics, they are limited in the application and development of composite materials. In addition, although CVD and PVD produce parts with very low HAZ, no dilution and minimal coating thickness, they continue to remain irrelevant in applications that require a thick coating to withstand severe impact and sliding conditions.

Furthermore, as can be seen in Table 2.6, and Table 2.5 the emergence and recent development in laser cladding (LC) technology as surface modification and repair technology offers more advantages than other techniques as far as the application of the drive tumbler teeth is concerned. These advantages include small HAZ, low dilution rate, and strong metallurgical bond between coating and substrate after rapid solidification. This makes it a go-to choice for surface modification of damaged and worn-out machine components using different alloys and composite materials (Liu et al., 2021).

2.4.1.1 Laser Cladding Process

Laser cladding as depicted in Figure 2.21 is a variant of the directed energy deposition (DED) process in additive manufacturing that utilizes laser energy to melt and fuse coating materials mostly in powder form onto a base metal otherwise known as substrate. It also ensures a strong metallurgical bond between the cladded surface and the underlying surface.

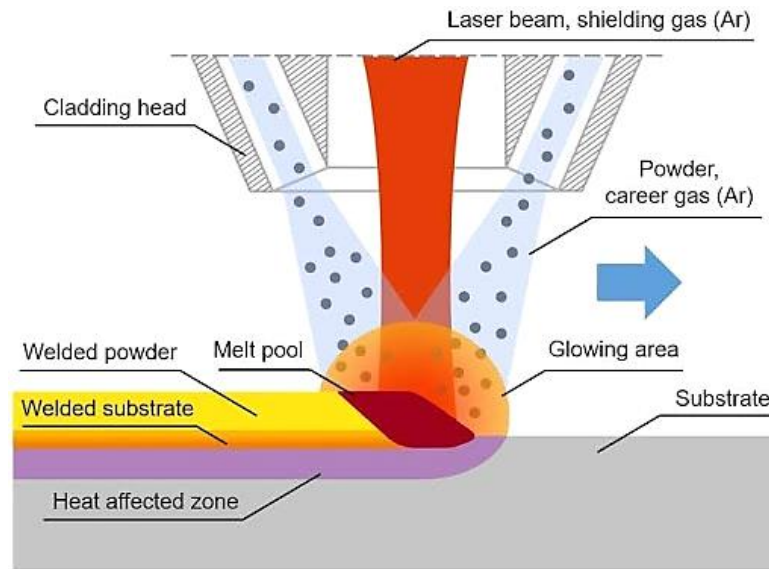


Figure 2.21: Laser Cladding Process (Baddiehub, 2024)

This process results in the formation of a new strong and uniform layer with-quality surface finish. The surface is known as a clad. The clad can be formed as either single track or multiple tracks. While multi-track clads involve multiple overlapping passes, usually an overlap of 25%, 50% of already deposited clad or as desired by the required application, single-track is created when a single pass is applied to the substrate. According to Laeng et al., (2000), to maximize the cost associated with laser cladding and prevent the formation of gas pores between clad tracks, the overlapping factor should be less than 70% with 50% being an acceptable factor. The overlapping tracks can form a single layer or multiple layers. Multiple tracks and multiple layers are mostly adopted for the remanufacturing of components with complex geometry.

Due to the versatility in the application of laser cladding in the remanufacturing of damaged components and complex geometry structures, LC is explored in the remanufacturing of mining equipment components, such as gears, and heavy-duty sprockets (Zhu et al., 2020; Guo et al., 2022). Previous studies (Liu et al., 2017; Guo et al., 2022), show that LC is utilized in the mining industry for the remanufacturing of heavy-duty sprockets as depicted in Figure 2.22(a-c). Liu et al., (2017) explored the application of laser cladding for the repair of damaged sprockets, with an emphasis on optimizing process parameters using the Taguchi method. The primary objectives were to minimize dilution and enhance repair accuracy by systematically varying laser power, scanning speed, and powder feeding rate.

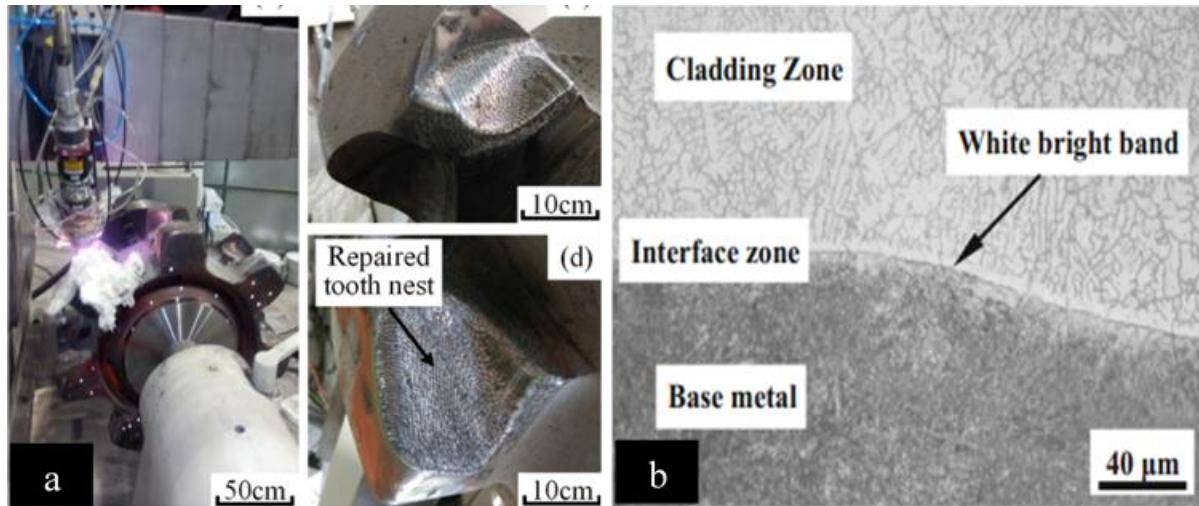


Figure 2.22: Remanufacturing of Sprocket by laser cladding (a), (b), (c) repair state, (d) microstructure of repaired sprocket. (Liu et al., 2017)

The optimal parameters determined were 1000 W laser power, 2.81 g/min powder feeding rate, and 1200 mm/min scanning speed, which resulted in a repair accuracy of 2.973 mm. Detailed analysis showed that the cladding zone exhibited significantly higher microhardness compared to both the heat-affected zone and the base metal. As depicted in Figure 2.23d, the cladding zone displayed a fine-grained microstructure and a white bright band line between the cladded surface and the substrate indicating a strong metallurgical bonding to the substrate, and good mechanical properties. Their results affirm the effectiveness and feasibility of the laser cladding process in the restoration of sprockets with complex shapes, offering a viable solution for extending the service life of the drive tumbler under study. This study also corresponds with the research of Guo et al., (2022). Guo and co-researchers carried out experimental research on laser additive remanufacturing technology for heavy-duty sprockets. Their study focused on analyzing the impact of key parameters like laser power, scanning speed, and powder feed rate on cladding height, cladding area, melting area, and dilution rate. These parameters were correlated with the geometric characteristics of the cladding layer and the level of dilution. By developing a multi-objective optimization (MOPSO) model, they identified the optimal parameters as 1150 W laser power, 950mm/min scanning speed, and 3.8rad/min powder feeding rate which produce exceptional surface properties and microstructure of the sprocket. Nonetheless, it can be argued in the literature, that although laser cladding process is effective and efficient in repairs and

remanufacturing with process parameters optimization, there is need to evaluate the associated cost of the process in order to ensure its profitability and sustainability for industrial applications. While this is lacking in the literature particularly in laser cladding technique for drive tumbler, some cost models have been developed by researchers to access the general economic feasibility of remanufacturing processes. The next section presents a brief discussion on these cost models.

2.5 Cost Models for Remanufacturing Processes

In remanufacturing, although cost models are quite limited, they have been developed as decision-making tools. These models assist in assessing economic feasibility and optimizing remanufacturing practices by analyzing the various costs associated with the entire process. For example, a general cost model that serves as a decision-making tool for remanufacturing practices was developed by Abbu et al., (2022). This model is based on activity- and performance-based costing, considering both the activities that occur during the process and their performance. This model addresses the total costs of the remanufacturing process and identifies critical parameters at each stage. But the need for well-structured data for every input to give a precise cost was pointed out as a major limitation of this model. Xu & Feng, (2014), on the other hand, developed a framework and a cost model to quantitatively evaluate the benefits of remanufacturing techniques, with a focus on additive manufacturing for end-of-life decision making strategies. They conducted a case study on the remanufacturing of a slat track of an aircraft wing, using this model to compare the benefits of remanufacturing the component versus producing a new one. The application of the developed cost model indicated that significant cost savings could be achieved by remanufacturing the slat track instead of manufacturing a new one.

Other researchers have proposed predictive and optimization models for remanufacturing routes to improve production efficiency and reduce production costs. For example, . Zhang et al., (2019) developed a remanufacturing cost prediction model of used parts based on the framework as shown in Figure 2.23 considering failure characteristics based on least squares support vector regression and semi-supervised learning. The k-nearest neighbor (k-NN) algorithm was introduced to increase forecast precision. The prediction model, validated through the case study on electromechanical waste products, showed strong performance and is highly valuable for practical application and dissemination.

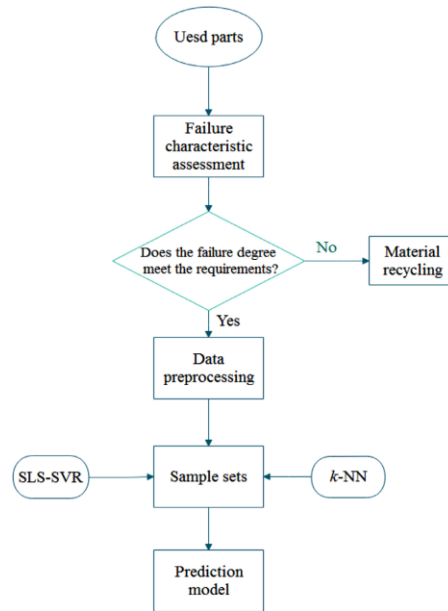


Figure 2.23: Framework for remanufacturing cost prediction (Zhang et al., 2019).

In addition, Peng et al., (2019) developed an optimisation model aimed at enhancing eco-efficiency in the remanufacturing process routes. Using fault tree analysis, they identified key factors associated with products used and applied the Incident Cause Analysis Method (ICAM) definition method to design alternative remanufacturing routes. An eco-efficiency objective function with a hybrid optimization approach combining simulated annealing (SA) and particle swarm optimization (PSO) was employed to determine the most eco-efficient manufacturing process. The model was tested on the remanufacturing of a used helical cylindrical gear (Figure 2.24), with the optimization implemented through MATLAB programming.

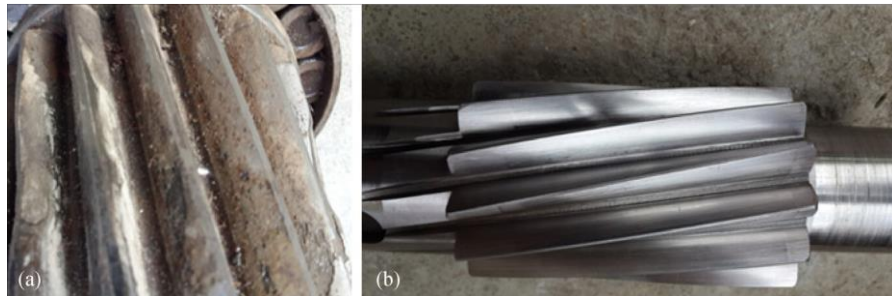


Figure 2.24: Used cylindrical helical gear (a) before and (b) after remanufacturing (Peng et al., 2019).

The model's effectiveness was validated by comparing its performance to standard SA and PSO methods, and the results of algorithm optimization verified that combined simulated annealing and swarm optimization (SAPSO) is more suitable for remanufacturing process route optimization than SA and PSO (Figure 2.25 & Figure 2.26)

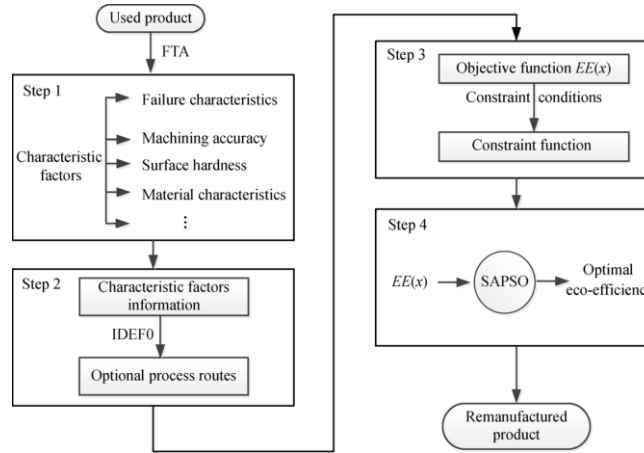


Figure 2.25: Remanufacturing process route optimization flowchart (Peng et al., 2019).

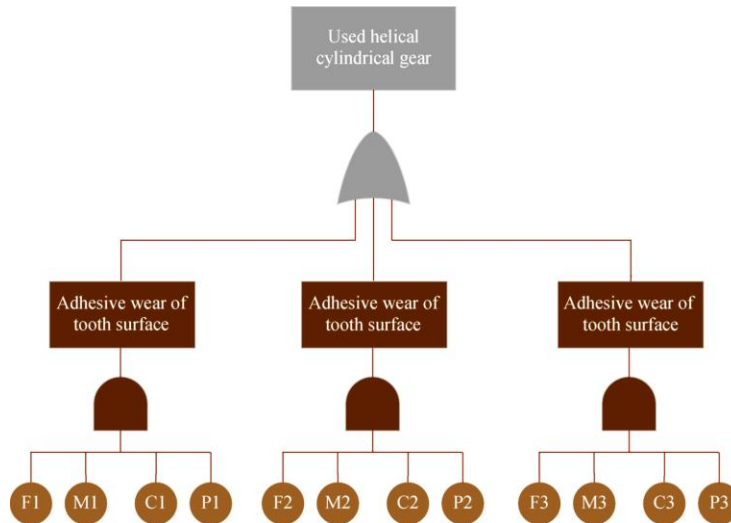


Figure 2.26: Characteristic factor analysis of the used helical cylindrical gear (Peng et al., 2019).

Where F is the failure characteristics, M is the material characteristics, C is the surface hardness, and processing accuracy (P). (F1, M1, C1, P1), (F2, M2, C2, P2), and (F3, M3, C3, P3) denote (moderate wear, cast iron, 46HRC, IT7), (moderate crack, cast iron, 50HRC, IT5), and (mild crack, cast iron, 46HRC, IT7), respectively.

However, researchers have reported limitations in these predictive and optimization mathematical models for remanufacturing, primarily due to the insufficient number of remanufactured samples and the challenges in obtaining experimental data. This highlights the need for a greater adoption of experimental studies focusing on both failure analysis and cost-benefit evaluation of selected materials and remanufacturing approach before the remanufacturing project of failed components is implemented so that accurate and reliable decision aiming towards profitability, sustainability and enhanced performance can be made.

2.6 Gap in Literature and Direction of this Study

Apart from the limited study in the failure investigation of drive tumbler of electric mining shovel loaders in diamond mining application, existing studies on the failure analysis of similar components left out some gaps that are needed to be filled. Some of these gaps are elucidated below.

-  Failure analysis of similar components did not consider their operating environmental factors which are crucial in understanding the occurrence of failure modes and mechanisms in damaged mechanical components, particularly industrial equipment parts under harsh operating environment.
-  An extensive investigation on material, mechanical properties and microstructure of an undamaged part in the failed similar components to the drive tumbler or as-purchased ones, that could give a hint to the behavior of the component's materials during operations before failure, which might be responsible for the premature failures are not studied.
-  Mitigation measures to prevent the failures of similar components are not reported in the literature.
-  Although laser cladding has been reported to be a viable remanufacturing approach in restoring high-valued engineering component to its best performance in operations, to the best of our knowledge, existing literature focus primarily on experimental validation of cladding quality, wear-resistance properties or mechanical performance through materials and mechanical characterization, but lacks a direct connection to mitigating particular type of failure in failed industrial components, and do not provide detailed cost-based

justification in terms of techno-economic analysis for the choice of materials and laser cladding process in the context of remanufacturing feasibility.

This research addresses these gaps by:

- 🔧 Conducting an experimental failure investigation on a damaged drive tumbler from a diamond mining shovel loader to identify the root causes and failure mechanisms by evaluating the diamond mining environment, investigate the materials properties of the undamaged part hence giving a direction understanding the failure modes and the occurrence of failure mechanism in the drive tumbler teeth.
- 🔧 Proposing failure mitigation strategies by selecting a suitable candidate wear-resistant materials and remanufacturing approach from the literature and findings from failure analysis to prevent premature failures.
- 🔧 Performing a techno-economic evaluation, based on literature-sourced and industrial-sourced material costs, laser cladding processing cost, and deposition volume approximated from observed damage levels in the drive tumbler teeth to investigate the profitability remanufacturing.

Thus, this research bridges the gap between failure root cause analysis and economic feasibility assessment of laser cladding as a remanufacturing solution providing an informed basis for selecting cost-effective, technically viable remanufacturing strategies for heavy-duty mining equipment components

2.7 Chapter Summary/Conclusion

This chapter introduced the physical environment and the operating conditions of the drive tumbler in heavy-duty mining equipment as well as the nature of damage and mechanisms of similar components such as gears and sprocket encounters in service. The failures identified in the reviewed components include abrasive wear, adhesive wear, surface contact fatigue, and fracture. These gave hints into the possible causes of the failure encountered by the drive tumbler teeth. Following was the identification and selection of suitable materials for the remanufacturing of the drive tumbler. In the selection of materials, the type of failure encountered, the mode of operation of the drive tumbler, failure modes, and the cost associated with the materials were considered.

Therefore, to mitigate the premature failure of the drive tumbler teeth and provide the drive tumbler with materials that can withstand the sliding and impact stress experienced in service, Fe-based alloys such as 316L, H13, WC-12C0, WC and MMCs are the potential materials that were identified. While MMC has proven to be the best because of its potential for high-performance applications, stemming from its ability to combine the best properties of two or more constituent materials and the flexibility to be tailored to specific operating conditions, MMC of H13 and WC-12Co are considered suitable materials for the drive tumbler teeth, because of their excellent wear resistance and mechanical properties.

Having established that remanufacturing contributes to the global circular economy by eradicating the effect of environmental pollution through waste and energy consumption reduction, as well as the benefits it offers to end-of-life components with properties equivalent to or more than that of a new component, surface modification techniques suitable for depositing identified materials towards remanufacturing were analyzed. These techniques include welding, thermal spraying, CVD, PVD, WAAM, and laser cladding. After this, LC was considered the most efficient surface modification technique for mitigating the issue of premature failure in heavy-duty mining equipment. This is because of the advantages it has over other surface modification techniques. The advantages include low HAZ, low porosity, high bonding strength and good metallurgical bonding between coating and substrate, high retaining of mechanical properties, and thickness flexibility on complex geometry.

3 Chapter Three: Materials and Methodology

3.0 Chapter Summary:

This Chapter describes the approaches and methods that were adopted to achieve the set objectives (i) and (iii) of this project. This research methodology was designed to investigate (i) typical failures, their causes, and mechanisms in the drive tumbler teeth via an engineering failure analysis (EFA); (ii) select appropriate candidate wear-resistant materials and remanufacturing approach to remanufacture the drive tumbler based on literature review and the information obtained from the EFA Objective (i), and (iii) investigate the profitability of remanufacturing drive tumbler teeth by evaluating the cost-benefits of adopting selected materials and remanufacturing approach by analyzing the geometry of damaged surface, amount of materials required in grams in conjunction with information of laser cladding processing cost from the industry and materials cost from suppliers. Therefore, the experimental equipment, methods, materials, process engaged, sample preparation methods, and characterisation techniques and step-by-step procedure of the TEA are herewith described.

3.1 Methodology for investigating premature failure for damaged drive tumbler teeth

Figure 3.1 depicts the experimental methodology employed to investigate the underlying causes of drive tumbler teeth failures.

3.1.1 Collection of Samples

In February 2024, a field investigation was conducted at an open-pit diamond mine in Botswana, to fully understand the problem experienced by the drive tumbler, its operating and environmental conditions. The electric rope shovel loader in this diamond mining company was completely shut down due to the failure of its drive tumbler. Through visual inspection, the drive tumbler, that has 18 teeth, was found to have experienced severe damages on the teeth surfaces (Figure 1.5b). Due to the similarity in location of failures in the failed drive tumbler teeth (Figure 1.5b), two (2) failed teeth were collected out of the 18 teeth as samples for further analysis (Figure 3.2). The teeth were cut using an oxyacetylene cutting flame with care far away from areas of interest, to avoid thermal effects on failed surfaces.

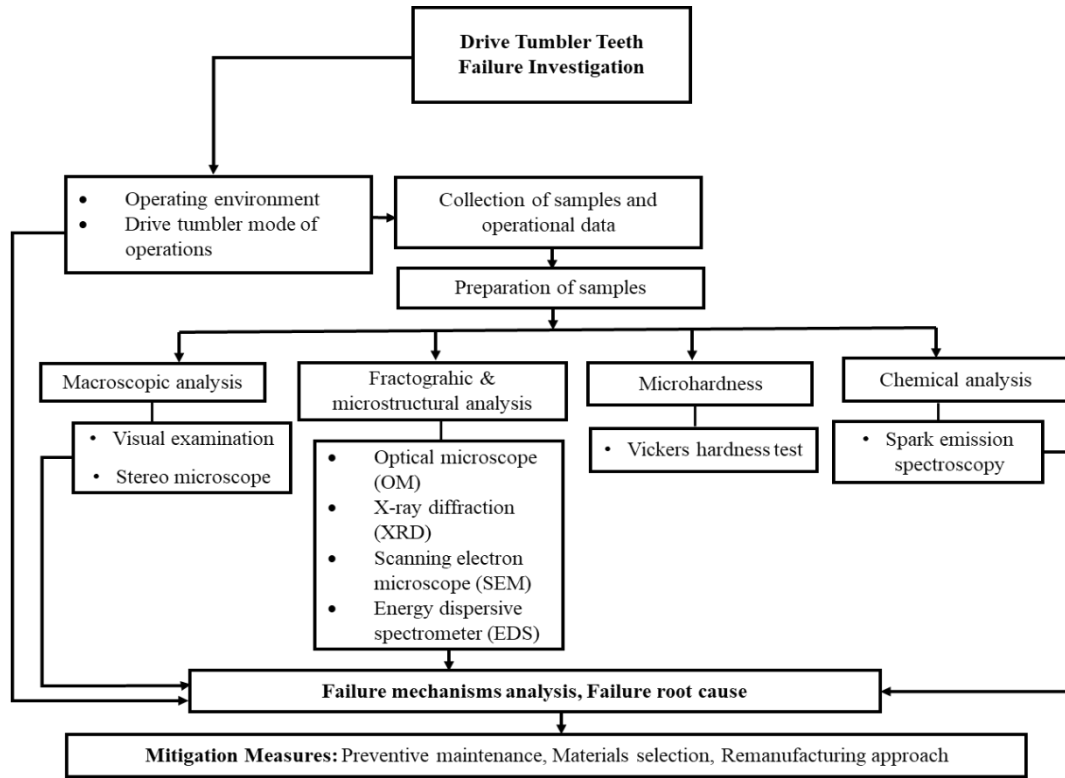


Figure 3.1: Experimental approach used to analyze the cause of drive tumbler teeth failures.

