



School of Earth Sciences and Engineering
Department of Chemical, Materials and Metallurgical Engineering

**ANALYSIS OF FAILURE MODES AND MECHANISMS OF DOZER
BLADE LINERS (DBLs) IN A KIMBERLITE TAILINGS
ENVIRONMENT AT THE ORAPA DIAMOND MINE IN BOTSWANA**

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Dedication

I dedicate this work to my loving parents, Mr. and Mrs. Jere.

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List of Symbols and Abbreviations

DBLs	: Dozer blade liners
Semi U dozer blade	: Semi universal dozer blade
KT	: Kimberlite Tailings
PSD	: Particle size distribution
SEM	: Scanning Electron Microscopy
EDS	: Energy Dispersive Spectroscopy
BWP	: Botswana pula
USD	: United States dollar
LC	: Laser Cladding
CBA	: Cost-Benefit Analysis
EFA	: Engineering Failure Analysis

List of Publications

- 1) A.E. Jere, T.P. Leso, P.V.S. Raghupatruni, E.O. Olakanmi, K. Setswalo, A. Botes, R. Ndeda, B. Maruping, and N.Y. Ematang, The potential use of laser cladding as a remanufacturing technique for worn-out track dozer blade liners (DBLs) in mining operations: A review, The international journal of advanced manufacturing technology, 2025, [doi:10.1007/s00170-025-15670-0](https://doi.org/10.1007/s00170-025-15670-0).
- 2) A.E. Jere, T.P. Leso, P.V.S. Raghupatruni, E.O. Olakanmi, K. Setswalo, A. Botes, R. Ndeda, B. Maruping, and N.Y. Ematang, Analysis of wear and failure mechanisms of dozer blade liners (DBLs) in a kimberlite tailings environment at a diamond mine in Botswana, Engineering failure analysis ([Under review](#)).
- 3) A.E. Jere, T.P. Leso, P.V.S. Raghupatruni, E.O. Olakanmi, K. Setswalo, A. Botes, R. Ndeda, B. Maruping, and N.Y. Ematang, Microstructural evolution, consolidation behaviour, and mechanical performance of laser-cladded WC reinforced H13 composites for AISI 1018 dozer blade liners in a kimberlite tailings environment ([In progress](#)).

Abstract

This research investigates the premature wear and failure of dozer blade liners (DBLs) on a track dozer operating at the Orapa diamond mine in Botswana, with the aim of identifying the dominant wear mechanisms and proposing mitigation measures to improve their service life. DBLs sustain heavy abrasion as the dozer blade pushes kimberlite tailings (KT) - abrasive waste material left after diamond extraction and rich in hard minerals such as silica, alumina, and diamond, leading to accelerated wear. These minerals exceed the hardness of the steel used in DBLs, resulting in material degradation. The DBLs were observed to fail after approximately 11125 operational hours, significantly below the expected service life of 15000 hours. This resulted in cost implications of ~USD 8950 (BWP 127904) per dozer due to 5 hours of unplanned downtime, increased maintenance, and DBLs replacement. To determine the root causes of wear and failure, four worn DBL samples and one control sample were analysed using scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy (SEM-EDS), stereo and optical microscopy, and Vickers microhardness testing. The study identified sliding abrasive wear, surface cracking, deformation, and pitting as the primary failure modes. Dominant wear mechanisms included ploughing, microcutting, plastic deformation, grooves, and spalling. The findings highlight that the abrasive mineral composition of KT is a critical factor in the premature failure of DBLs. Based on the analysis, several cost-effective mitigation measures were recommended to prevent premature failure and extend blade life: the use of wear-resistant materials with improved hardness, toughness, and refined microstructures for DBLs manufacturing; exploration of manufacturing technologies that improve the bonding of the coating materials with the substrate of the DBLs; and the implementation of routine inspections before each shift to detect early signs of wear. These measures are expected to extend the service life of DBLs and improve overall operational efficiency at the mine.

Keywords: wear, failure mode and mechanisms, dozer blade liners, track dozer, kimberlite tailings, mitigation measures, cost-benefit analysis, mining

1 Chapter One: Introduction

1.1 Chapter summary

Chapter one provides the background for this study, outlining the key concepts, relevant theories, and previous work in the field to establish a foundation for understanding the research problem. It also presents the problem that guides the direction of the study and justifies the need for conducting the research. The section on expected outcomes highlights the anticipated findings that will emerge from the study. The main goal and specific objectives of this study are defined to address the ultimate outcome the research seeks and to provide a clear roadmap for how the research will be conducted. The scope of the research is also clarified. Finally, the outline of this thesis is presented, and the findings from this chapter are summarised in the conclusion.