3.1.2 Visual and macroscopic examination

Before sample preparation, the two damaged drive tumbler teeth were cleaned with high-pressure water and acetone and then dried using hot air (Lindsay et al., 2023). Afterwards, they were visually examined to establish and categorise the modes of failure and characteristics features which are presented in section 4.1.3.1. This was done in line with the studies of Lindsay et al., (2023), and Akintunde et al., (2023), and Kyekyere et al., (2024).

3.1.3 Sample preparation for fractographic and microstructural analysis

Following the identification of various failure modes and characteristic features in the as-received samples through visual examination, both the damaged tooth surfaces and the undamaged sections were cut and sectioned at different locations for chemical analysis, metallography, and morphological (fractographic) examinations (Figure 3.2). As shown in Figure 3.3a, the cutting was carried out using a Multicam V-Series CNC waterjet machine (Akintunde et al., 2023; Lindsay et al., 2023; Kyekyere et al., 2024). The CNC waterjet machine provides excellent cutting precision,

low heat influence, and minimal stress induction on the workpiece compared to other cutting techniques. Furthermore, the samples were cleaned with acetic acid in a scientech ultrasonic cleaner as shown in Figure 3.3b before analysis (Kyekyere et al., 2024). The samples with size 10 mm x 10 mm were carefully sectioned and prepared so that evidence on damaged surfaces was not destroyed prior to fractographic and metallographic analysis. Afterwards, the drive tumbler failed specimens were properly labelled and stored neatly in an air tight container for traceability and repeatability of this study procedure.

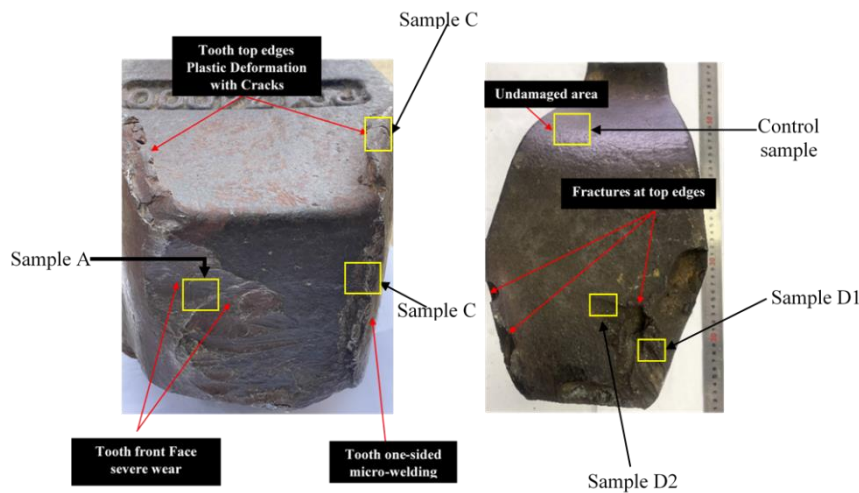


Figure 3.2: Locations of samples section for fractographic and microstructural analysis

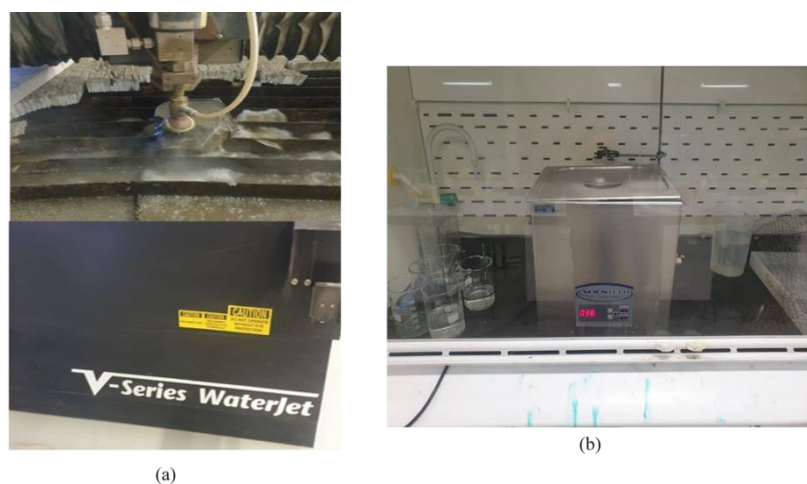


Figure 3.3: (a) A V-series waterjet machine used for sample preparation (b) scientech ultrasonic cleaner

The cross-section of the undamaged parts (control sample) and damaged samples were mounted in multifast phenolic hot mounting resin, using struers CitoPress-5 mounting press at 180° for 8 minutes (Figure 3.4a), ground with abrasive paper of grit size 180 to 1200 using a MRC M-1B grinding and polishing machine (Figure 3.4b). Subsequently, the samples were polished to 3 microns using a diamond suspension, and etched with 3% Nital following ASTM E3 standards for metallographic analysis (Lindsay et al., 2023; Kyekyere et al., 2024).

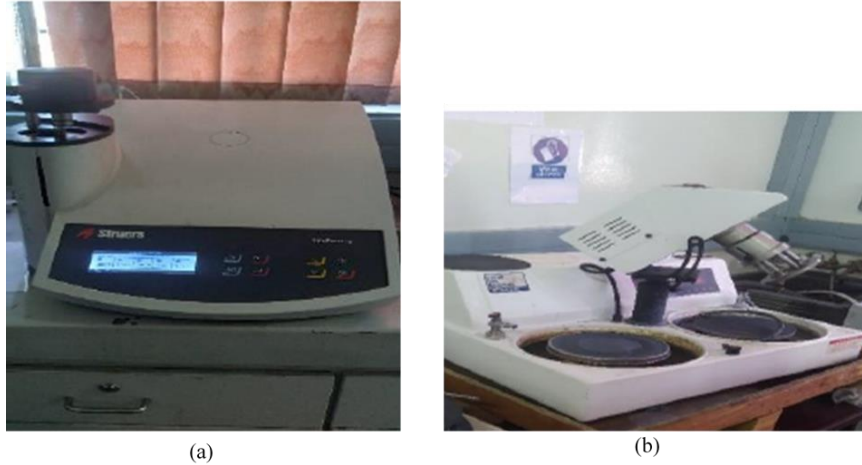


Figure 3.4: (a) Struers CitoPress-5 mounting press (b) MRC M-1B grinding and polishing machine

3.1.4 Chemical Analysis of control sample

To verify the materials used in manufacturing of the drive tumbler, the chemical composition of the cross-section of the undamaged part (control sample) was analysed using a spark emission spectroscopy (SPECTROMAXX LMX10 ARC/SPARK OES ANALYZER). A small section of the undamaged drive tumbler teeth was vaporised using an electrode, and the light emitted from the sample was analysed with a spectrometer in line with ASTM E415 standards and the study of Kyekyere et al., (2024).

3.1.5 Chemical analysis of water sample from the mine.

The water sample from the tailing dams in the mine was analysed using H19811-5 water analyser to determine the pH, conductivity, and total dissolved salt (TDS). The Dionex Aquion IC system (Figure 3.5) was used to characterise the anions in the water sample from the mine. A dilution ratio of 1:10 was used to reduce TDS below 1000 mg/L. The water sample was filtered using filter paper of 45 microns to remove any existing particles (Willison & Boyer, 2012). Anions present were then detected, and the plots for each water from the mine are presented and discussed in section 4.1.2. This analysis was carried following ASTM D4327-17 standards for anions in water by ion chromatography.



Figure 3.5: Picture showing Dionex Aquion ion chromatography system

This analysis was essential because the presence and concentration of chemically aggressive ions influence the initiation and propagation of corrosion-assisted pits and cracks (Willison & Boyer, 2012; Peng et al., 2013). Understanding the chemical aggressiveness of the operating environment allowed fracture and worn surface observations to be interpreted in the context of possible corrosion fatigue or stress corrosion cracking mechanisms.

3.1.6 Microscopic examination of damaged and undamaged samples of drive tumbler teeth

The cross-section of the control sample (undamaged part) was analysed using an Olympus DSX1000 Digital Optical Microscope (OM) to identify the microstructure and microstructural

defects of the drive tumbler material. Furthermore, a microscopic examination was carried out to understand the morphologies and failure mechanism that contributed to the respective failure modes. The damaged surfaces samples were examined using a JSM-IT100 series scanning electron microscope (SEM) without grinding or polishing, while X-ray spectroscopy (EDS) was used to analyze the elemental composition present on the damaged surfaces. An optical microscope and SEM/EDS were utilized to analyse the cross-sections near the damaged surfaces. The images were captured at different locations from a low magnification (5 X) to a higher magnification (6000 X) for proper revealing of the failure mechanism, with representative micrographs presented in section 4.1.1.1.

3.1.7 Mechanical testing (Micro-Hardness)

Microhardness tests were conducted on five samples of drive tumbler teeth. Samples include cross-sections of control sample (undamaged parts) and the cross-sections of damaged surfaces (failure modes A-D). A 300 g indentation load was applied to the polished specimen for 15 seconds, with 15 hardness measurements taken per sample. Then the average microhardness of the control sample was then determined. The test was carried out using the EMCO test and indenter nr: ENT5010 according to ASTM E92 / E384 standards (Akintunde et al., 2023; Lindsay et al., 2023; Kyekyere et al., 2024). The analysis was carried out to examine surface hardness of the drive tumbler teeth and to verify its ability to resist plastic deformation and if the damaged drive tumbler teeth experienced surface hardening during operations.

3.2 Techno-economic analysis of laser-based remanufacturing approach.

This section outlines the step-by-step approach used to evaluate the techno-economic feasibility of remanufacturing the damaged drive tumbler teeth by estimating the cost of selected materials from literature and laser cladding processing. This methodology is based on manual and mathematical estimations of materials volume loss from the surface area of failure mode A and B, with cost calculations encompassing amount of materials required for deposition and laser cladding processing.

3.2.1 Estimation of volume of wear in failure mode A and B surface of the drive tumbler teeth

To quantify the material loss due the severe wear and gouging on the drive tumbler tooth face (failure mode A & B), a simplified geometric approach was adopted. Given the irregular nature of the wear, the damaged zones were approximated as standard geometric shapes, primarily cuboidal forms as shown in Figure 3.6. A simplified geometric model based on single-track wear analysis was developed to ease the calculation of material loss in complex wear profiles. This approach, inspired by the methods of Qu & Truhan, (2006) and Shebani & Pislaru, (2015) allowed for a more practical estimation of wear volume in the drive tumbler tooth front face using equation 3.1.

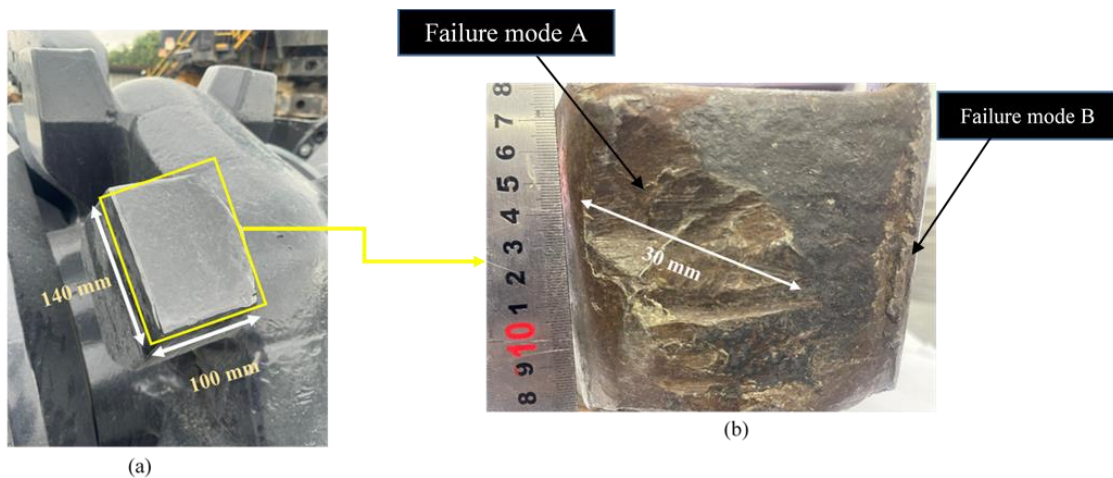


Figure 3.6: (a) As-purchased drive tumbler teeth showing tooth geometry and dimension (b) Failed drive teeth showing remanufacturable failure modes and depth of materials loss from surface

$$V_{loss} = L \times W \times D \dots\dots\dots 3.1$$

Where, L is length of wear region (mm), W is width of the worn region and D is the depth of worn area into the drive tumbler teeth.

Surface Area Estimation for Deposition

The surface area to be rebuilt or coated with new material was calculated based on the affected surface dimensions (Figure 3.6 a & b). The area of the damaged surface of the drive tumbler teeth was determined by equation 3.2.

$$A_{damaged\ surface} = L \times W \dots\dots\dots 3.2$$

Where L and W represent the length and width (in mm) of the deposition surface, respectively.

3.2.2 Volume and Cost of Material Required for Deposition

Having established the surface area of the material to be deposited and thickness of over the damaged surface of the drive tumbler, the volume of material deposition is computed using equation 3.3.

$$V_{dep} = A \times t \dots\dots\dots (3.3)$$

Where A is the surface area to be coated (mm²) calculated from equation 3.2, and t (mm) is the required thickness of the deposited layer based on the depth of materials loss from damaged surface (Figure 3.6b). The mass (M) of the powder of candidate wear-resistant materials that would be needed to restore material loss from surface was determined using equation 3.4.

$$M = V_{dep} \times \rho \dots\dots\dots (3.4)$$

Where ρ is the density of the metallic matrix composite of H13/WC-12Co selected from the literature, assumed to be in a ratio of 75% H13 and 25% of WC-12Co which is further estimated using equation 3.5.

$$\rho = w_1\rho_1 + w_2\rho_2 \dots\dots\dots 3.5$$

where ρ_1 and ρ_2 are the density H13 and WC-12Co respectively. The density of H13 and WC-12Co have been reported to be 7.8 g/cm³ (0.0078 g/mm³) and 14.5 g/cm³ (0.0145 g/mm³) (Zhao et al., 2022).

This blended density is used in Equation 3.4 to determine the total mass of powder required for deposition. The individual powder masses are then calculated as follows:

Mass of H13: $M_{H13} = M \times 0.75$, Mass of WC-12Co: $M_{WC-12Co} = M \times 0.25$, this was done to estimate the cost of individual material using equation 3.6 & 3.7 respectively.

$$Cost\ of\ H13 = \frac{M_{H13}}{1000} \times P_{H13} \dots\dots\dots 3.6$$

$$Cost\ of\ WC-12Co = \frac{M_{WC-12Co}}{1000} \times P_{WC-12Co} \dots\dots\dots 3.7$$

Where P_{H13} and $P_{WC-12Co}$ are the cost of H13 and WC-12Co powder (USD/Kg). The cost of the powders was estimated from information gathered from powder suppliers in South Africa. Thereafter, the total cost of materials to be used was calculated by summing the cost of individual material as estimated using equation 3.8.

$$C_{mat} = Cost\ of\ H13 + Cost\ of\ WC - 12Co) \dots\dots\dots 3.8$$

3.2.3 Laser cladding processing Costs

To conduct the techno-economic assessment of laser cladding remanufacturing technique, the processing cost is often calculated on a per-hour based which already considers labor, machine time, and energy consumption. Due to the limited availability of a comprehensive equation in literature that directly relates laser cladding processing cost to geometric features (such as surface area and coating thickness) and process parameters (like scanning speed and track overlap), this study develops a simplified cost model based on physical deposition time. While previous studies such as Peng et al., (2024), who optimized overlap rate using Gaussian models, and Bax et al., (2018), who mapped the influence of scanning speed and layer thickness on deposition quality and efficiency highlighted the critical role of these variables, they stop short of integrating them into a unified techno-economic cost model. Hence, equation 3.9 & 3.10 introduce a novel, yet practical, equation to estimate laser cladding cost based on cost of laser cladding processing per hourly rate, and the deposition duration which can be estimated using laser scanning speed and assumed deposited layer geometry for the damaged surface to be remanufactured.

$$Cost_{LC} = C_{LC/hr} \times T_{hours} \dots\dots\dots (3.9)$$

$$T_{hours} = \left(\frac{L \times \left(\frac{W}{w \cdot (1 - \alpha)} \right) \times \left(\frac{t}{h} \right)}{v \times 3600} \right) \dots\dots\dots (3.10)$$

Where $Cost_{LC}$ is the total cost of laser cladding processing in USD, $C_{LC/hr}$ is cost of cladding per hour, T_{hours} is total deposition time in hours, L is length of the damaged surface to be cladded (mm), W is the width of the surface (mm), w is the track width per pass (mm), α is the overlap fraction of clads, t is the desired coating thickness, h is the layer height per pass, and v is the

scanning speed. The expression $\left(\frac{w}{w \cdot (1 - \alpha)}\right)$ was used to determine number of tracks, and $\left(\frac{t}{h}\right)$ was used to determine number of layers using an overlapping ratio of 50%. This approach fills a methodological gap in remanufacturing studies, particularly for economic estimations in industrial settings where cost prediction is essential for cost-benefit evaluation.

3.2.4 Assumptions of cost model estimation

At the time of writing this thesis, the deposition of selected candidate materials via laser cladding has not been carried out, as a result, the following assumptions were made for process parameters and geometry features, based on outcomes from various researchers (Cunningham et al., 2017; Di & Yang, 2020; Nyadongo et al., 2021; Olakanmi et al., 2023a, 2023b; Kyekyere et al., 2025) to estimate T_{hours} .

- 🔧 Track width per pass = 2mm
- 🔧 Effective overlapping ratio = 50%; step-over = track width $\times (1 - \alpha) = 1$ mm
- 🔧 Number of tracks = width of damaged surface/1 mm, width of damaged surface area = 140 mm (Figure)
- 🔧 Desired coating thickness: 30 mm (to be able to fully restored material loss on damaged surface) and 2 mm if LC is to be adopted with WAAM for surface coating.
- 🔧 MMC Composition: 75% H13 + 25% WC-12Co %wt. Densities: $\rho(\text{H13}) \approx 7.8 \text{ g/cm}^3$, $\rho(\text{WC-12Co}) \approx 14.5 \text{ g/cm}^3$
- 🔧 Three varied scanning speeds: 5 mm/s, 10 mm/s & 15mm/s.

3.2.5 Techno-Economic Analysis (TEA)

The techno-economic analysis of the laser cladding process, employed as a remanufacturing strategy for damaged drive tumbler teeth, was conducted by estimating the potential cost savings or profitability. This was achieved by summing the possible total cost of materials required for deposition and the possible laser processing cost, and subsequently subtracting this from the cost of procuring a new drive tumbler to estimate potential cost of savings, as expressed in Equation 3.11, 3.2, & 3.13 respectively. Additionally, a comparative cost evaluation was performed between the annual replacement cost of the drive tumbler and the cumulative cost of

remanufacturing failure modes A and B, including the refurbishment of the as-purchased drive tumbler teeth (Cunningham et al., 2017; Di & Yang, 2020).

$$C_{reman.} = C_{mat} + Cost_{LC} \dots\dots\dots (3.11)$$

$$\text{Potential savings cost:}(C_{PS}) = C_{newDT} - C_{reman.} \dots\dots\dots (3.12)$$

The percentage savings (%S) was then calculated using equation 3.13

$$\%S = \frac{C_{newDT} - C_{reman}}{C_{newDT}} \times 100 \dots\dots\dots (3.13)$$

Where C_{reman} is the total cost of remanufacturing, C_{mat} is the total cost of required materials to be deposited for remanufacturing, $Cost_{LC}$ is the total cost of laser cladding processing, and C_{newDT} is the cost of new drive tumbler.

3.3 Conclusion

This chapter begins by outlining the methodologies employed in conducting the failure analysis of the damaged drive tumbler, aimed at identifying the underlying failure mechanisms and root causes of the premature failure. Furthermore, it details the systematic approach adopted in assessing the cost-effectiveness of selected materials and deposition techniques proposed for the remanufacturing of drive tumbler teeth.

4 Chapter Four: Results and Discussion

4.0 Chapter Summary:

In this Chapter, the failure modes and mechanism of damaged drive tumbler teeth in the electric mining shovel loader were analysed by macroscopic and microscopic failure analyses. The analysis of hardness quartz from kimberlite and crawler belt were analysed from the literature. The corrosiveness of the mine was also investigated via ion chromatographic analysis. Fractographic examination by scanning electron microscopy (SEM) equipped with energy-dispersive X-ray spectroscopy (EDS) was performed to uncover the failure mechanisms. EDS spectra were used to analyse the presence of entrapped kimberlite particles and its intermixing in the drive tumbler damaged surface. Finally, mitigation measures were offered on the proper selection of materials, remanufacturing process, and maintenance approach to improve the performance and durability of the drive tumbler.

4.1 Failure Investigation of Damaged Drive Tumbler

4.1.1 Microstructural, X-ray diffraction, microhardness and chemical analyses of the undamaged drive tumbler teeth

A comprehensive characterisation of the undamaged part of the drive tumbler teeth is crucial to understand and establishing the baseline materials against which failure mechanisms can be evaluated. Microstructural characterisation enables the identification of the phases, grain morphology, and potential inclusions, which directly influence mechanical behaviour and wear resistance of the drive tumbler teeth. X-ray diffraction (XRD) analyses phase constituents that may influence the performance of the drive tumbler teeth under severe operating conditions. Furthermore, chemical composition analysis is carried out to validate material conformity to required standards, ensuring consistency in alloying elements that govern wear resistance and toughness. Establishing this baseline in this section is fundamental for understanding deviations and mechanisms observed in the failed region of the drive tumbler.

4.1.1.1 Microstructural observations of undamaged drive tumbler teeth via OM and SEM

The micrographs of the cross-section of undamaged drive tumbler teeth (control sample) are presented in Figure 4.1, Figure 4.2, and Figure 4.3.

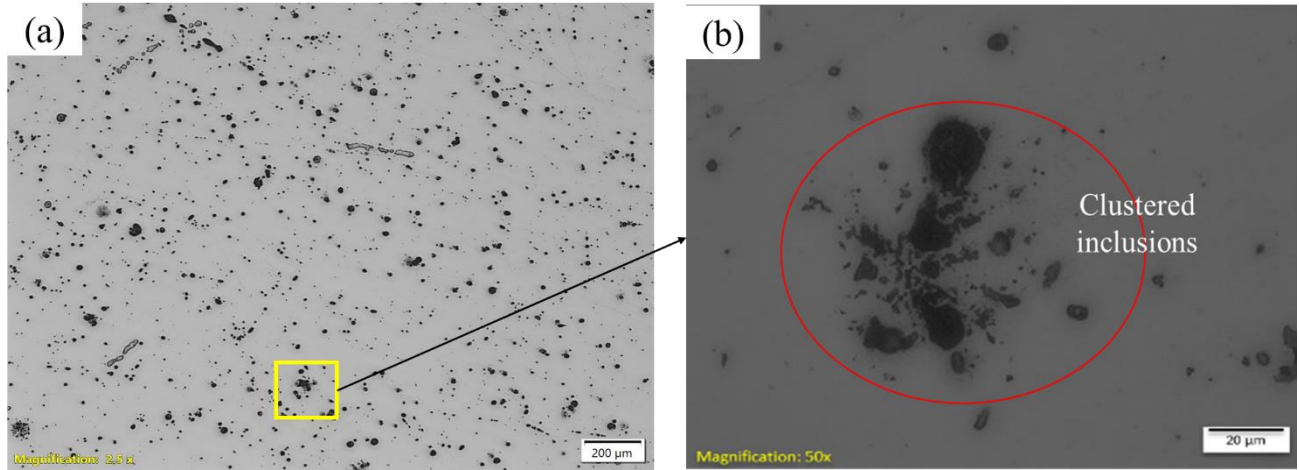


Figure 4.1: (a) Optical micrograph of as-polished control sample showing inclusions in as-polished sample, (b) clustered inclusions in (a) at higher magnification

The optical micrograph of the as-polished samples, shown in Figure 4.1a, reveals presence of inclusions of about 3.75 volume fraction with varying sizes and morphology (Figure 4.1a-c) dispersed throughout the drive tumbler material. These inclusions, typically non-metallic, likely result from residual impurities not fully removed during the steelmaking process (Malcolm Blair, Thomas L. Stevens, 1995). These inclusions' heterogeneous distribution and varying sizes suggest a non-uniform solidification process during casting process (Gorkusha et al., 2020). This is in agreement with the works of Zheng et al., (2015) and Gorkusha et al., (2020) who established that the irregularly shaped and clustered inclusions (as depicted in Figure 4.1c), are usually identified to be MnS and Al_2O_3 . The Al_2O_3 is usually formed during the deoxidation (killing) process of molten cast steel when aluminum is used as a deoxidizer. These inclusions, if retained in the solidified steel, have the potential to significantly compromise the mechanical performance of the steel (Zhang & Thomas, 2002; Jung et al., 2008; Zheng et al., 2015; Gorkusha et al., 2020).

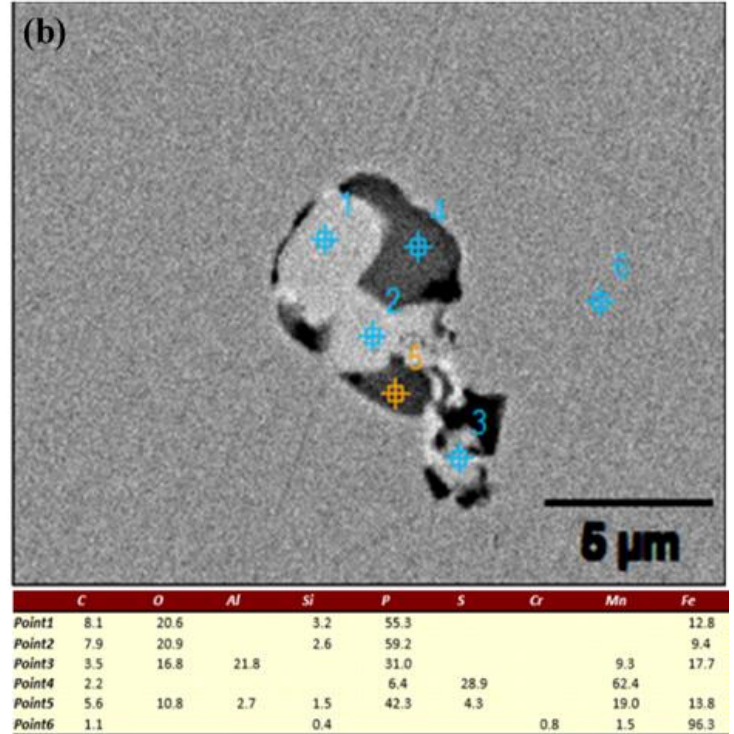
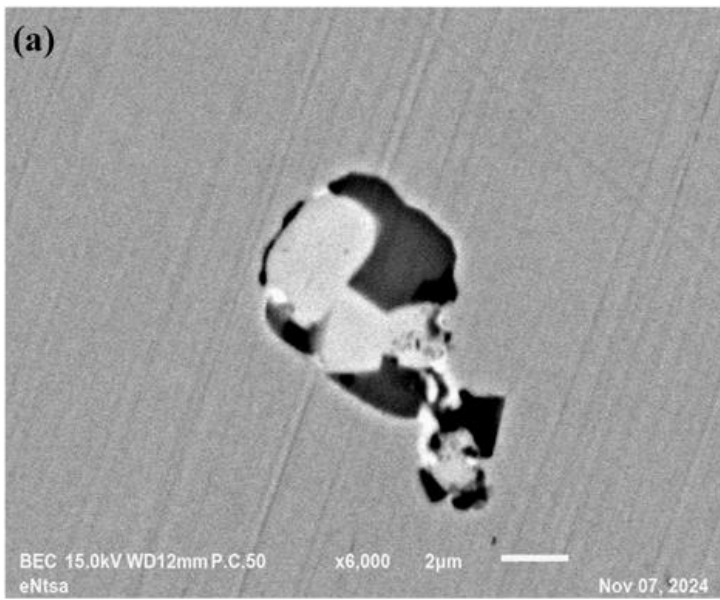


Figure 4.2: (a) SEM micrograph showing inclusions, and (b) EDS spectrum of (a) showing elemental composition of inclusion in unetched control sample

Meanwhile, the elemental composition of the inclusions in Figure 4.1b was further confirmed using SEM/EDS. The SEM and EDS analysis of the unetched control samples revealed the presence of manganese, sulphur, oxygen, silicon, phosphorus, and aluminium in the inclusions (Figure 4.2 a & b). These elements are the main components of MnS, Al₂O₃, and AlPO₄ inclusions in steels, particularly in cast components (Zhang & Thomas, 2002; Jung et al., 2008; Maciejewski, 2015; Zheng et al., 2015; Gorkusha et al., 2020). These inclusions within the material can act as stress raisers that could initiate failure, potentially affecting the drive tumbler's functional performance under operational conditions. This is the case for the oxide-type inclusions, and normally considered less so for MnS inclusions as they are of lower hardness (Maciejewski, 2015; Y. Song et al., 2024). However as shown in Figure 4.1a and Figure 4.2b, there appears to be a high level of MnS inclusions, which could also have a detrimental effect on fracture toughness of the drive tumbler material (Maciejewski, 2015; Y. Song et al., 2024). They may significantly reduce the fatigue resistance and overall service life, particularly in accelerating the initiation and propagation of cracks from the subsurface (inclusion regions) of the drive tumbler teeth when

subjected to a combination of sliding, cyclic and impact stresses (Stevens, 1995; Jung et al., 2008; Zheng et al., 2015 Gorkusha et al., 2020).

The optical micrograph of the sample etched with 3% nitric acid (Nital) is presented in Figure 4.3. The microstructure reveals a tempered martensitic microstructure and inherent defects such as inclusions from the manufacturing process as depicted in Figure 4.2 & Figure 4.3. A tempered martensitic microstructure indicates that the drive tumbler passes through a quenching and tempering heat treatment to achieve a balance of hardness and toughness. In its quenched form, martensite is extremely hard but inherently brittle. To reduce this brittleness, martensitic steels are generally tempered, a heat treatment that restores ductility and increases toughness while maintaining the hardness of the material (Bramfitt, 1998; Zhang et al., 2022). This also attests to the untransformed ferrite in the microstructure (Figure 4.3).

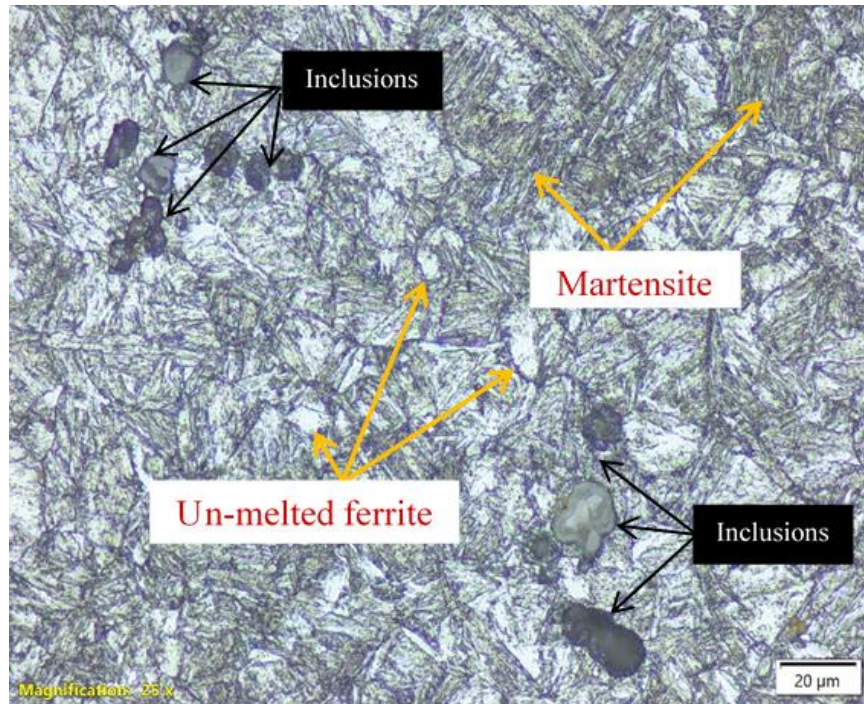


Figure 4.3: Optical Micrograph of etched cross-section of control sample.

4.1.1.2 X-ray diffraction analysis of undamaged drive tumbler teeth

Figure 4.4 shows the XRD pattern of the control sample (undamaged area of the drive tumbler teeth). The material showed the peaks conforming to BCC/BCT crystal structures, which is

ferrite/martensite phase accompanied with some minor retained austenite phase, i.e. FCC crystal structure. The presence of α -phase with diffraction peaks (110) at 44.47° , (200) at 65.06° and (210) at 82.38° is revealed, attributed to martensite (Abbaszadeh et al., 2010; Roy et al., 2024). This is validated by the study of Abbaszadeh et al., (2010) in which the martensite phase was detected on the (200) at $2\theta = 65.2^\circ$ and (211) plane at $2\theta = 82.5^\circ$. The similarity in peak positions supports the identification of the martensitic phase (Figure 4.3) in the present study. Roy et al., (2024) also reported diffracted peaks α' -(110) at $2\theta = 44.6^\circ$, α' -(200) at $2\theta = 65.14^\circ$ and α' -(211) at $2\theta = 82.22^\circ$ in an iron-based material as martensite. Furthermore, the presence of minor γ -phase with peaks (111) at 42.99° close to the α -phase with diffraction peaks (110) at 44.47° , and (200) 47.34° corresponds to retained austenite or untransformed ferrite in the microstructure. According to Baek et al., (2020) these phases are known to be present in a quenched and tempered steels. This is in affirmation of the tempered martensite microstructure in the drive tumbler teeth (Figure 4.3).

Retained austenite can improve impact toughness and delay crack propagation through its ability to transform into martensite under mechanical stress (transformation-induced plasticity, TRIP) (Abareshi et al., 2011). However, excessive retained austenite can reduce wear resistance due to its lower hardness compared to martensite (Abareshi et al., 2011; Liu et al., 2019). In the drive tumbler, the presence of minor γ -phase likely offered limited transformation toughening without significantly compromising wear resistance.

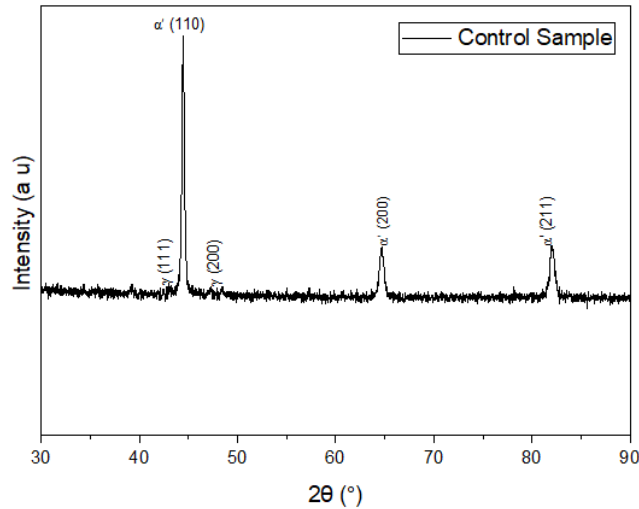


Figure 4.4: XRD pattern of control sample showing revealing tempered martensitic phase.

4.1.1.3 Evaluation of microhardness and mechanical properties of drive tumbler teeth (control sample), quartz, and crawler belt material

The mechanical properties and the microhardness of the control sample, crawler belt, and quartz are presented in Table 4.1, Figure 4.5, and Figure 4.6 respectively. These analyses were carried out to determine the suitability of the drive tumbler material with its interacting components to propel the mining equipment in the abrasion-prone terrain. According to Singh et al., (2014) and Röttger et al., (2015) quartz has a microhardness ranging from 1100 HV to 1200 HV. According to the OEM of the crawler belt in the machine, the crawler belt material (G30CrMoV6-4) (Yu et al., 2010; Bošnjak et al., 2013) was induction hardened (Walkson, n.d.) resulting in microhardness of 700 HV. As can be seen in Figure 4.5 & Figure 4.6., the average hardness of the drive tumbler material (control sample) is 353 HV which is lower than the crawler belt materials and quartz by approximately 50% and 71% respectively. Furthermore, variation in microhardness is observed in the control sample (Figure 4.5). This may be due to the non-uniform microstructure of the material due to the presence of tough ferrite, hard martensite and inherent defects in the drive tumbler materials, as depicted in Figure 4.1, Figure 4.2, and Figure 4.3.

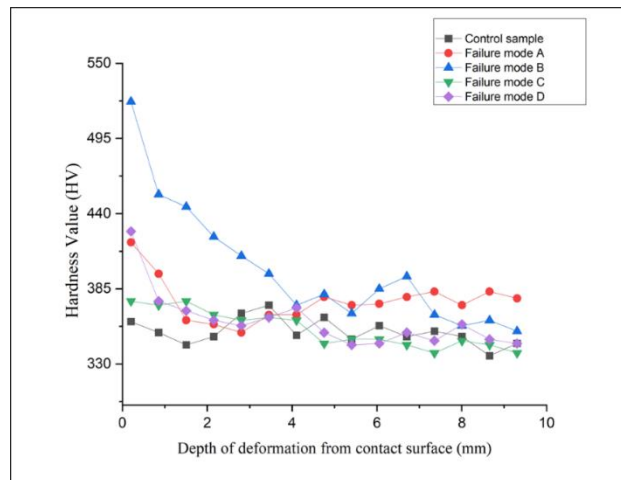


Figure 4.5: Microhardness profile of undamaged and damaged parts of the drive tumbler tooth.

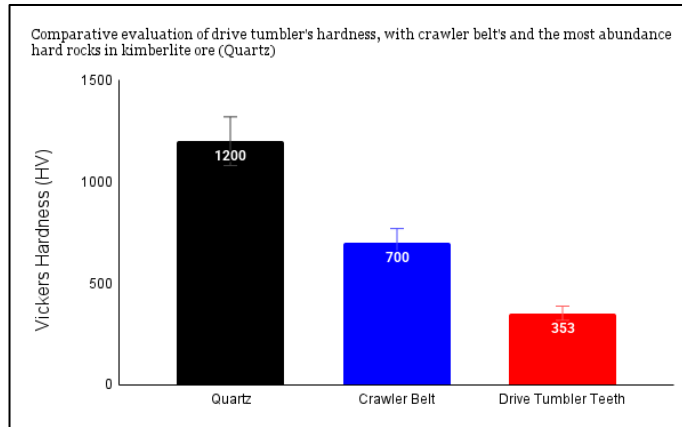


Figure 4.6: Comparative analysis of microhardness for undamaged drive tumbler teeth, crawler belt and abrasive mineral (quartz)

Table 4.1: Mechanical properties of Control Sample O (Undamaged part of the drive tumbler teeth), Quartz, and the mating material (Crawler belt)

Materials	Fatigue Strength (MPa)	Tensile strength (MPa)	Yield Strength (MPa)	Hardness (HV)	Elongation %	Elastic Modulus (GPa)
Drive tumbler teeth	650	1260	1120	353	6.8	190
Crawler Belt (Induction-hardened) (Yu et al., 2010; Bošnjak et al., 2013; Matmakefrom, 2020).	660	1130	1060	700		190
Quartz (Singh et al., 2014)	-	-	-	1161	-	-

Furthermore, the microhardness test provides a localised measurement of the drive tumbler material's resistance to plastic deformation, abrasive wear, and its behavior during work hardening. As shown in Figure 4.5, the microhardness of failure mode A-D as indicated in the red, blue, green and purple lines respectively, increased beyond the original microhardness of the drive tumbler (control sample, in the black line). This indicates that the drive tumbler is susceptible to plastic deformation, abrasion and work hardening. This strain hardening results from the accumulation of dislocations and possible mechanically induced martensitic transformation. While

work hardening can locally improve wear resistance, it may also increase brittleness at the surface, promoting crack initiation under cyclic loading and reducing overall fatigue life (Chong & Chidlow, 2016; Xu et al., 2018; Tressia et al., 2021; Leso et al., 2024).

The implication of these findings on the failure modes, particularly the mismatch in microhardness of drive tumbler teeth, crawler belt and abrasive minerals (quartz) observed in Figure 4.6 are further discussed in section 4.1.3.1.1, section 4.1.4.1 and section 4.1.4.2.

4.1.1.4 Chemical analysis of undamaged drive tumbler teeth

The chemical composition of the drive tumbler from the undamaged area presented in Table 4.2 reveals that it is made of low carbon low alloy steel with a carbon equivalent of 0.38, which is generally consistent with ASTM A148 grade 160-145 cast steel, with the exception of a slightly high molybdenum (Mo) content. This agrees with the findings in section 4.1.1.1 and Figure 4.1 suggesting that the drive tumbler is produced through a casting process. The material is enhanced by the addition of alloying elements such as manganese (Mn), chromium (Cr), molybdenum (Mo) and nickel (Ni) to improve its hardness, wear resistance, and toughness respectively. Mn improves mechanical strength and hardenability, but can contribute to the formation of soft and ductile MnS inclusions as shown in Figure 4.1 & Figure 4.2, particularly, when sulphur is present in the steel (Table 4.2) (Song et al., 2024). Although MnS inclusions contribute to the machinability of steel components, they can act as stress raisers under cyclic or impact loading conditions, promoting crack initiation and propagation, particularly in harsh mining environments where the drive tumbler teeth experience repeated sliding and impact loads (Maciejewski, 2015; Y. Song et al., 2024). This also attests to the presence of MnS inclusion in the control sample (Figure 4.2). Cr and Mo are added to low alloy steels to further improve hardenability, wear resistance and corrosion resistance (Xia et al., 2024). However, in the case of the drive tumbler teeth, their effect on corrosion resistance will be limited because of their low concentration in the material which is below 1% (Table 4.2). Ni contributes to strengthening and toughening of the ferrite phase in a low carbon low alloy steel (El-Bitar et al., 2011).

Table 4.2: Chemical composition by wt% of Drive Tumbler and Corresponding materials (ASTM A148 Grade 160-145 Cast, 2015)

Element	C	Mn	S	P	Si	Cr	Mo	Ni	Fe
Control sample	0.22	1.01	0.016	0.024	0.44	0.83	0.59	0.98	Bal
A148 Grade 160-145	0.20-0.27	1.0-1.2	≤0.060	≤0.050	≤0.60	0.70-0.90	0.45-0.55	0.80-1.0	Bal

The presence of chromium (Cr) promotes the formation of hard chromium carbides and oxides, which are generally beneficial for enhancing wear resistance. Nevertheless, if these carbides and oxides are unevenly distributed or become fragmented under frictional stress, they may detach and function as abrasive particles (Pourasiabi & Gates, 2022). This may significantly increase the susceptibility of the drive tumbler teeth contact surfaces to both abrasive and adhesive wear, particularly under severe operating conditions.

4.1.2 Analysis of Water Samples from the Diamond Mine using Ion Chromatography

The physico-chemical analysis of the water sample from the open-pit diamond mine is presented in Table 4.3 and Figure 4.7. The high conductivity (3310 $\mu\text{S}/\text{cm}$) and total dissolved salt (1640 mg/L) suggest a significant presence of dissolved ions, which can accelerate electrochemical corrosion processes (Fortes et al., 2020). The alkaline pH (8.3) indicates buffering capacity. However, it cannot neutralise the corrosive impact of aggressive ions such as sulphate and chloride that dominate the water chemistry (Rathnayake et al., 2021). Figure 4.7 represent the ion chromatogram of the water sample, confirming distinct peaks corresponding to sulphate, chloride, and nitrate with approximately 2423 ppm, 1973 ppm and 102 ppm respectively. This indicates that chloride and sulphate are present in abundance in the mine water. These ions are known to be highly corrosive to metals (Willison & Boyer, 2012; Peng et al., 2013). The high chloride content can induce pitting and crevice corrosion in steel components (Atkinson & Shi, 2003). Chloride ions often disrupt passive oxide films on metal surfaces, allowing corrosion attack on metallic component with limited chromium concentrations, which can compromise their mechanical performance under high stresses (Willison & Boyer, 2012; Peng et al., 2013). This finding establishes the corrosive nature of the diamond open-pit mine. Additionally, relationship between

environmental chemistry and microstructural susceptibility was factored into the interpretation of damage mechanisms (section 4.1.3.1.4 and 4.1.4.4)

Table 4.3: Mine water parameters from multi-parameter water analyzer H19811-5 and Ion Chromatography Dionex Aquion IC system

Parameters for Analysis	
Conductivity ($\mu\text{S}/\text{cm}$)	3310
pH	8.3
Total dissolved salts (mg/L)	1640
Contaminants present (ppm)	
Sulfate	2422.8556
Chloride	1972.5298
Nitrate	101.826
Phosphate	-
Fluoride	-

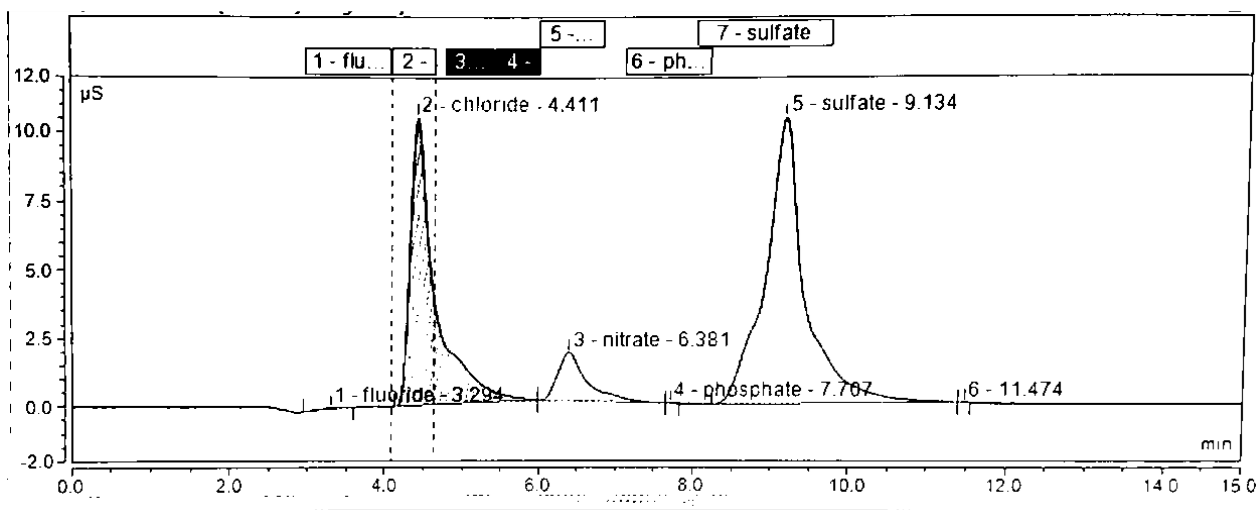


Figure 4.7: Ion chromatography plot for water from the mine

4.1.3 Macroscopic analysis for establishing failure modes in damaged drive tumbler teeth

To achieve the stated objective of this study, a comprehensive failure analysis of the failed drive tumbler is essential to identify the underlying causes responsible for its premature failure. This requires a multi-scale analytical approach, beginning with macroscopic examinations to classify the failure modes and microstructural fractographic analysis to elucidate the specific failure

mechanisms that contribute to the identified failure modes. This section provides the macroscopic analysis of the failed drive tumbler teeth to identify its failure modes.