1.2 Background to the study

Kimberlite is an igneous rock that serves as the primary host for diamonds and is rich in other minerals such as mica, olivine, ilmenite, and chrome diopside (Mat, 2023). The processing of kimberlite to extract diamonds involves several key stages, starting with crushing the ore to progressively smaller sizes in order to liberate the diamonds from the surrounding rock (Brook, 2021). Once the ore is sufficiently reduced in size, it undergoes dense media separation (DMS), where a ferrosilicon slurry is used to create a mixture with a density similar to diamonds (Brook, 2012). This allows heavier particles, including diamonds, to settle at the bottom for further concentration. The DMS process is followed by cyclones that apply centrifugal forces to separate diamonds from lighter waste materials (Bosman, 2014). In some cases, coarse DMS tailings are recrushed to recover any trapped diamonds. After DMS, the concentrate is exposed to X-ray beams, as diamonds luminesce under X-rays, and air jets are used to separate them for sorting. The final recovery step involves sorting and cleaning the diamonds for valuation while the waste is taken for disposal.

At the Orapa diamond mine in Botswana, the leftover material called kimberlite tailings, which contain minimal traces of diamonds, are stored for potential future processing, as

current technology at the mine does not allow complete recovery. **Plate 1.1** shows piles of kimberlite tailings at the Orapa diamond mine in Botswana.



Plate 1.1: Piles of Kimberlite tailing particles at the Orapa diamond mine in Botswana.

The tailings are pushed and scattered by eleven (11) track dozers working in rotation at the mine to sun-dry before being stockpiled for storage. A track dozer is a crawler that has a tractor for supplying power and a metallic blade at its front to cut, push, level or grade soil (Barakat & Sharma, 2019). Dozer blades are of different kinds. They include universal (U) dozer blade, semi-universal (semi-U) dozer blade, angle dozer blade, straight (S) dozer blade, etc. (Caterpillar Inc., 2019). Dozer blades perform a range of earthmoving tasks, such as land clearing, grading, backfilling, excavation, and material transport (Özdoğan & Özdoğan, 2021). At the Orapa diamond mine in Botswana, a track dozer uses its blade to push and scatter piles of kimberlite tailings (KT) to facilitate drying before stockpiling for future diamond recovery. The blade is protected by 16 mm thick, replaceable lining plates known as dozer blade liners (DBLs), which shield the blade's front surface and side wings. The dozer blade liners (DBLs) are attached to the blade using arc welding. **Plate 1.2** illustrates the track dozer, used at the Orapa diamond mine in Botswana and equipped with a semi-U blade covered with dozer blade liners (DBLs).

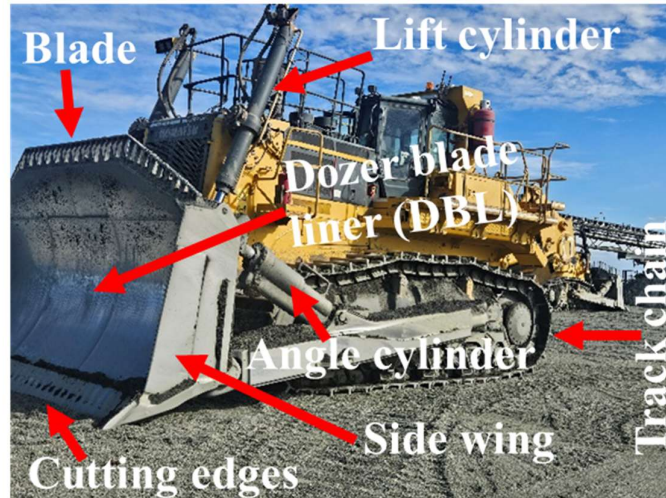


Plate 1.2: Picture of a track dozer used at the Orapa diamond mine in Botswana, with DBLs on its blade.

According to the literature Komatsu Limited (2019), the semi-universal (U) blade combines the desirable characteristics of both straight (S) and universal (U) blades into a single design. Its short wings, which include the dozer end bits, increase the blade's capacity and improve load retention while maintaining the ability to penetrate materials and load efficiently, even in confined spaces. This makes the blade effective in handling various materials in production- orientated applications. The tilt cylinders of the dozer improve its productivity and versatility. **Table 1.1** provides the specifications for the semi-U dozer blade used on the track dozer at the Orapa diamond mine in Botswana.