4.1.3.1 Identification of failure modes of the Drive Tumbler teeth

From the macroscopic examination carried out on the as-received damaged samples of the drive tumbler teeth, four (4) failure modes were identified. These include severe wear at the front face of the tooth (failure mode A), adhesive wear one side of the tooth edges of the tumbler teeth (failure mode B), plastic deformation with cracks at top edges of the tooth (failure mode C), and fracture at the top edges of the tooth (failure mode D) (Figure 4.8), and are represented as failure modes A-D respectively (Table 4.4). However, the part of the as-received sample that does not have any interaction with the contact surfaces of the machine, particularly, the crawler belt remains undamaged and is classified as undamaged area (control sample). The macroscopic features and causative factors of the identified failure modes are summarised in Table 4.4.

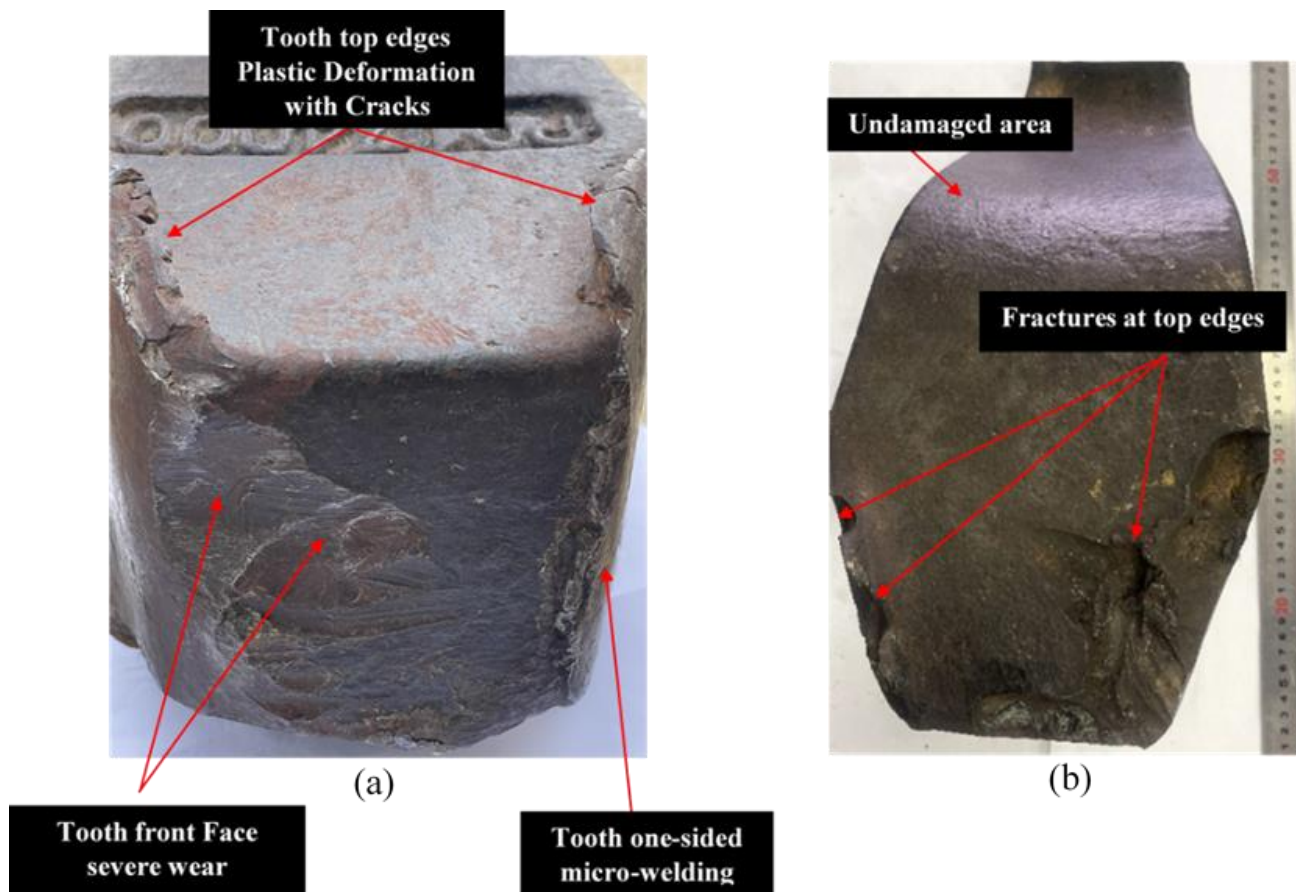
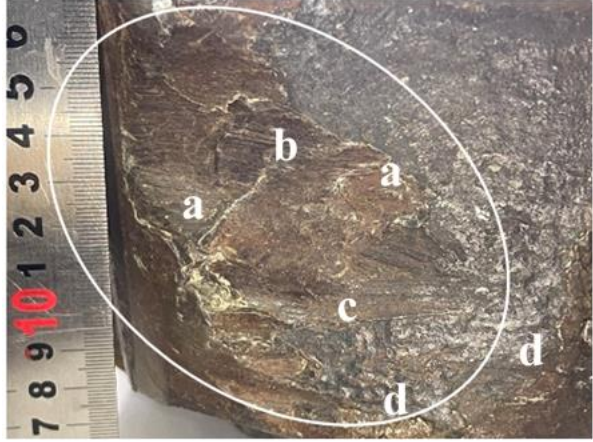


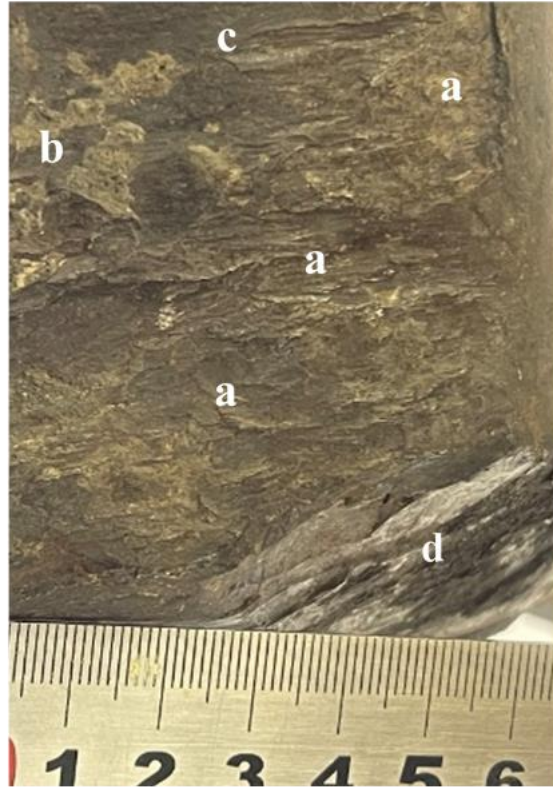
Figure 4.8: (a), and (b) Identification of failure modes from as receive damaged drive tumbler teeth from the mine.

It can be seen in Figure 4.8 a & b, that the damaged teeth were located predominantly on the top edges and contact surfaces of the drive tumbler, where there is direct metal-to-metal contact between the drive tumbler teeth and the crawler belt (Figure 1.2 & Figure 1.5a). This region corresponds to the zone of highest load concentration in the drive tumbler's operating cycle, where the shovel loader engages with the track and crawler belt links during forward motion and braking under load. The teeth were subjected to repeated high contact stresses due to both the initial engagement sliding-impact and the steady-state pushing force required to advance the crawler belt. The load distribution pattern of the tumbler indicates that the leading teeth during forward travel experienced the greatest force, causing the severe damages as shown in Figure 4.8 a & b.

Table 4.4: Summary of macroscopic evaluation of damaged drive tumbler teeth.

Failure Modes	Pictorial view	Features	Causative factors	Reference
A (Severe wear at the tooth front face)		(a) Material removal from the tooth's front face. (b) Severe scratches on worn surface. (c) Grooves on worn surface. (d) Surface roughness on tooth surface.	(a) Due to the direct metal-metal contact between the drive tumbler and crawler belt and insufficient surface hardness of the drive tumbler to withstand sliding-impact with crawler belt. (b), (c) Continuous sliding contact in the presence of hard mineral particles or wear debris entrapped between the drive tumbler teeth and the crawler belt. (d) Poor lubrication which results in surface irregularities, generating a rough and uneven surface texture.	(Alpas et al., 2018)

B (Adhesive wear at one-sided edge of the tumbler teeth)



(a) Scuffing on the tooth's side edge.
 (b) Oxide layer
 (c) Groove on scuffed surface.
 (d) Chipping of material from drive tumbler tooth surface.

(a) Caused by high friction and localized welding due to inadequate lubrication, and high contact pressure between the tumbler teeth and crawler belt. It occurs when the surface adheres to the crawler belt surface and peels off during sliding.
 (b) Due to tribo-oxidation from repeated frictional heating.
 (c) Caused by the sliding of harder abrasive particles in the kimberlite ore which plow into the scuffed surface.
 (d) Due to repeated stress cycles and adhesion-induced crack initiation.

(Rich et al., 2023; Xu et al., 2023)

(C) Plastic deformation with cracks at tooth top edges



- (a) Edge Warping.
- (b) Cracks on deformed edges.
- (c) Surface wear on the deformed edge.
- (d) Rust on worn surface.

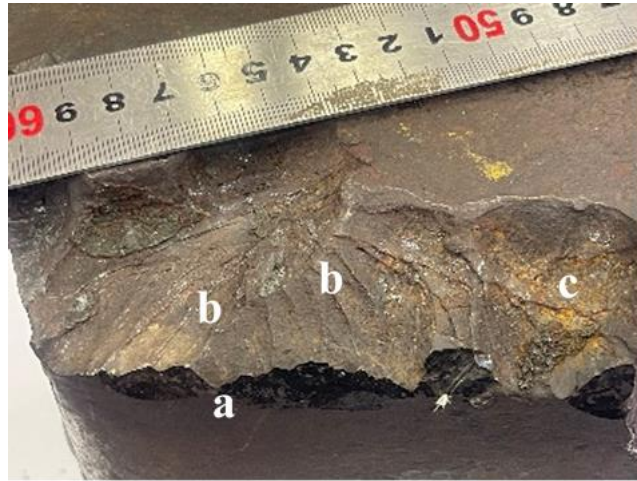
(a), (c) This is due to the combined effects of localized shear stress at the edges of the tooth, repeated impact and sliding with crawler belt and insufficient surface hardness to withstand the sliding-impact from crawler belt.

(a), (b) Due to small fillet radii at the drive tumbler teeth edges, making it high stress concentration area, where cracks are easily initiated and propagated.

(d) The surface breakdown of protective oxide layers due to surface wear, exposed the drive tumbler materials to the chlorine-rich water/moisture in the open pit mine, leading to oxidation of the steel.

(Zhao et al., 2019; Myszkowski et al., 2023; Onyono et al., 2025),

(D) Fracture at the tooth top edge



(a) Crack initiation at the tooth edge.

(b) Crack propagation and beach marks away from the edge.

(c) Rust on fractured surface.

(a) Due to sharp edges and pre-existing cracks from failure mode C, that act as stress risers, where cracks preferentially initiate.

(b) Cyclic loading (repeated impact and sliding) leads to crack growth, with beach marks forming as the initiated crack progresses in discrete steps over time. These changes in loading conditions result in periodic crack growth, leaving visible beach marks.

(c) The exposure of the freshly fractured surface to the mine's chlorine-rich water, combined with oxygen from the environment, facilitates an accelerated oxidation process, resulting in the rust formation

(Hein et al., 2017; Papadopolou et al., 2019; Jiao et al., 2020; Zhang et al., 2020; Luo et al., 2023).

4.1.3.1.1 Macroscopic analysis of failure mode A

The macro-morphology of failure mode A is presented in Figure 4.9. The severe wear is characterised by material loss from the tooth's front face, severe scratches, grooves on the worn surface and roughness on the tooth surface (Figure 4.9). This is due to the continuous interaction between the crawler belt and the drive tumbler during operation. Although this interaction is crucial for torque transmission, the low surface hardness of the drive tumbler teeth compared to the crawler belt (Table 4.1, Figure 4.6), promotes severe wear revealed as delamination and spalling (Figure 4.9b) on the surface (Resendiz-Calderon et al., 2020). This wear is compounded by the presence of hard abrasive particles, such as quartz, which are harder than the steel material (Table 4.1, Figure 4.6), causing several scratches and grooves on the already worn surface (Figure 4.9b). This contributed to the surface irregularities, generating a rough and uneven surface texture on the surface of the drive tumbler teeth (Figure 4.9b). According to Mouritz and Hutchings 1993, under high contact stress, the rate at which wear occurs in mechanical components increases significantly when the surface hardness is low (Clayton & Danks, 1990). This effect is particularly pronounced when two metallic components are directly engaged with each other, leading to excessive wear when the hardness ratio between the interacting surfaces exceeds one (1) (Mouritz & Hutchings, 1993).

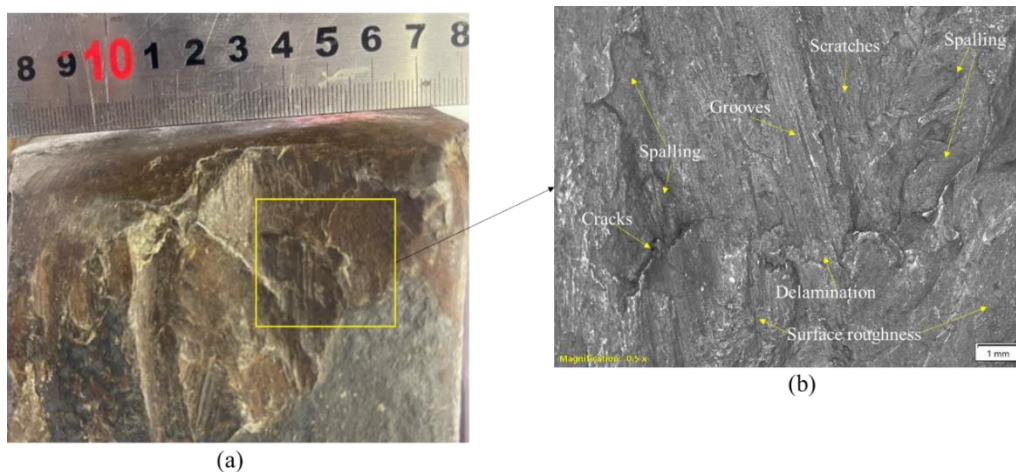


Figure 4.9: (a) Visual Macro morphology of failure mode A, (b) Stereo macrograph of (a)

4.1.3.1.2 Macroscopic analysis of failure mode B

The adhesive wear failure observed on the one side edge of the drive tumbler teeth resulted from high sliding contact with the crawler belt. Moreso, when the drive tumbler is not properly lubricated or there is a breakdown in the applied lubricant, high friction between the contact surfaces occurs during sliding contact, which can result in scuffing as shown in Table 4.4 and Figure 4.10. Kaczor & Machno, (2021) reported that scuffing is a type of wear that occurs on the surface of components operated in sliding contact under poor lubrication condition. Under continuous sliding in the absence of lubricants, frictional heating occurs at the drive tumbler–crawler belt interface, which generates the observable oxidised layer in Figure 4.10. This phenomenon can be attributed to tribo-oxidation from the repeated frictional heating. Stott et al., (1985) described three models of oxide formation influenced by sliding and environmental conditions. Initially, high local temperatures cause oxidation of contact surfaces, asperities and wear debris. The sliding motion then removes the oxide layer, exposing fresh metal for continued oxidation.

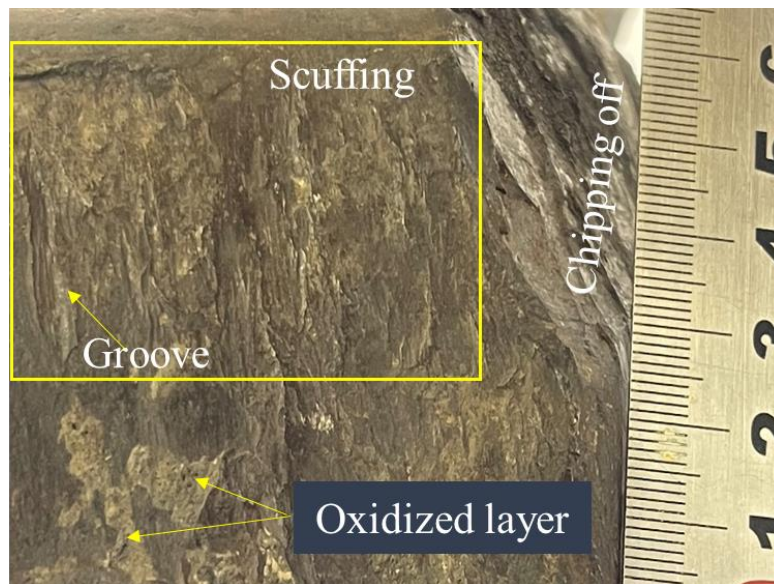


Figure 4.10: Macroscopic View of failure mode B

The groove feature observed on scuffed surface in Figure 4.10 further affirms the presence of hard third-body particles, such as quartz from the kimberlite ore in the mine, embedded between the contact surface. This is corroborated by the study of Nkgakile, (2023) in which it was reported that the kimberlite ore in a diamond mine consists of predominantly of about 30% country rock clasts

of quartzitic shale, which is about 1200 HV (Singh et al., 2014; Röttger et al., 2015). Furthermore, chipping (Figure 4.10) in the drive tumbler teeth is primarily due to a fatigue-driven failure, which is influenced by prior adhesion, oxidation, and abrasive interactions. Repetitive sliding-impact induces crack initiation and propagation, eventually leading to material detachment from the surface of drive tumbler teeth.

4.1.3.1.3 Macroscopic analysis of failure mode C

The warping observed at the edges of the drive tumbler is seen to alter the original geometry of the drive tumbler teeth (Figure 4.11a). This suggests plastic deformation due to extensive impact loads imposed by repeated engagement with the crawler belt. This also affirms to the fact that the drive tumbler teeth have a low surface hardness of 353 HV compared to the crawler belt which has a hardness of 700 HV, as established in section 3.1.1. This agrees with the work of Myszka et al., (2023) wherein it was reported that deformation of a low power transmission gear is influenced by the dynamic force interaction exerted by its mating parts. An observation of the sharp edges with small fillet radius in the as purchased drive tumbler (Figure 4.11b) revealed possible design imperfections that can contribute to the drive tumbler premature failure which are linked to the plastic deformation. The sharp edges with a small fillet radius in the as purchased (Figure 4.11b) show that the drive tumbler tooth edges will make contact with the crawler belt at a point or along a narrow line, instead of having a broad surface-to-surface contact (William D. Callister, 1970).

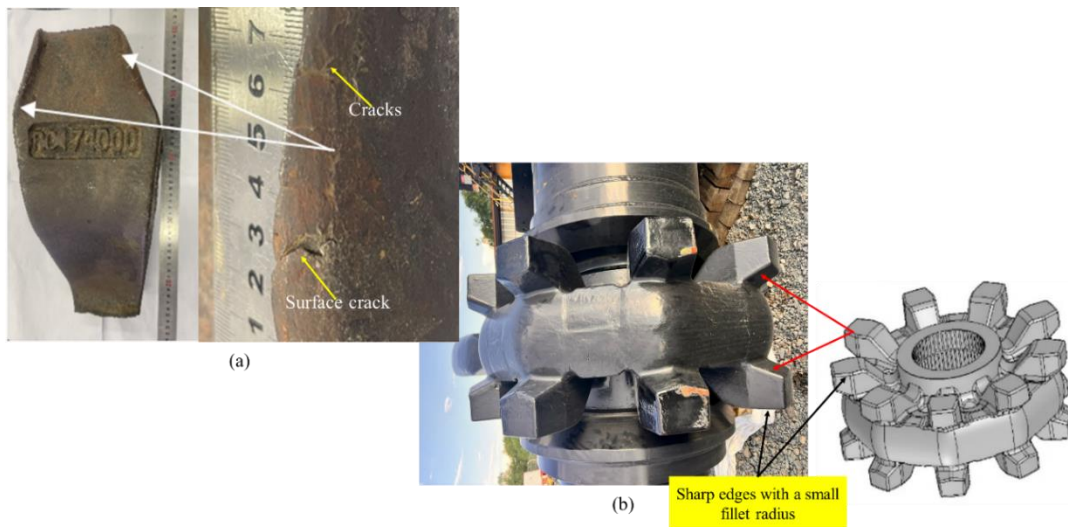


Figure 4.11: (a) Macro representation of failure mode C, and (b) As-purchased drive tumbler revealing sharp edges

It is established that mechanical parts, with edges that have insufficient fillet radius or curvature, to evenly distribute the stress exerted during operation, are more vulnerable to bending forces and high stress concentration (Onyono et al., 2025). This is due to the high contact pressure exerted by the contacting surfaces at that point, making it a highly stressed region (Ike, 2003; Chong & Chidlow, 2016). This is in line with the work of Zhao et al., (2019). It was established that fatigue failure in a drive shaft to improper design, from a small fillet radius at the shaft's spline, resulting in high stress at the root fillet. In addition, due to the combined effect of insufficient surface hardness to resist repeated sliding-impact stresses and high stress concentration, cyclic loading resulted in cracks at the deformed edges, which will gradually grew deeper into the drive tumbler material (Figure 4.11a).

4.1.3.1.4 Macroscopic analysis of failure Mode D

The fracture at the edges of the drive tumbler teeth is seen to occur near the area where failure mode C had occurred. This failure mode resulted from cyclic loading (repeated sliding and impact against the crawler belt) during operation, where a crack is initiated and progressively grow to leave beach marks on fractured surface as seen in the region marked a1, and an eventual break-away of the material at point a2 (Figure 4.12) (Jiao et al., 2020; Zhang et al., 2020; Luo et al., 2023).

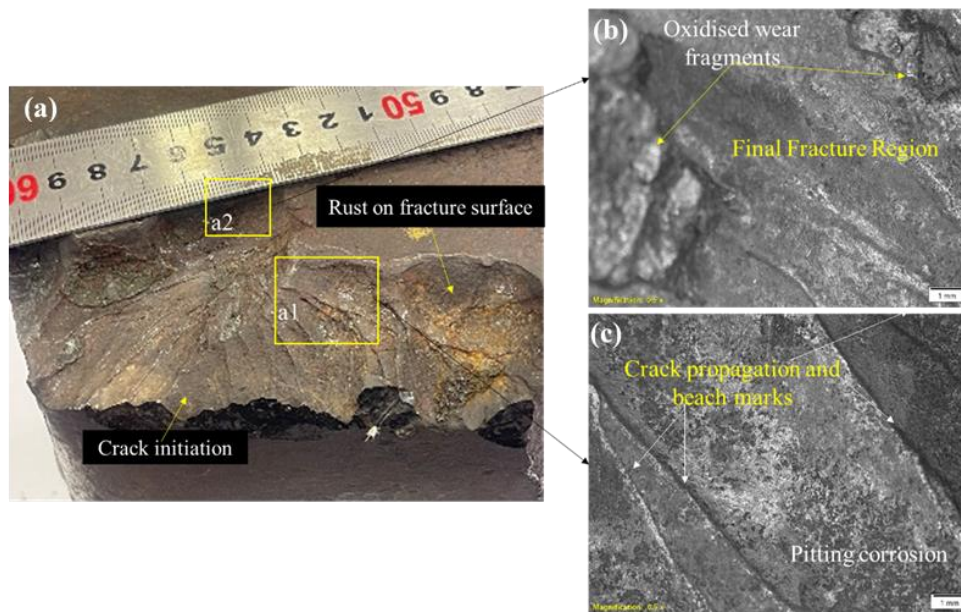


Figure 4.12: (a) Visual macro morphology of failure mode D revealing fatigue fracture characteristics, (b) stereo macrograph of point a2, and (c) stereo macrograph of point a2

The formation of rust on the fracture surface (Figure 4.12a), resulted from oxidation and chemical reactions induced by prolonged exposure to moisture that led to pitting corrosion at point a1 (Figure 4.12c). Water used as lubricant during drilling operations, along with seepage from tailing dams, accumulates within the open-pit mine. This water is contaminated with chlorine, nitrogen, and sulphur creating a highly corrosive environment (section 4.1.2) that can affect the fracture surface. The operation of the drive tumbler during excavation in an open-pit mine where contaminated water is present allows it to experience continuous wet-dry cycles that enhances its oxidation and corrosion (Willison & Boyer, 2012; Peng et al., 2013).

4.1.4 Microscopic analysis of failure mechanisms observed in failure mode A-D of the damaged tumbler drive teeth via optical micrographs and fractographs

This section provides a detailed microscopic analysis of the damaged samples. Optical microscopy and SEM were used to examine the failed surfaces and their cross-sections. This was conducted to understand and establish the failure mechanisms in failure mode A-D.

4.1.4.1 Mechanism of occurrence of failure mode A; via OM and SEM/EDS

Figure 4.13 represents the morphology of failure mode A as observed using a SEM. The appearance of surface cracks (Figure 4.13 a-d), spalling (Figure 4.13c), pits (Figure 4.13b-d), grooves (Figure 4.13b), micro ploughing (Figure 4.13a & b), oxidation (Figure 4.13b), abrasion marks, adhesion and delamination (Figure 4.13d), suggest a combination of fatigue-induced abrasive wear, and adhesive wear of the drive tumbler caused by metal-metal sliding contact between the drive tumbler teeth and crawler belt. The pits (Figure 4.13b-d) are small depressions or craters on the surface caused by localized material removal (Akintunde et al., 2023; Lindsay et al., 2023). They are formed due to the entrapped abrasive particles in the mine and exposure to contaminated moisture in the mine during sliding contact and impact between the surface of the drive tumbler tooth and the crawler belt. Additionally, micro-ploughing and minor surface grooves, as seen in Figure 4.13b, can be attributed to the abrasive action of hard rocks such as quartz found within the kimberlite ore. These minerals, which are harder than the drive tumbler teeth and wear debris generated during operation, lead to three-body abrasive wear mechanisms. Three-body abrasion is typically divided into sliding and rolling abrasion. Sliding abrasion

characterised by the formation of ploughing, scratches and grooves parallel to the abrasion direction (Kyekyere et al., 2024), resulting from the sliding of hard abrasive particles on the surface, while in rolling abrasion, the particles roll over the surface (Gheisari & Polycarpou, 2018; Resendiz-Calderon et al., 2020; de Paula et al., 2023). Sliding abrasion occurs when the third-body particle or interacting surface is harder than the contacting surface (Resendiz-Calderon et al., 2020; de Paula et al., 2023; Kyekyere et al., 2024).

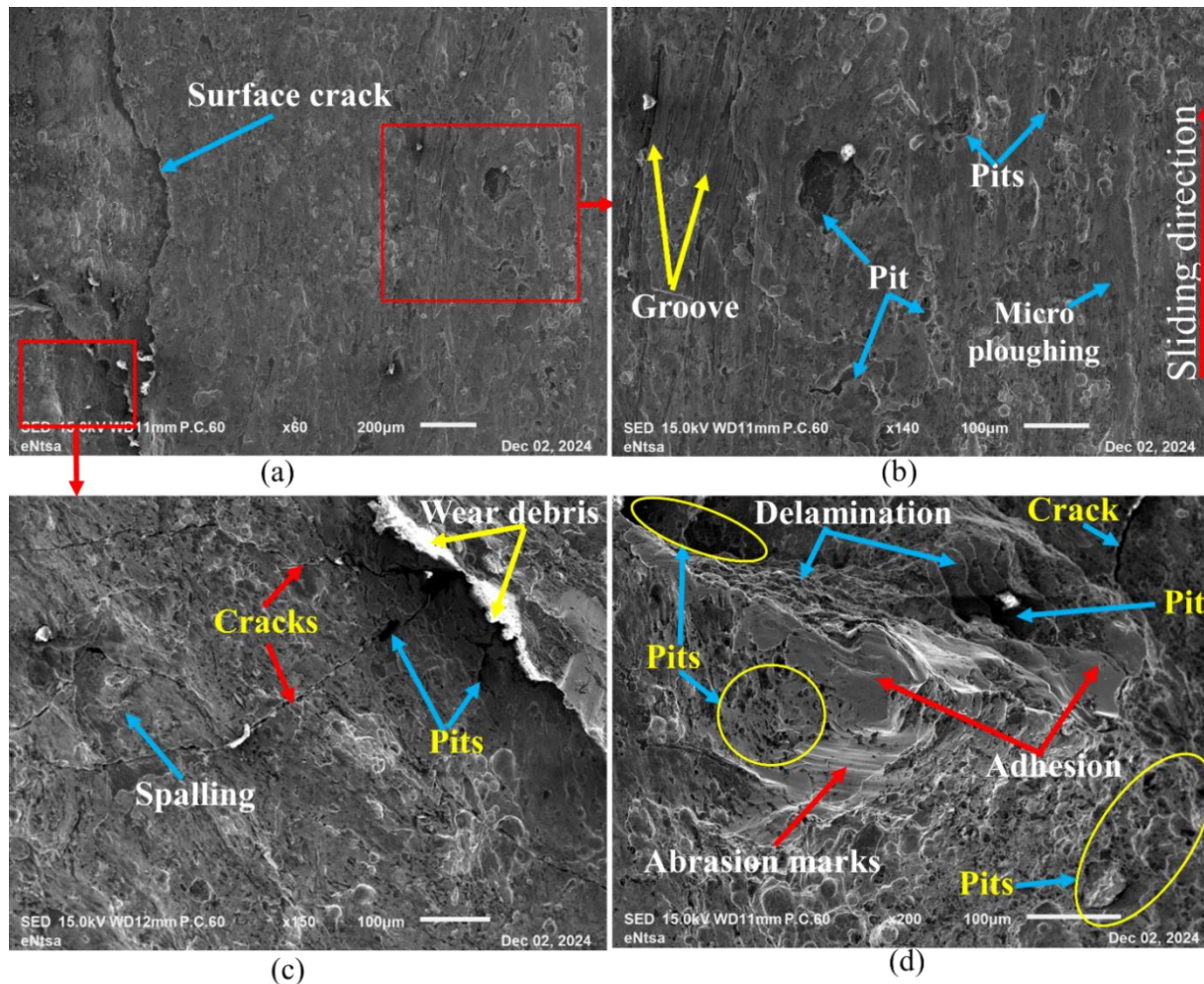


Figure 4.13: SEM micrograph of failure mode A showing abrasive, adhesive and fatigue wear mechanisms (a) worn surface (b) magnified portion of (a), (c) magnified portion of (a), (d) worn surface.

Since the hardness of the crawler belt and quartz is relatively higher than the hardness of the drive tumbler surface (Table 4.1, Figure 4.6), the high contact pressure between them causes grain pull in layers, which manifests as a delaminated surface, spalling, grooves, ploughing, surface cracks

and abrasion marks (Figure 4.13c & d) (Gheisari & Polycarpou, 2018). The continuous sliding and impact result in a high degree of frictional heating and also play a significant role in adhesion in the form of micro-welding (Figure 4.13d) (Xu et al., 2023). Under frictional heat condition, the available lubricant on the drive tumbler teeth surface is decomposes and oxidises, causing a reduction in the lubricating ability. According to Xu et al., (2023), adhesion, which is also known as cold or micro-welding occurs under conditions of lack of lubrication between contacting surfaces and is associated with the breakdown of the lubricating oil films. Figure 4.14 depicts the EDS spectrum of the worn surface of Figure 4.13b, revealing a high carbon from kimberlite and oxygen in the pits, evidencing the formation of oxides on the drive tumbler surface (Stott et al., 1985). The presence of calcium, copper, and chlorine in the pits on damaged surfaces as confirmed through EDS analysis is an indication of contamination by ore deposits from kimberlite and moisture in the diamond mine. This phenomenon may contribute to the premature failure of the drive tumbler teeth in the diamond mine.

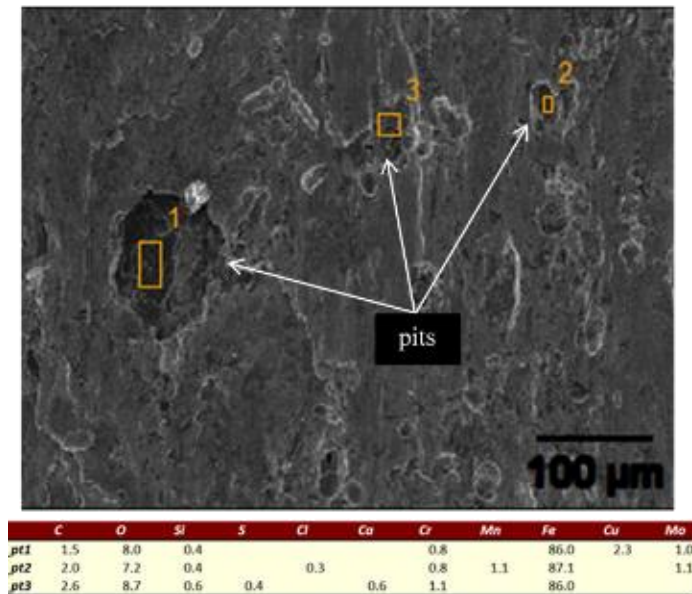


Figure 4.14: EDS spectrum of Figure 4.13b (failure mode A).

The optical micrograph of the cross-section of the damaged surface (failure modes A) revealed extensive plastic deformation of about 2.10 mm depth in the microstructure (Figure 4.15a). In Figure 4.17b, white etch cracking (WEC) initiating from inclusions already present in the drive tumbler material (Figure 4.1, Figure 4.2, Figure 4.3) and spalling are identified near the damaged

surface of the drive tumbler teeth. The WEC is often formed due to localised heating and rapid cooling during severe mechanical contact, such as sliding and frictional contact under cyclic loading and starved lubrication (Gould et al., 2019; Abdullah et al., 2020; López-Uruñuela et al., 2021). This result agrees with the works of Gould et al. (2017a) and (Gould et al., 2017b) who demonstrated that WECs are more likely to initiate at the inclusions region consisting of a combination of manganese sulphide and aluminium oxide, which can also be attested by the presence of these defects in the control sample (Figure 4.2) and may have contributed to the formation of WECs and the initiation of crack as shown in Figure 4.15.

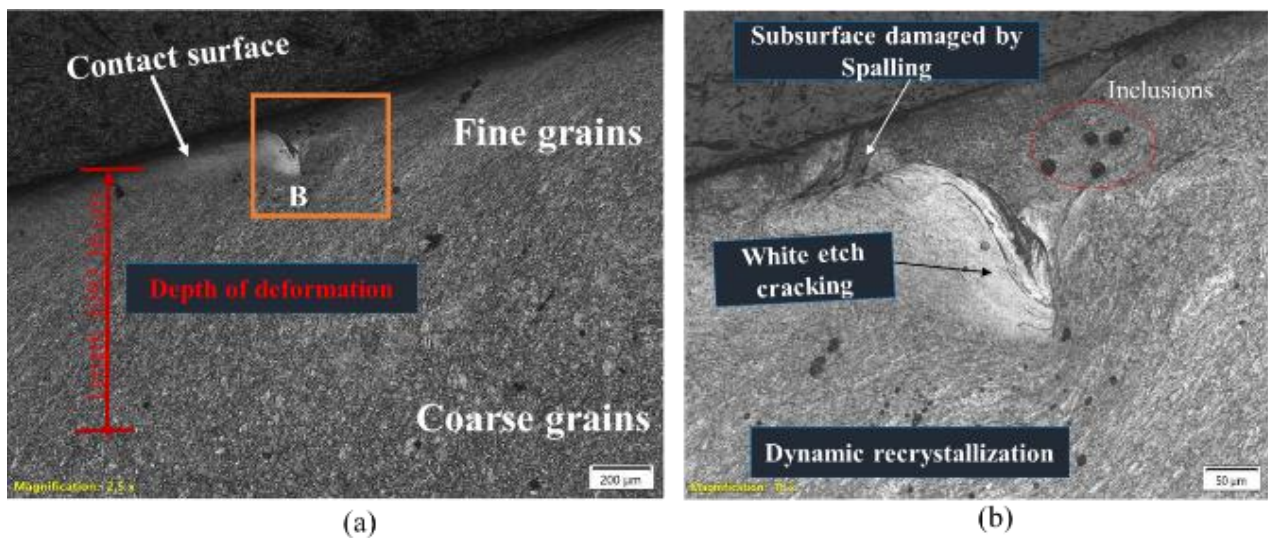


Figure 4.15: (a) Optical micrograph of the cross-section of failure mode A near damaged surface, (b) Optical micrograph of point B in (a) at a higher magnification.

In addition, according to Bhattacharyya et al., (2014) and Fu et al., (2017), the formation of white etching layers (WEL) and white etching cracks (WEC) is linked to the subsequent softening of the subsurface zone subjected to rolling contact fatigue (RCF) stresses.

Furthermore, the sliding friction at the contact surface between the drive tumbler teeth and the crawler belt during continuous rotation can cause the sub-surface layer to reach high temperatures due to thermal stress and makes it susceptible to surface contact fatigue failure. Boucly et al., (2005) demonstrated via thermo-elastic-plastic analysis, that the heat generated during rolling-sliding contact in metallic surfaces not only reduces the material's resistance to critical Hertzian pressure but also significantly impacts the stress distribution within the material, both during and

after loading. It can be seen in Figure 4.15a & b that dynamic recrystallisation of the microstructure that leads to grain refinement occurs. Fine grains typically form in regions undergoing dynamic recrystallisation or severe plastic strain (Figure 4.15a), indicating that the drive tumbler material has been heavily work hardened near the surface due to operational stresses (Chong & Chidlow, 2016; Xu et al., 2018; Tressia et al., 2021). This results in the high microhardness of the damaged surface (Figure 4.5). The microhardness of failure mode A increases from the contact surface with a microhardness value of 419 HV, which is 18.7% higher than that of the drive tumbler materials (Figure 4.5). It is worth mentioning that this surface hardness due to work hardening cannot still withstand the surface hardness of the crawler belt of 700 HV and quartz present in the kimberlite ore of about 1100 HV (Figure 4.6). Hence, failure is still bound to occur. Because of this, the abrasive wear resistant capacity and the rolling-sliding contact fatigue life of the drive tumbler teeth are compromised (Boucly et al., 2005), which resulted in the fatigue-induced abrasive wear mechanisms observed on the surfaces of the drive tumbler teeth (Figure 4.13) (Leso et al., 2024).

4.1.4.2 Mechanism of occurrence of failure mode B via OM and SEM/EDS

The SEM/EDS morphology of failure mode B is presented in Figure 4.16. The SEM analysis revealed pits, micro-ploughing, shallow groove, cracks, spalling and oxidation as primary failure mechanisms (Figure 4.16a). Cyclic loading and repeated sliding under starved lubrication improve the accumulation of stress on the drive tumbler teeth surface, resulting in the occurrence of a deep crack (Figure 4.16b). During continuous usage of the machine, the cracks develop into pits (Figure 4.16c) and material detachment from drive tumbler surface, which later occur as spalling (Figure 4.16a & b). These also attest to metal-metal contact of the drive tumbler with the crawler belt due to poor lubrication reported in section 4.1.3.1.1 and 4.1.4.1.

Figure 4.17 revealed the major elemental composition in the damaged surface of the drive tumbler teeth with some deviations from its fundamental material composition in Table 4.2. The presence of potassium, aluminium, calcium, magnesium and an increase in silicon, as revealed by the EDS spectra in Figure 4.17 establish interaction of the kimberlite ore particles and intermixing with the surface of the drive tumbler teeth. These elements are the main components in the formation of oxides such as CaO, SiO₂, MgO, Al₂O₃, and K₂O attesting to the increase in oxygen content (Figure 4.17). This finding is corroborated by the study of Nkgakile, (2023), who established the presence

of these oxides in the mineralogy of the kimberlite in a diamond mine. This phenomenon can contribute to premature failure of the drive tumbler teeth. This is in agreement with Akintunde et al., (2023) who established that these oxides resulted in weaker mechanical properties, reduced performance, and increased vulnerability to abrasive and adhesive wear of components in mining machineries.

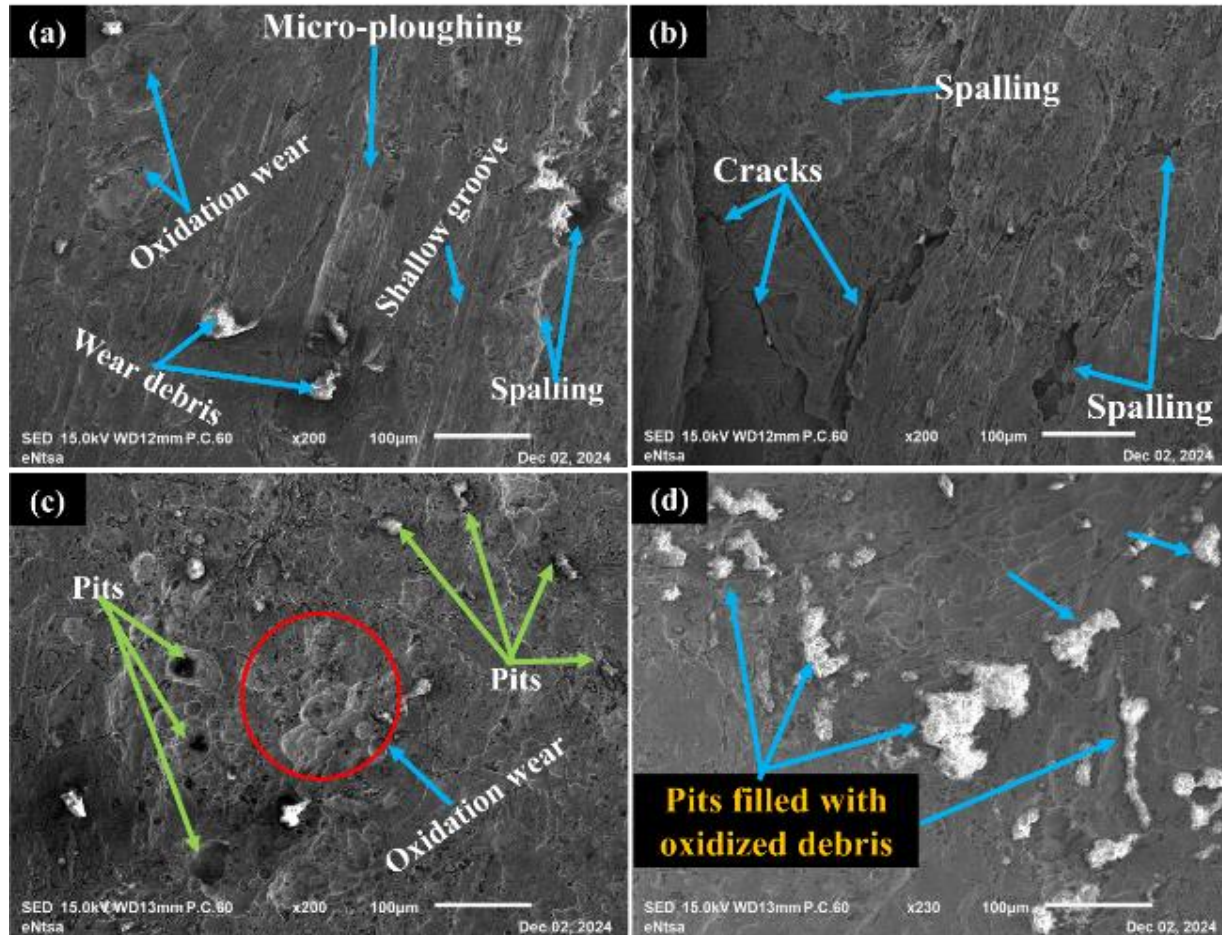


Figure 4.16: (a), (b), (c), and (d) SEM micrographs of failure mode B representing the worn surface at different locations of damaged surface and magnification.

The EDS spectrum in Figure 4.17 further reveals a certain amount of chlorine on the damaged surface of the drive tumbler teeth that can pose a risk of corrosion pitting and oxidation wear on the drive tumbler teeth surface (Figure 4.16 a & c) (Tan et al., 2021; Liu et al., 2022). Furthermore, the interaction of hard abrasive particles from the kimberlite ore further ploughed into the adhesive-worn surface, generating micro-ploughing and shallow grooves. Consequently, the

failure mechanism of failure mode B is thus described as adhesive wear transitioning into an adhesive-abrasive-fatigue wear mode. This is also in line with the work of Sun et al., (2019) where a mixed wear mode resulted in surface fatigue failure of a 40Mn2 sprocket wheel in a crawler bulldozer walking system.

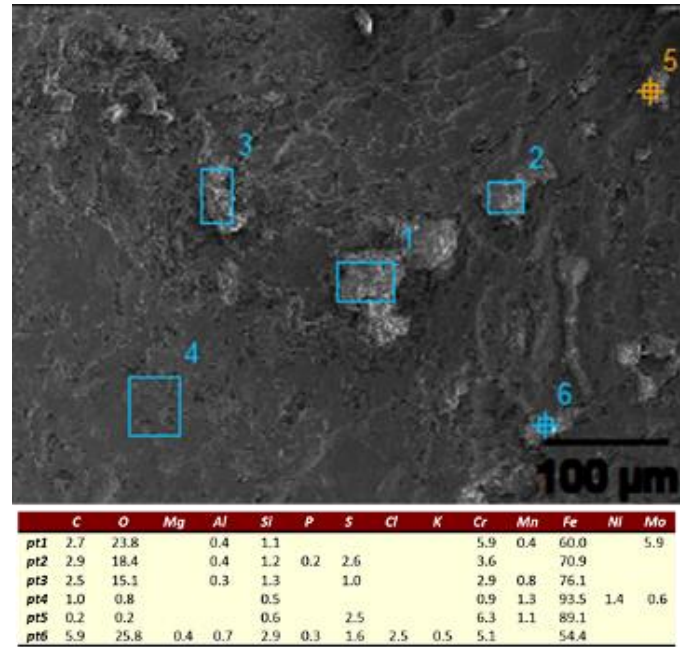


Figure 4.17: EDS spectrum of Figure 4.16d (failure mode B)

Additionally, tribo-oxidation effects were confirmed through EDS composition analysis (Figure 4.17), where an increase in oxygen (O), chromium (Cr), silicon (Si), on the worn surface indicates the formation of hard oxide compounds with the drive tumbler base material, due to the subsequent material detachment and wear debris from the surface. This may be attributed to the strong tendency of Cr to form hard carbides and oxides phases (section 4.1.1.4, Table 4.2) (Pourasiabi & Gates, 2022), as confirmed by the increased content of chromium, carbon and oxygen through the EDS spectrum (Figure 4.17). This oxide layer is formed due to thermally activated oxidation, driven by frictional heating (Boucly et al., 2005). Furthermore, the wear process intensifies as oxidised particles, usually harder than the parent metal, act as abrasives against the surface which can also exacerbate wear through micro-ploughing mechanisms (Figure 4.16a) (Pourasiabi & Gates, 2022). This phenomenon led to the microstructural evolution of the sub-surface layer from tempered martensitic to martensitic structure, the white etch layer (WEL), and the oxidised layer

(Figure 4.18b & d) observed below the damaged surface (Bhattacharyya et al., 2014; Gould et al., 2019; Abdullah et al., 2020; López-Uruñuela et al., 2021). These were revealed by optical microscope after grinding and etching the cross-section of failed surface. This agrees with the failure mechanism observed in failure mode A (section 4.1.4.1). To understand the relationship between the failure mechanisms between failure mode A & B, the depth of deformation and the contributing factors in failure mode B, the result was compared with failure mode A.

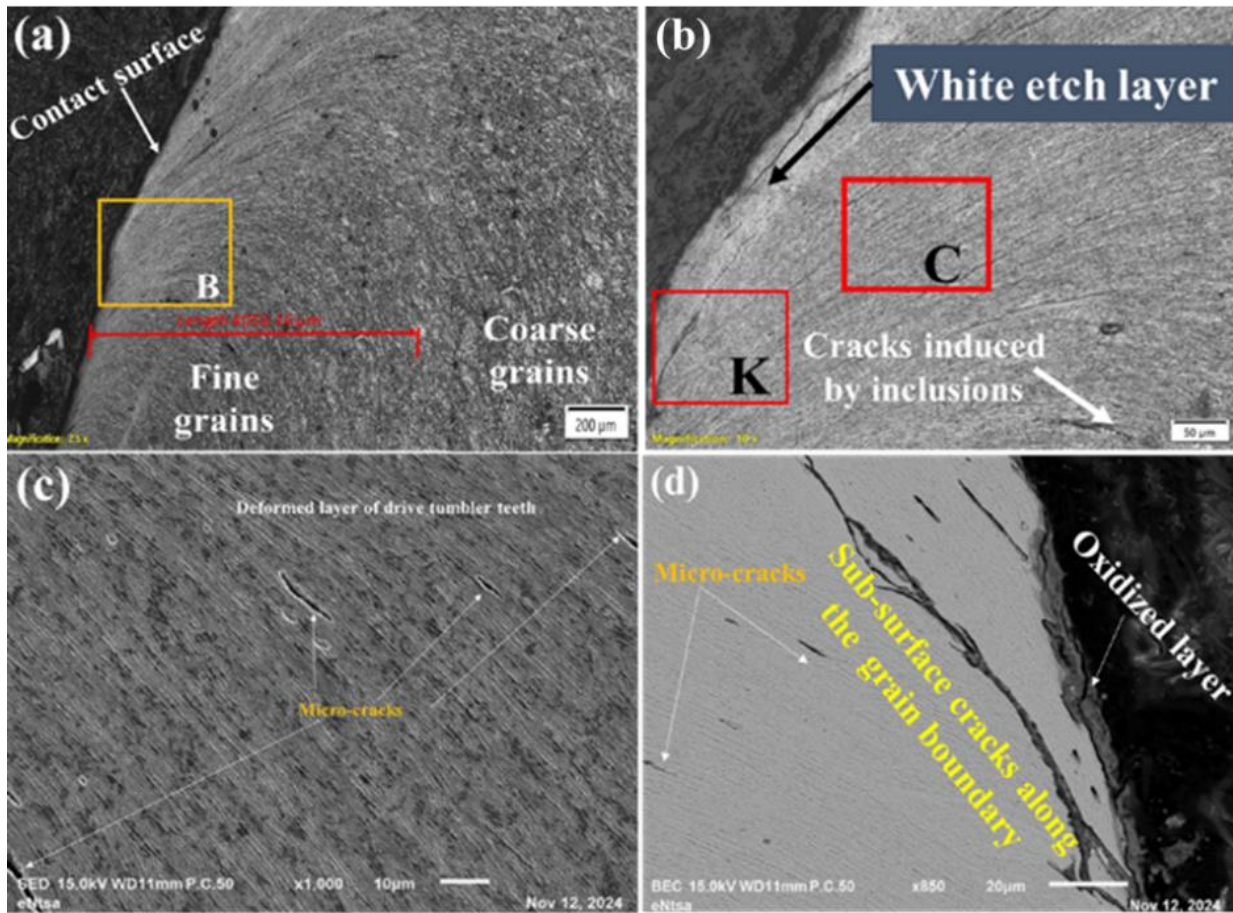


Figure 4.18: (a) Optical micrograph of the cross-section of failure mode B near the damaged surface, (b) optical micrograph of point B in (a) at higher magnification, (c) SEM micrograph of point C in (b), and (d) SEM micrograph of point K in (b).

Similar to failure mode A, recrystallisation of the microstructure and martensitic transformation occur in failure mode B, where both failure modes experienced significant plastic deformation. However, with varying deformation depth (Figure 4.15a, Figure 4.18a), and failure mode B having

a higher deformation depth of 4.5 mm characterized by fine grains. This attests to the significant increase in its microhardness from the contact surface of the drive tumbler teeth. The microhardness increased by 48%, from 353 HV of the control sample to 522 HV due to the work hardening effect and grain refinement, having a 25% increase in the microhardness compared to failure mode A (Figure 4.5). This result can be attributed to the misalignment of the undercarriage crawler frame. When the crawler belt is not properly tensioned, it becomes too loose during operation due to vibration and causes misalignment between the contacting surfaces (valuetrackparts, 2018). As a result, the shear stress is more concentrated on the side edge (failure mode B) of the drive tumbler teeth (valuetrackparts, 2018). Therefore, sliding and impact force of the crawler belt links on the drive tumbler teeth side edge will be greater than other parts when sliding against the crawler belt. This can lead to excessive slippage and localised slip ratio on the side edge of drive tumbler teeth, thus making the surface experience excessive work hardening and higher depth of deformation in the subsurface layer compared to failure mode A, C & D (Figure 4.5). This finding aligns with the work of Leso et al., (2022) who posited that severe adhesive-abrasive wear and the depth of plastic deformation in a wheel steel increased with an increase in slip ratio when running against rail steel during rolling and sliding wear simulation.

Furthermore, the formation of micro cracks (Figure 4.18c & d) in the subsurface, suggests that the drive tumbler material experiences fatigue cracking along areas of localised stress concentration due to repeated rolling and sliding-impact contact between the drive tumbler teeth and crawler belt, evidencing rolling-sliding contact fatigue failure (Bhattacharyya et al., 2014). As the grains have been refined and reoriented by plastic deformation, the cracks propagate and follow the path of least resistance along the direction of grain boundaries (Figure 4.18d). These cracks under cyclic loading propagate rapidly as they are exposed to environmental contaminants such as debris and carbon from kimberlite ore in the mine, which amplify stress intensity at the crack tips and the WEL (Fu et al., 2017).

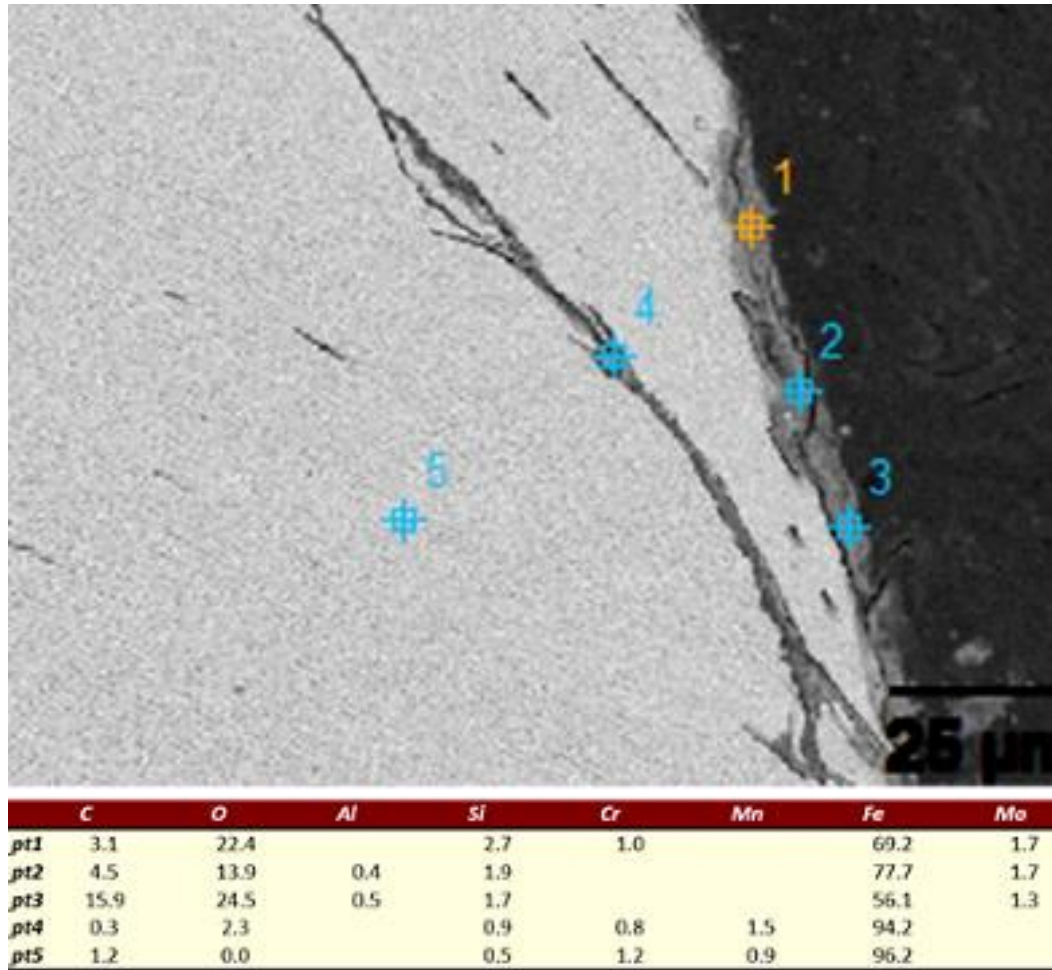


Figure 4.19: EDS Spectrum of cross-section of failure mode B

The EDS spectrum shown in Figure 4.19, reveals the elemental composition that validates the formation of oxide layers such as iron oxide, alumina oxide, and silicon oxide, in the WEL, and along the grain boundary, reducing cohesion between the grains in the drive tumbler material (Fu et al., 2017).

4.1.4.3 Mechanism of occurrence of failure mode C; via stereo microscope and SEM

Figure 4.20 shows the morphology of failure mode C. The stereo micrograph shows branching of deep surface cracks (Figure 4.20a). Figure 4.20b & c represent the SEM micrographs of failure mode C which revealed the surface cracks initiating from a void on the surface of the drive tumbler teeth, delamination, cluster of pits, micro-ploughing as observed in failure modes A and B, and pits filled with wear debris as major failure mechanisms (Figure 4.20 b & c). Furthermore,

smearing is visible along the sliding direction which alters the texture of the drive tumbler surface (Figure 4.20c), indicating plastic deformation, contact fatigue, and adhesion. Fowell et al., (2014) reported that smearing mechanisms on interacting surfaces are a result of high contact shear stress and friction, particularly in a high stress concentration region. This also confirms the causative factors of this type of failure as established in section 4.1.3.1.3 and Table 4.4.

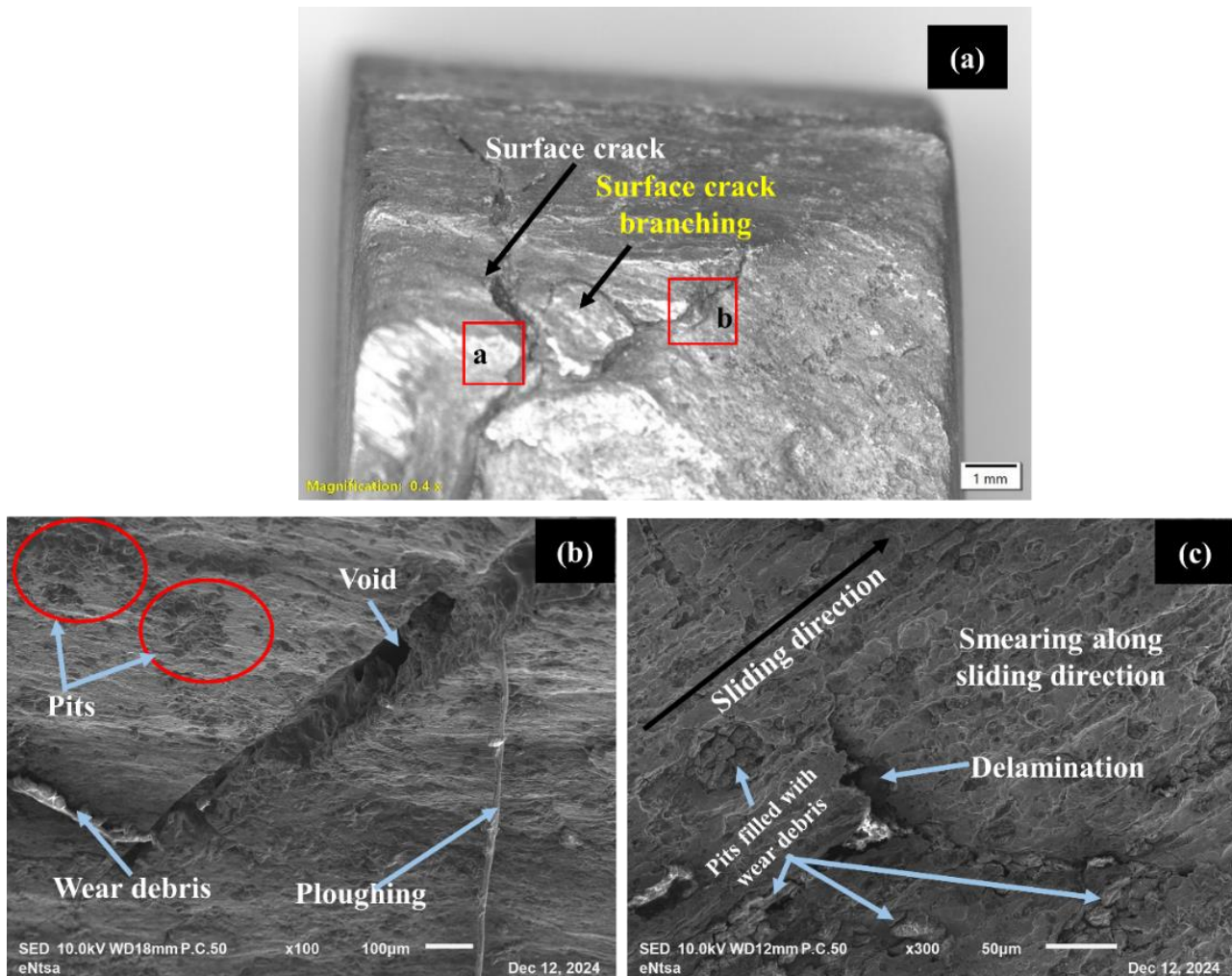


Figure 4.20: (a) Stereo micrograph of failure mode C, (b) SEM micrograph of area labelled a, (c) SEM micrograph of area labelled b.

4.1.4.4 Mechanism of occurrence of failure mode D; via SEM/EDS

Figure 4.21 shows the macroscopic view and SEM micrographs of the fracture surface of failure mode D. The fracture surface is characterised by crack initiation at the top edge of the drive tumbler

teeth, a propagation zone toward the top centre of the drive tumbler teeth, and the region with the final sudden fracture (Figure 4.21a). As depicted in Figure 4.21a, macroscopic examination of the fracture surface also reveals beach marks in the crack propagation region as a failure mechanism, indicating fatigue fracture (Jiao et al., 2020; Zhang et al., 2020; Luo et al., 2023). SEM analysis of the fracture surface shows a shear-dimpled morphology at the crack propagation region (Figure 4.21b). These dimples indicate the nucleation, growth, and coalescence of already existing voids (Figure 4.1, Figure 4.2, and Figure 4.3) during plastic deformation, which is often associated with shear-induced ductile fractures at a very low-stress triaxiality not greater than 0.33 (Lou et al., 2018). Under bending, impact, and sliding contact stresses, these inclusions and voids grow along the direction of the shear bands (Figure 4.21b) at maximum shear stress (François et al., 2012; Pineau et al., 2016; Abbasi et al., 2018; Lou et al., 2018; Viswanathan et al., 2020). This attests to the presence of MnS in the drive tumbler material (Figure 4.1, Figure 4.2). According to Maciejewski, (2015) and Song et al. (2024), MnS inclusions reduce fracture toughness and contribute to ductile fracture behavior by promoting the nucleation and growth of micro-voids during plastic deformation (Figure 4.21b). Figure 4.21c-d depicts the SEM morphology of the final fracture zone characterised by corrosion pitting, and inter-granular cracks (Figure 4.21c), grain boundary shearing, and shallow dimples (Figure 4.21d), evidencing a mixed mode fracture where ductile fracture transitions to rapid intergranular fracture (François et al., 2012; Viswanathan et al., 2020).

Figure 4.21e presents the EDS spectrum, revealing the presence of chlorine, nitrogen, and sulphur contaminants from the mine, as well as iron oxides formed due to reaction of oxygen with the base metal in the final fracture zone. These elements contribute to localised corrosion pitting, intergranular cracking, and stress corrosion cracking observed on the fracture surface and its transverse section (Figure 4.21c and Figure 4.22a-b). This occurrence weakens the grain boundaries, leading to embrittlement that causes sudden intergranular fracture in the drive tumbler teeth (Figure 4.21a and c) (Lynch & Moutsos, 2006). Furthermore, as plastic deformation progresses under increasing maximum tensile and shear stress, and corrosive environmental attack, the plasticity and ability of the drive tumbler teeth materials to absorb energy is reduced (Zhu et al., 2010). This can be attributed to excessive loading at contact interface that contributed to the multiple cracks propagation at about 45 degrees, perpendicular to the contact surface, and crack

branching beneath the drive tumbler material (Figure 22a). Although the drive tumbler materials may be ductile due to tempering, the weakened grain boundaries by inherent defects in the drive tumbler teeth and environmentally assisted cracking (Figure 4.21c and Figure 4.22a-b) by a corrosive medium in the mine contribute to the premature failure of the drive tumbler teeth.

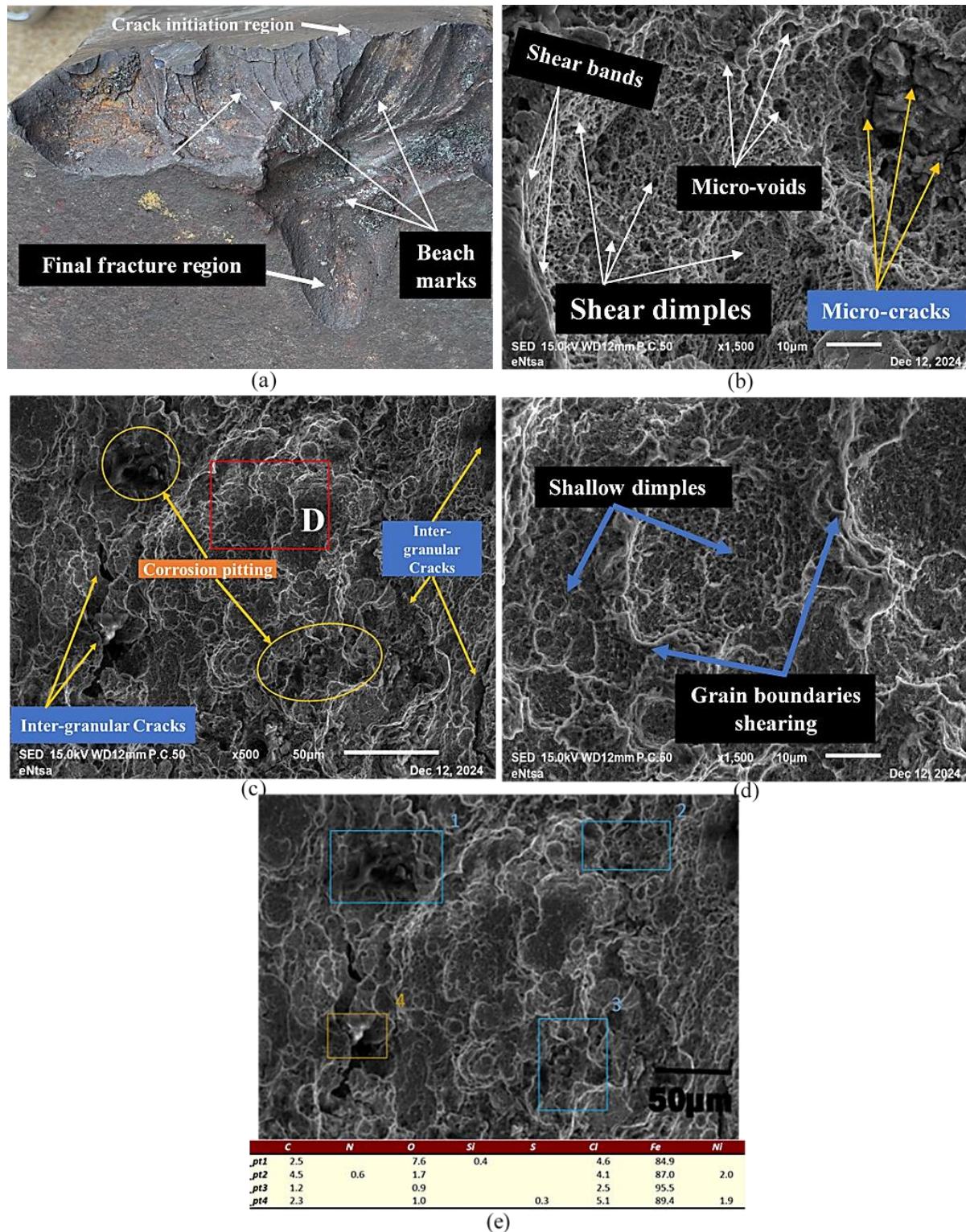


Figure 4.21: (a) Macroscopic view of fracture surface (failure mode D), (b) SEM micrograph of crack propagation region in (a), (c) SEM micrograph of final fracture region in (a), (d) SEM micrograph of point D in (c) at higher magnification, (e) EDS Spectrum of fracture surface

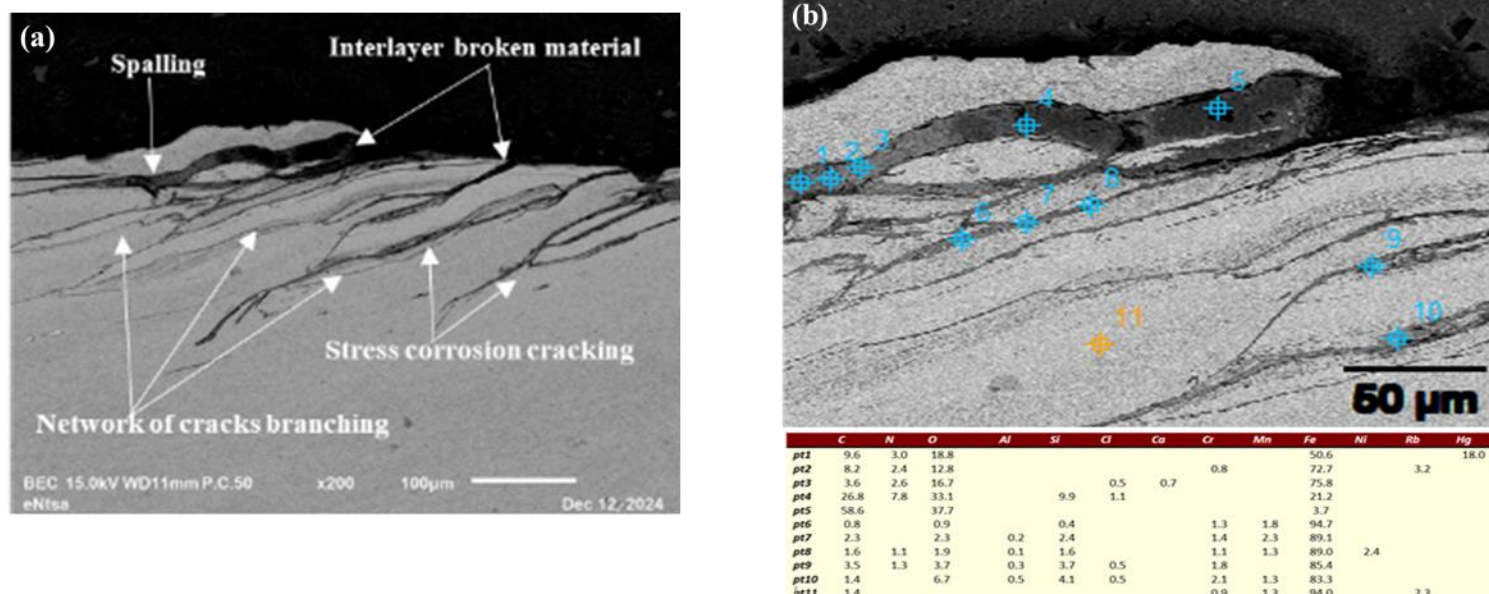


Figure 4.22: (a) SEM micrograph of the cross-section of failure mode D, and (b) EDS Spectrum of (a)

Figure 4.22 shows the SEM morphology of the cross-section of the fracture surface (failure mode D). Stress corrosion cracking occurs towards the subsurface of the drive tumbler teeth where the simultaneous action of tensile, bending, shear stress, and a corrosive environment characterised by contaminated water in the mine leads to intergranular cracking (Lynch & Moutsos, 2006). Furthermore, under repetitive rotation and sliding of the drive tumbler teeth against the contact surfaces like the crawler belt and abrasive debris from kimberlite ore, the corrosive medium, in conjunction with the contaminants in the mine, as shown in the EDS spectrum analysis (Figure 4.22a-b), caused embrittlement at grain boundaries, making them susceptible to multiple crack initiation and branching beneath the drive tumbler tooth surface, interlayer broken materials and spalling near the teeth surface (Figure 4.22a) which contribute to the premature failure of the drive tumbler teeth.

4.1.5 Interconnection of various failure modes and mechanisms

Figure 4.23 illustrates the observed failure modes, their corresponding mechanisms, and the interconnections between these failure mechanisms. Due to poor lubrication at the contact surface and low surface hardness of the drive tumbler to withstand contact pressure of the harder crawler

belt, metal-metal contact as depicted in (1) of Figure 4.23, and the presence of hard kimberlite particles aggregate material loss which stimulate delamination, surface cracks, micro-ploughing and grooves, pits and scratches on the drive tumbler teeth surface leading to a two-body and three-body sliding abrasive wear in (2) Figure 4.23.

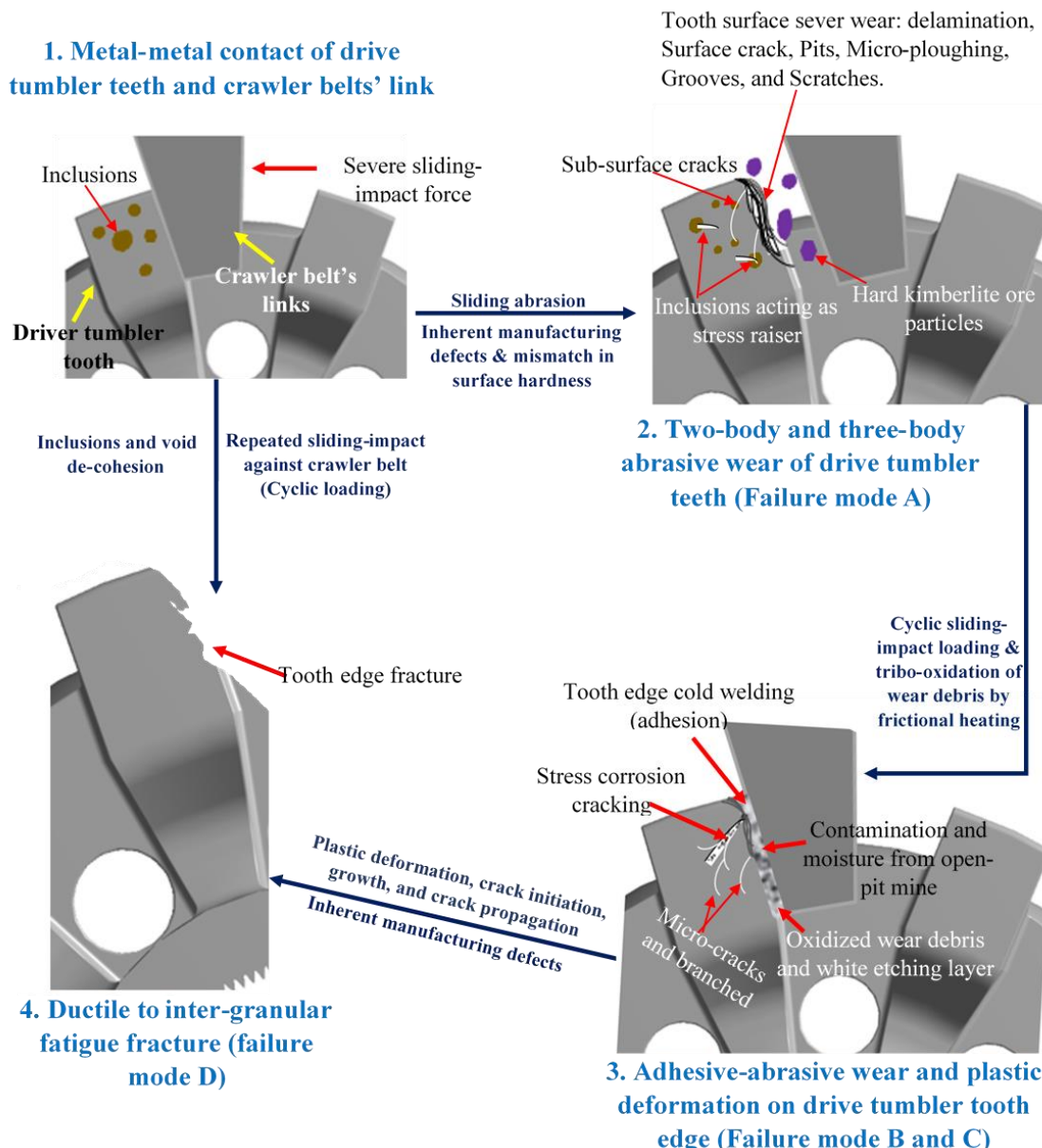


Figure 4.23: Schematic diagram depicting the interconnections of various failure mechanisms.

The inherent defect acted as a stress raiser that promoted the formation of micro cracks in the subsurface layer of the drive tumbler teeth. Additionally, during repeated sliding-impact by the

crawler belt, the damage caused by a two-body and three-body sliding abrasive wear increases friction between the contacting surface, further stimulating scuffing, cold-welding, and tribo-oxidation of wear debris leading to adhesive wear observed in (3) Figure 4.23. Exposure of the worn surface to the aggressive environment of the open pit mine aggravated corrosion pitting, which further escalated to stress corrosion cracking under sliding-impact stresses (Figure 4.23, 2). Furthermore, the combined effect of severe sliding-impact loading by crawler belt, inherent defect, damages caused by sliding abrasion, adhesion, and contaminated moisture accelerate plastic deformation at the drive tumbler tooth edge and trigger the growth and propagation of cracks from surface to the subsurface contributing to the ductile to inter-granular fatigue fracture as observed in (4) of Figure 4.23.

Additionally, the microhardness profile from the worn surface toward the core revealed a pronounced gradient, indicative of severe plastic deformation and strain-induced phase transformation at the contact interface. The surface layer, enriched in dislocations and possible mechanically induced martensite, exhibited elevated hardness values that enhanced its resistance to abrasive wear. However, this strain-hardened zone also possessed reduced ductility, rendering it susceptible to microcrack initiation under cyclic contact stresses. Once initiated, cracks preferentially propagated through the brittle, work-hardened layer before branching into the tougher, lower-hardness core, where subsurface fatigue mechanisms dominated the final fracture process (Figure 4.23, 3 & 4).

4.1.6 Strategies for mitigating failures of a Drive Tumbler

The following are recommended as mitigation measures that can be followed to prevent future premature failure of the drive tumbler.

-  **Manufacturing Defects in Cast Steels:** Drive tumbler material (ASTM 148 grade 160-145 cast steel) should undergo proper deoxidation and refining processes using advanced secondary steel making techniques such as vacuum arc remelting (VAR), during the casting process. This will help to remove entrapped oxygen and inclusions such as MnS, Al₂O₃ and AlPO₄ from the molten steel, which act as stress raisers during direct sliding contact of the drive tumbler teeth with contacting surfaces (crawler belt).

🔧 **Surface Modification:** Before subjecting the drive tumbler teeth to continuous sliding-impact stress, the surface of the as-purchased drive tumbler teeth should undergo surface treatment using a laser shock peening and deposition of wear resistant materials via laser cladding process to extend its service life. These techniques have the potential to increase surface hardness to 800 HV-1500 HV, achieve deep compressive residual stress at a strain rate of $10^6/s$ and case depth between 2-3 mm, with no change in surface roughness (Jia et al., 2014; Sundar et al., 2019; Tan et al., 2019; Munther et al., 2020). These can be achieved by optimising critical parameters during the shock peening process which include the pulse energy pulse duration, spot diameter scan rate, track-to-track displacement and the shock wave pressure. This will help improve the fatigue resistance, wear resistance properties, and crack resistance in the drive tumbler teeth to withstand high hertzian contact stress exerted by the crawler belt surface.

🔧 **Materials Selection and Remanufacturing:** As already established in section 2.3.1, selection of new and compactible materials, with excellent mechanical properties, improved hardness, wear resistance, corrosion resistance and toughness is paramount. The already damaged drive tumbler teeth (Failure mode A and B) characterized by severe material loss about 30 mm deep in the tooth surface (Figure 3.6b) can be restored using a hybrid remanufacturing technique that incorporates tungsten inert gas (TIG) or metal inert gas (MIG)-based wire arc additive manufacturing (WAAM) with laser cladding (LC) technique. WAAM-based TIG or MIG is essential to build up excessively worn and fractured parts, while LC is essential in coating and modifying the build-up surfaces which helps in minimizing production costs. WAAM-based GMAW (Xiong & Zhang, 2014; Nagamatsu et al., 2020; Chaturvedi et al., 2021; Shah et al., 2023; Akintunde et al., 2025) and LC are unique techniques in remanufacturing damaged industrial components to achieve desirable mechanical and tribological properties (Ehsan et al., 2021; Gong et al., 2021; Guo et al., 2022; Yao et al., 2022). However, the successful implementation of WAAM and LC in the remanufacturing damaged drive tumbler teeth and in the refurbishment of as-purchased drive tumbler teeth involve adequate surface preparation of the damaged drive tumbler teeth such as machining and cleaning, 3D scanning of damaged

area and path planning, selection of suitable wear-resistant materials based on compatibility with the drive tumbler material and improved mechanical properties, careful optimization of key laser processing parameters such as laser power, scanning speed, laser spot diameter, and feed rate, and trained personnel (Guo et al., 2022; Yao et al., 2022; Xiao et al., 2023; Akintunde et al., 2025). The implementation framework of the remanufacturing and refurbishment of the damaged drive tumbler teeth is illustrated in Figure 4.24. The development of hybrid composite materials such as H13/WC-12Co and 316L/WC-12Co to mitigate abrasive wear and corrosion through the LC technique is currently under study. This is done to remanufacture the damaged drive tumbler teeth. Remanufacturing prevents normal practice of discarding damaged equipment parts at the diamond mine. Therefore, it provides economic viability. The techno-economical evaluation of the recommended approach (WAAM & LC) for remanufacturing is provided in the next chapter of this thesis.

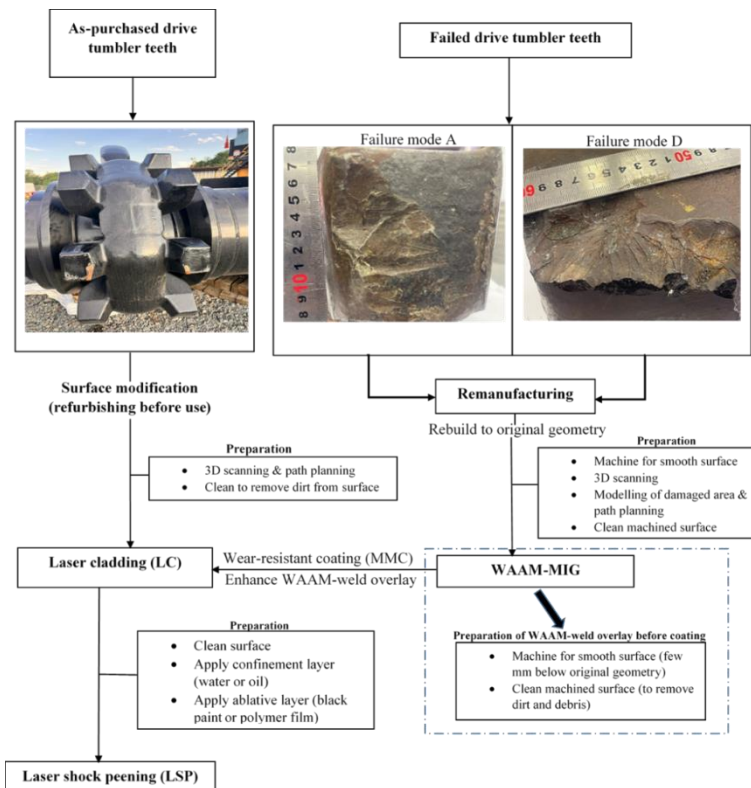


Figure 4.24: Implementation framework for recommended mitigation methods; surface modification and remanufacturing of drive tumbler teeth.

-  **Maintenance Practices:** A timely inspection should be performed to ensure the drive tumbler is properly lubricated, and proper tensioning of crawler belt according to original equipment manufacturer's specification should also be adhered to.

4.1.7 Conclusion/ Summary of findings from failure investigation

1. This study was carried out to reveal and understand the various failure modes and mechanisms that led to premature failure of the drive tumbler of an electric shovel in a diamond mine to identify measures for mitigating its failure. Experimental methods vis a vis macroscopic and microscopic analysis was adopted.
2. Visual examination of the damaged drive tumbler teeth revealed four failure modes that include (1) severe surface wear at the front of the drive tumbler teeth with about 30 mm deep gouged surface, (2) adhesive wear at one side edge of the drive tumbler teeth, (3) plastic deformation with cracks at the top edges of the drive tumbler teeth, and (4) fracture at the top edge of the drive tumbler teeth. Observation of as-purchased drive tumbler teeth revealed potentials design deficiency characterized by small fillet at teeth edges, leading to the plastic deformation and warping that acted as stress concentration and crack initiation site.
3. Analysis of the undamaged part of the drive tumbler revealed that the drive tumbler material is made of a tempered martensitic ASTM 148 grade 160-145 cast steel, with a significant amount of non-metallic inclusions such as manganese sulphide and aluminium oxides originating from the manufacturing process. Although the drive tumbler material exhibits good tensile and yield strength properties, with its toughness enhanced through tempering, its low fatigue strength and the low surface hardness of the drive tumbler teeth compared to the contacting surface (crawler belt) makes it unsuitable for high sliding-impact contact stresses. As a result, severe surface wear, fatigue wear, material transfer from contacting surfaces, surface cracks, and fractures, were recorded on the surfaces of the drive tumbler teeth.

4. Ion chromatography evaluation of the water sample from the mine revealed significant amount of chlorine and sulphur ions present in mining environment. This justifies the formation of rust on worn surface, tribo-oxidation, corrosion pitting and stress corrosion cracking beneath the damaged surface of the drive tumbler teeth.
5. Fractographic analysis revealed that two-body sliding abrasion due to surface-to-surface contact led to fatigue wear characterised by surface cracks, delamination, and spalling, three-body abrasion characterised by micro-ploughing, and grooves due to the presence of hard particles (quartz) in the kimberlite ore and wear debris, adhesion due to insufficient and broken-down lubrication oil films, and mixed-mode fatigue fracture (ductile-intergranular fracture) were the primary failure mechanisms. The study indicated that the fracture at the top edge of the drive tumbler teeth was brought caused by the 'plastic deformation with cracks' failure mode.
6. Additionally, this study indicated that sliding abrasion wear was predominant in failure mode A-C, which attest to the low surface hardness of the drive tumbler compare to mating parts and hard kimberlite ore present in the mine. Furthermore, EDS analysis of damaged surface revealed the presence of an increase in oxygen (O), chromium (Cr), silicon (Si), on the worn surface indicates the formation of hard oxide compounds with the drive tumbler base material. The increase in Cr and Si content established subsequent material detachment and wear debris from the surface causing tribo-oxidation effects, formed due to thermally activated oxidation and frictional heating.
7. The fractography and microscopic analysis of the cross-section of the damaged surfaces revealed WEC and martensite transformation due to frictional heating and plastic deformation and sliding/rolling contact fatigue failure mechanisms in the subsurface layer of the drive tumbler teeth. EDS analysis of the cross-section of the fracture surface in the subsurface crack regions revealed the presence of nitrogen, oxygen, calcium, chlorine, and high silicon and carbon content with varying amount, indicating environmentally assisted and stress corrosion cracking.

8. The root cause of the premature failure of the drive tumbler was the combined effects of the manufacturing defects in the drive tumbler teeth which acted as stress raisers, low surface hardness of the drive tumbler teeth, continuous metal-to-metal sliding and impact contact of the drive tumbler teeth against the crawler belt, misalignment of the drive tumbler teeth due to vibration and poor tensioning of crawler belt, and poor routine maintenance practices.
9. Mitigation strategies to increase the service life of the drive tumbler teeth were recommended. To improve the surface properties, functional performance, of the as-purchased drive tumbler, the adoption of surface modification technique such as laser shock peening process and LC was suggested.
10. Remanufacturing the damaged drive tumbler by depositing wear and corrosion resistant materials with improved mechanical properties on damaged surfaces via hybrid remanufacturing approach using WAAM and LC was also suggested as a means of reducing waste and cost of purchasing new ones.
11. Other mitigation measure suggested is maintaining good preventive maintenance practices. These suggested mitigation measures are assumed to prevent future premature failures of the drive tumbler teeth, increase the reliability of the shovel loader, and reduce downtimes in diamond mining operations when implemented.

5 Chapter Five: Techno-Economic Analysis

5.0 Chapter Summary:

This chapter presents a techno-economic analysis of remanufacturing drive tumbler teeth using laser cladding and a hybrid WAAM + LC approach. Material usage, processing time, and cost were estimated using simplified geometric models and defined process parameters. Following the analysis, conclusions were drawn on the remanufacturing approach with the greatest potential for sustainability and profitability in the diamond mining industry.

5.1 Cost-Benefit Analysis for the Remanufacturing of failure mode A & B, and Refurbishment of As-purchased Drive Tumbler Teeth.

Table 5.1 presents a comparative techno-economic assessment of three different remanufacturing approaches for the restoration of damaged drive tumbler teeth which include adopting LC alone to remanufacture failure mode A and B, hybrid remanufacturing which incorporate wire arc additive manufacturing (WAAM) to restore failure mode A and B, and LC for refurbishment of as-purchased drive tumbler teeth. The total cost of remanufacturing was computed by summing the material cost of H13 and WC-12Co, and the laser cladding processing cost across three assumed scanning speeds (5 mm/s, 10 mm/s, and 15 mm/s) for the laser cladding process. The performance of each approach was benchmarked against the cost of acquiring a new drive tumbler.

For LC Alone, the build-up volume (30 mm thickness) required a material mass of 3979.5 grams, resulting in a total material cost of \$6,674.76. At a scanning speed of 15 mm/s, the laser cladding processing cost was \$31,120, leading to a combined remanufacturing cost of \$37,795. This yielded a 24.41% cost saving compared to a new purchase. However, at slower speeds (5 mm/s and 10 mm/s), the processing cost increased significantly to \$93,320 and \$46,680, respectively. Notably, at 5 mm/s, this resulted in a negative saving (-102%), indicating that adopting only LC for remanufacturing would be more expensive than acquiring a new one. Although there could be potential cost savings at high scanning speed (Table 4), the effect on profitability and sustainability can be minimal. This aligns with the report of Akintunde et al., (2025), who asserted that the laser cladding process holds significant promise for remanufacturing applications within the mining industry, but its high initial investment cost, particularly for depositing bulk materials to

Table 5.1: Techno-economic analysis of possible remanufacturing approach of the drive tumbler

Failure to Address & Remanufacturing approach	Required Materials in grams		Total Cost of materials (\$)	LC processing cost at different scanning speed (\$)		
Cost _{nwDT} = 50,000 USD	Build- up (30mm thickness)	Coating (2 mm thickness)				
Failure mode A and B				5mm/s	10mm/s	15mm/s
LC Alone	3979.50	-	6674.76	93320	46680	31120
Total Cost of Reman. (\$)				100,995	53,355	37,795
% Savings				- 102	- 6.71	24.41
Hybrid (WAAM + LC)	3,449.50	530	1414	6240	3120	2080
Total Cost of Reman. (\$)				7654	4534	3494
% Savings				85.74	91.99	94
As-Purchased (LC alone)	-	530	889.92	6240	3120	2080
Total Cost of Reman. (\$)				7,130	4,001	2,970
% Savings				84.69	90.93	93

remanufacture specific failure mode such as severe wear or fracture, remains a major limitation to widespread adoption in order to avoid financial loss.

In contrast, the Hybrid WAAM + LC strategy utilized WAAM for bulk material deposition (3,449.5 g) and LC for a 2 mm wear-resistant coating (530 g), resulting in a significantly reduced material cost of \$1,414. The corresponding processing costs at the three scanning speeds were \$6,240, \$3,120, and \$2,080, leading to total remanufacturing costs of \$7,654, \$4,534, and \$3,494. These translate to cost savings of 85.74%, 91.99%, and 94%, respectively, demonstrating that this hybrid approach is both cost-effective and technically viable (Cunningham et al., 2017; Akintunde et al., 2025). Similarly, the as-purchased (LC Alone) strategy was evaluated if only a 2 mm wear-resistant coating is to be deposited on new drive tumblers. The deposition of selected materials on the as-purchased would possibly incurred the lowest material cost of \$889.92. Additionally, with the same processing costs applied, the total remanufacturing costs were \$7,130, \$4,001, and \$2,970 at 5 mm/s, 10 mm/s, and 15 mm/s, respectively. These yielded cost savings of 84.69%, 90.93%, and 93%, respectively.

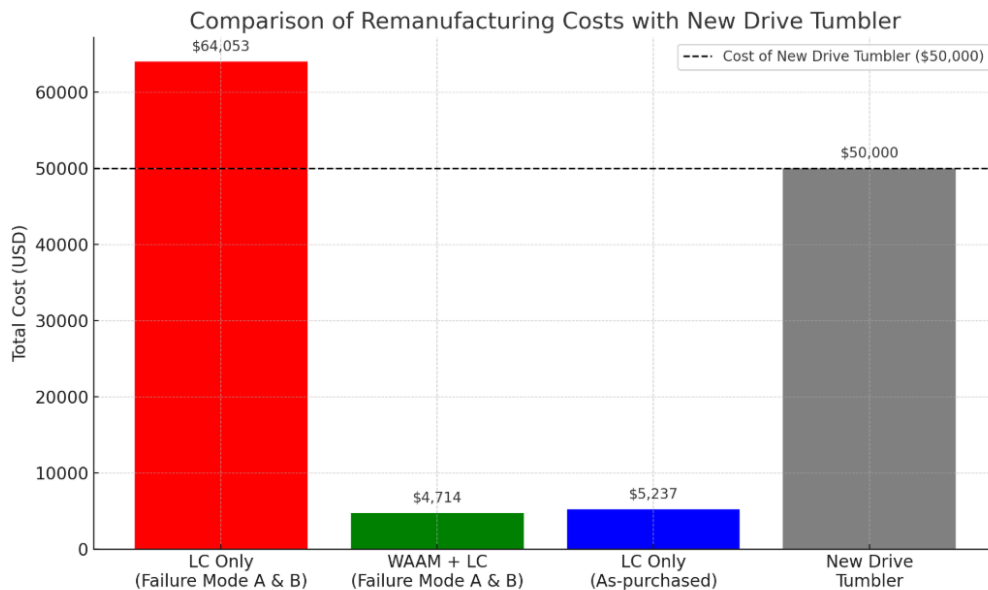


Figure 5.1: Graph showing comparison of potential average cost of different remanufacturing approach and cost of new drive tumbler.

Furthermore, the average total cost of remanufacturing at the different scanning speed is presented in Figure 5.1. This approach allows decision-makers to assess cost-effectiveness more reliably, accounting for real-world variations in process parameters like the scanning speed. Overall, this cost model analysis revealed that the adoption of monolithic LC approach in depositing a 3,449.5 g of materials on the failure mode A and B (sliding abrasion wear and adhesive wear) is challenging due to the extremely high cost of \$64, 053, especially when it is required to repair the severely damaged surface of the drive tumbler teeth with the surface area of 140 mm x 100 mm and gouging depth of about 30 mm (Figure 3.6)

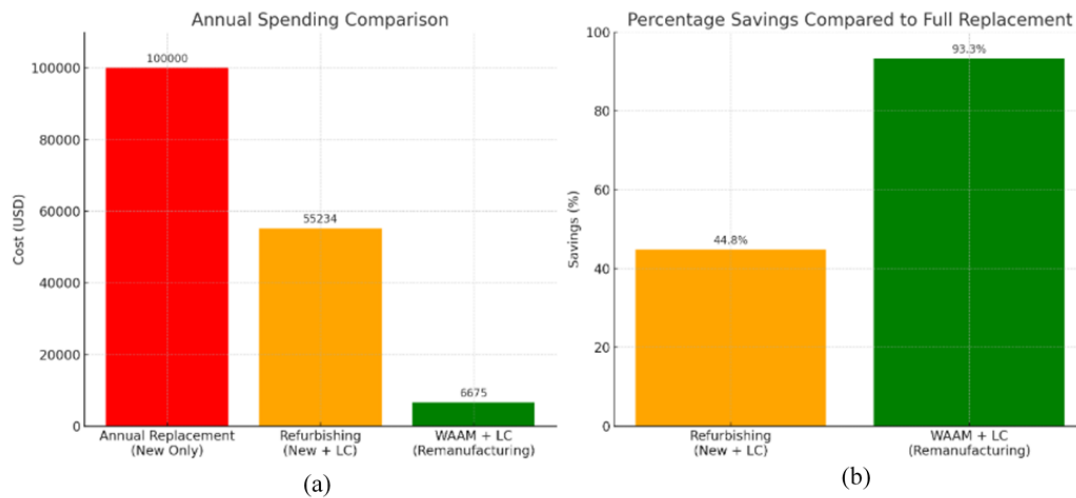


Figure 5.2: Graph showing (a) cost of replacing drive tumbler, remanufacturing and refurbishing in a year (b) % savings of remanufacturing via hybrid approach and refurbishing via LC annually.

Additionally, it can be seen in Figure 5.1 & Figure 5.2, that incorporating WAAM-based GMAW with LC process as hybrid remanufacturing approach have the potential to minimize replacement cost with potential remanufacture cost of \$4,714 (Figure 5.1) and about 93% savings annually (Figure 5.2b) in remanufacturing failure mode A & B in drive tumbler teeth caused by sliding-impact abrasion of harder interacting part (crawler belt) and presence of hard kimberlite mineral (quartz) in the diamond mine (Cunningham et al., 2017). This is because the WAAM-based GMAW has a higher deposition rates of about 9.5 kg/h, reduced materials waste, low energy consumption, lower capital and operating cost (Akintunde et al., 2025; Chaturvedi et al., 2021;

Nagamatsu et al., 2020; Shah et al., 2023; Xiong & Zhang, 2014). However, the refurbishment of as-purchased drive tumbler teeth via laser cladding process by depositing a 2 mm thick wear-resistant MMC materials on new drive tumbler before subjecting them to sliding-impact stress, provides a great opportunity for about 90% cost-savings by just incurring a refurbishing cost of \$5,237 (Figure 5.1), however, with a 44.8% savings annually when summed with the cost of new drive tumbler for twice performance of the new drive tumbler savings annually. This is due to the unique advantages LC process provides, including ability to improve surface and wear-resistant properties, and extend service life by 150% (Ehsan et al., 2021; Gong et al., 2021; Guo et al., 2022; Yao et al., 2022). As a result, the refurbishing teeth of as-purchased drive tumbler, and remanufacturing of failed drive tumbler teeth (failure mode A & B) could be achieved with economically viable wear-resistant material MMC by employing hard face cemented carbides (WC-12Co) reinforced iron-based steel (H13 powder) composites fabricated via laser cladding technology as established from the literature and the TEA. This would guarantee excellent restoration of the damaged drive tumbler teeth surface with enhanced wear-resistance, corrosion-resistance and hardened clad teeth, having the potential to withstand high sliding-impact stresses encountered during engagement and interaction with the crawler belt and hard kimberlite particles present in the open-pit diamond mine during operation. This would consequently eliminate premature failure challenges in the mining industry (Tan et al., 2015).

Furthermore, it has been reported that the adoption of laser cladding for the remanufacturing of high-valued components such as heavy-duty sprocket (Guo et al., 2022), conical picks and sleeves (Akintunde et al., 2025), power steam circuit parts (Raju et al., 2015), aero engine parts (Díaz et al., 2012), cone bit, railway wheels and shearer spiral blade (Dass & Moridi, 2019; Akintunde et al., 2025), hydraulic piston rods (Tuominen et al., 2015), single crystal turbine blades (Rottwinkel et al., 2014), gas-turbine blades (Bi & Gasser, 2011), shear picks (Che et al., 2014) and railway rails (Robles Hernández et al., 2016) exhibited improved hardness, toughness, and fatigue strength, which contributed to an increase in their operational lifespan. In addition, remanufactured components have demonstrated performance levels up to five times higher than new components, alongside savings of approximately 70% in materials, 60% in energy consumption, and 30% in overall cost (Che et al., 2014; Akintunde et al., 2025). Their operational lifespan can also be extended by as much as 150% relative to newly manufactured ones (Che et

al., 2014; Akintunde et al., 2025). These attest to the findings in this research, with the TEA validating the cost-benefit of remanufacturing damaged drive tumbler teeth or refurbishing the as-purchased via laser cladding process compared to purchasing new one. Therefore, remanufacturing the drive tumbler teeth with economically feasible high wear-resistant materials using laser cladding will reduce overhead costs of replacing drive tumbler every 5,000 running hours that led to replacement cost of 100, 000 USD annually, and increase sustainability of diamond mining business.

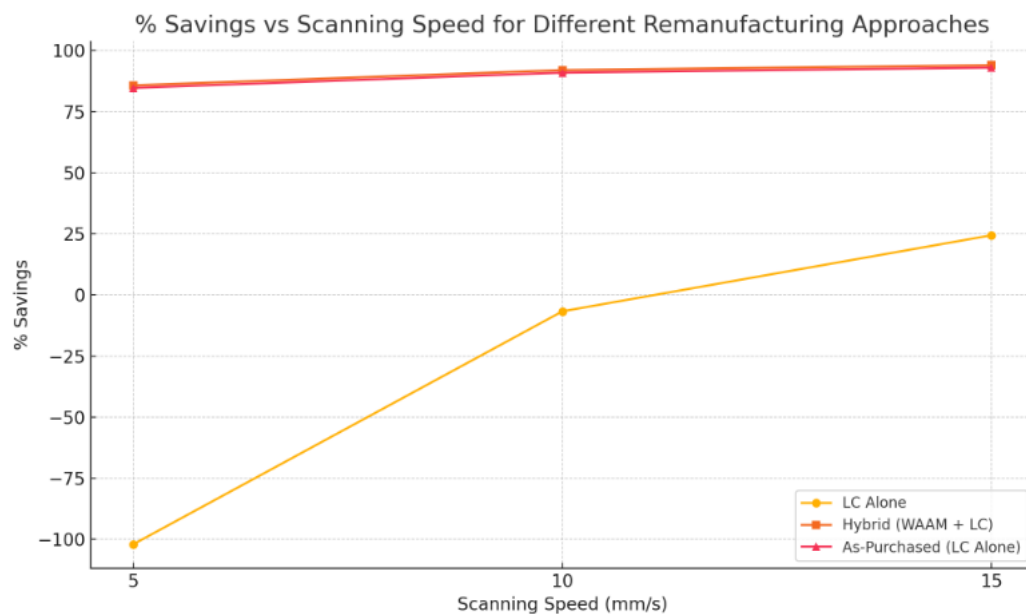


Figure 5.3: % savings with respect to assumed scanning speeds.

Figure 5.3 present the correlation between scanning speed and cost savings. The analysis reveals that the scanning speed significantly affects the economic viability of laser cladding-based remanufacturing, with higher speeds greatly reducing process costs. Moreover, integrating WAAM for volume build-up and limiting LC to surface modification provides an optimal balance between material efficiency and cost, outperforming LC Alone in most scenarios (Table 4 and Figure 5.2.). This cost sensitivity to scanning speed is primarily due to its direct influence on processing time (Di & Yang, 2020). At lower scanning speeds (e.g., 5 mm/s), the laser moves more slowly across the surface, which increases the time required to cover the entire deposition area (Li et al., 2024). Since laser cladding is typically charged per hour of operation based on information gather from the industry, longer processing times translate to higher labor, equipment usage, and

energy consumption costs. Conversely, at higher scanning speeds (e.g., 15 mm/s), the same area can be processed in a significantly shorter duration, thereby reducing the total number of processing hours and associated operational expenses (Figure 5.3). Additionally, high scanning speeds allow for greater throughput and productivity, which is particularly advantageous in large-scale industrial settings where minimizing downtime and maximizing equipment utilization is crucial. However, it is important to balance scanning speed with deposition quality, as excessively high speeds may compromise layer bonding or result in incomplete melting of feedstock material (Liu et al., 2021). In this analysis, the selected range of scanning speeds (5–15 mm/s) reflects practical operating range that maintain coating metallurgical and mechanical integrity while optimizing cost efficiency. The rapid solidification rates inherent to laser cladding, which are strongly influenced by scanning speed, refine dendritic arm spacing, promote uniform carbide precipitation, and suppress the formation of coarse, brittle carbides at grain boundaries. Higher scanning speeds reduce the heat input per unit length, accelerating solidification and producing a more homogeneous distribution of carbides such as TiC and WC. This refined carbide morphology may enhance resistance to microploughing and cutting wear in abrasive mining conditions, while reducing preferential crack initiation sites, thereby improving both wear resistance and fatigue performance under combined impact and abrasion loading (Che et al., 2014; Liu et al., 2021; Guo et al., 2021; Akintunde et al., 2025).

Hence, choosing the optimal scanning speed becomes a critical process parameter in techno-economic decision-making for laser cladding operations in performance-cost evaluation, especially when evaluating large components or multiple part repairs, such as the drive tumbler teeth considered in this research. To ensure the field reliability and economic viability of the remanufactured drive tumbler, non-destructive testing (e.g., ultrasonic testing for subsurface defects, magnetic particle inspection for surface cracks) should be integrated with post-process metallurgical inspections such as microhardness profiling and microstructural analysis. This combined approach verifies that the coated surface/clad meets metallurgical and mechanical property requirements while preventing premature failure. Integration of these quality-control measures into the remanufacturing workflow would mitigate premature failures by ensuring defect-free clads prior to deployment.

5.2. Conclusion

This chapter presented a comprehensive techno-economic evaluation of the proposed mitigation strategy for the damaged drive tumbler teeth using laser cladding (LC) and a hybrid approach involving wire arc additive manufacturing (WAAM) combined with LC. The methodology detailed the assumptions, equations, and computational framework for estimating processing time, material volume, and cost components including laser cladding processing and material costs. A cost comparison was conducted between three key approaches: full replacement with a new drive tumbler, refurbishment of as-purchased drive tumblers using LC, and remanufacturing of damaged drive tumblers (Failure Modes A & B) via LC alone and WAAM + LC hybrid strategy. Results were illustrated through cost and percentage savings graphs, which revealed that hybrid WAAM + LC provides the most economical solution, yielding significant annual cost savings when compared to complete replacements. Additionally, reinforcing as-purchased drive tumbler teeth show potential significant cost savings. The influence of scanning speed on processing time and overall cost was also analyzed, establishing its critical role in optimizing economic efficiency. The chapter concludes that remanufacturing via WAAM + LC and refurbishing the as-purchased drive tumbler teeth using LC alone, offers a potential sustainable and cost-effective strategy in improving surface properties and extending drive tumbler service life.

6 Chapter Six: Conclusion and Recommendations

6.0 Chapter Summary:

Chapter Six begins by revisiting the aims and objectives outlined in the study. It then provides a comprehensive summary of the key findings, aligning them with the stated research objectives. The chapter concludes by offering practical recommendations and outlining potential directions for future research.

6.1 Conclusions

This study started by highlighting the aim which was to carry out failure investigation of drive tumbler teeth of an electric mining shovel using experimental methods, and provide mitigation strategies that can prevent future failure in the drive tumbler with the objectives in section 1.3 of Chapter One stated below:

- a) To investigate the operating environment and material properties of the drive tumbler and analyse the failure modes and mechanisms of the damaged drive tumbler teeth, in order to identify the root causes of the premature failure.
- b) Propose mitigation measures that can prevent future failures of drive tumbler teeth, through selection of candidate materials and suitable remanufacturing approach from the literature and findings from objective one (1).
- c) Investigate the profitability of remanufacturing drive tumbler teeth by evaluating the cost-benefits of adopting selected materials and remanufacturing approach.

6.1.1 Findings from this research work

The main findings from this research work are now presented as follows:

6.1.1.1 Findings obtained from the literature review:

-  Failure analysis of drive tumbler are limited, hence the review of similar components such as gears and sprocket. The failures identified in the reviewed components are abrasive and

adhesive wear, surface contact fatigue, and brittle fracture. From the literature, failures of similar components (gears and sprocket) are linked to improper selection of materials and defects from manufacturing processes, however, without consideration of their operating environment.

👉 In selecting potential wear-resistant materials to address the premature failure of drive tumbler teeth via remanufacturing, metal matrix composites (MMCs) emerged as the most promising option. This is attributed to their potential for high-performance applications, stemming from their ability to combine the advantageous properties of multiple constituent materials, as well as the flexibility they offer in tailoring compositions to meet specific service conditions. Thus, H13 re-enforced WC-12Co was recommended as the suitable MMC for the drive tumbler teeth.

👉 Following selection of suitable candidate wear resistant materials, LC was found to be suitable material deposition technique for the purpose of remanufacturing damaged drive tumbler teeth and refurbishment of as-purchased drive tumbler teeth. This is because of its ability to impart excellent mechanical properties with low dilution, low HAZ and ability to produce thick coatings with high dimensional accuracy. However, WAAM was appreciated more for rebuilding excessively damaged surface such as rebuilding of fractured surface owing to its high deposition rate and low cost of production. Thus, hybrid remanufacturing approach was recommended for restoring damaged drive tumbler teeth after a systematic techno-economic evaluation.

6.1.1.2 Findings obtained from experimental failure investigation of drive tumbler:

👉 The failure modes identified via visual examination were categorised as severe surface wear on tooth front surface, one-sided edge adhesive wear, plastic deformation with cracks at tooth edges, and fracture at the tooth edges.

👉 Chemical composition analysis of undamaged area of the drive tumbler through spark emission spectroscopy revealed drive tumbler material alignment with ASTM A148 grade 160-145 cast steel. The microscopic analysis of undamaged drive tumbler teeth via optical

microscope revealed a microstructure of tempered martensite which indicate the drive tumbler had pass through quenching and tempering after casting.

- 🔍 Failure mechanisms that show how the failure process occur were identified through scanning electron microscopy (SEM). These mechanisms include two-body sliding abrasion, adhesive-abrasive-fatigue wear, sliding contact fatigue, and ductile-intergranular fracture.
- 🔍 The corrosive and harsh operating environment of the diamond mine characterize by chlorine and sulphur ions and hard kimberlite minerals was established to aid the formation of pits and pitting corrosion on drive tumbler's teeth surface.
- 🔍 Consequent to the premature failure and based on the materials properties (microhardness) comparison of the kimberlite ore (predominantly quartz), crawler belt and the drive tumbler teeth, it was found that the drive tumbler's surface hardness is too low to withstand sliding-impact contact interaction between its crawler belt, and hard and abrasive foreign materials in the mine.
- 🔍 Manufacturing defects identified as brittle alumina and MnS inclusions contributed to premature failure as they acted as stress raisers that aided rapid initiation and propagation of cracks in the subsurface layer of the drive tumbler.

6.1.1.3 Techno-economic Analysis

- 🔍 Findings from the TEA revealed that remanufacturing via WAAM + LC and refurbishing the as-purchased drive tumbler teeth using LC alone, offers a potential sustainable and cost-effective strategy in improving surface properties and extending drive tumbler service life.

6.2 Recommendation and Future Research Direction

Despite the study's success in fulfilling its objectives and bridging significant knowledge gaps, further exploration is essential to deepen understanding and enhance the applicability of the findings. The following proposed directions, though not exhaustive, highlight key areas where future research could be meaningfully pursued.

- 🔧 Numerical failure analysis of failed drive tumbler through simulation and modelling, and finite element analysis to investigate the stresses the drive tumbler encountered during operations that could contribute to the premature failure.
- 🔧 Deposition and characterisation of selected materials (H13/WC-12Co composite) via laser cladding process to investigate the wear resistance, mechanical properties and suitability of the process to remanufacture the drive tumbler.
- 🔧 Optimization of materials and process parameters including laser power, scanning speed, feed rate and laser spot diameter to develop a process map, and validation of the techno-economic analysis model already developed in this research, towards the remanufacturing of the drive tumbler through both statistical analysis and artificial intelligence particularly artificial neural network.
- 🔧 Numerical simulation of clads using finite element analysis to investigate and validate the operational stresses fabricated coatings can withstand during operations.
- 🔧 Implementation of optimized materials and hybrid remanufacturing approach (WAAM & LC) process parameters to remanufacture failed drive tumbler teeth.

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