Table 1.1: Semi-U blade type specifications for a track dozer used at the Orapa diamond mine in Botswana (Komatsu Limited, 2019).

Specification	Description
Operating weight (kg)	13000
Dimensions (mm)	
• Overall width	1760
• Overall height	2610
• Overall length	5263
Blade Capacity (m ³)	27.2
Ground pressure (kg/cm ²)	1.69

The DBLs of the track dozer blade, used at the Orapa diamond mine in Botswana to push and level kimberlite tailings, have been observed to wear down prematurely. Despite efforts to address this issue through daily inspections and repairs via manual metal arc (MMA) welding, the problem persists. Premature wear of equipment is a major challenge within the mining industry, resulting in substantial economic losses (Dayo-Olupona et al., 2023). These losses arise from increased energy consumption, higher costs for replacement parts and spare equipment, higher maintenance expenditures, and interruptions to production (Holmberg et al., 2017).

Therefore, this study aimed to investigate the premature wear of dozer blade liners (DBLs) at the Orapa diamond mine in Botswana through experimental wear and failure analysis. Based on the findings, the study proposed cost-effective mitigation measures to extend the service life of the DBLs and to reduce associated operational and maintenance costs.

1.3 Problem statement

Field observations at the Orapa diamond mine in Botswana revealed that the dozer blade liners (DBLs) on the track dozer blade often experience premature wear due to interactions

with abrasive kimberlite tailings (KT) during pushing and levelling operations. The mine's current maintenance plan involves replacing these DBLs during the 15000-hour midlife overhaul of the track dozer. However, the DBLs tend to wear out prematurely, around 11125 hours, which is below expectations.

This early failure or wear leads to significant costs and operational downtime, adversely impacting the mine's productivity and profit margins. Wear, defined as progressive material loss due to relative motion between surfaces, is a significant maintenance challenge in the mining industry, accounting for up to 50% of total maintenance costs (Kovaříková et al., 2009; Leso et al., 2022; Saha, 2017; Shibe & Chawla, 2013; Svanberg et al., 2021).

Manual metal arc (MMA) welding has been used by local contractors to repair the prematurely worn dozer blade liners, but these efforts have been unsuccessful. Despite the critical need for improved wear resistance, current repair techniques and technologies have not offered a long-term fix.

Therefore, this research aims to uncover the root cause(s) of premature wear or failure of DBLs through engineering failure analysis (EFA). This information will assist the mine in implementing a long-term fix to tackle the challenge. This will enable extension of the service life of these liners to 15000 hours or more, the study seeks to reduce replacement costs, improve operational efficiency, and contribute to more sustainable mining practices at the Orapa diamond mine in Botswana.

1.4 General and Specific Objectives of this Study

This section provides the general and specific objectives of the project.

1.4.1 General objective

The main goal is to investigate the failure and wear mechanisms of Dozer Blade Liners (DBLs) and propose mitigation measures tailored to the conditions faced by DBLs operating in a kimberlite tailings environment at the Orapa diamond mine in Botswana.

1.4.2 Specific objectives

The general objective will be accomplished by achieving the following specific objectives.

- a) Investigate the operational and environmental conditions contributing to the wear and failure of DBLs at the Orapa diamond mine.
- b) Conduct experimental analysis of worn DBLs, including macro- and microstructural characterisation to uncover the root cause of premature wear/failure of the DBLs.
- c) Correlate observed failure modes with field conditions and DBLs material properties.
- d) Develop and recommend cost-effective mitigation strategies to the mine based on the results of the analysis of wear/failure modes of the DBLs.

1.5 Scope of the study

This research will involve experimental analysis to investigate the root causes of premature wear and failure on damaged dozer blade liners (DBLs). Based on the findings from the wear analysis. Mitigation measures that are economically and environmentally friendly will be proposed to the mine to implement them. The study will be limited to the experimental engineering failure analysis.

1.6 Specific theme of this thesis

Assessment of wear and failure of the dozer blade liners (DBLs) from Orapa diamond mine in Botswana was conducted to establish the root cause. A detailed field inspection of the DBLs at the site was carried out to understand the nature of the operational and environmental conditions of the DBLs at the mine. Samples were extracted from the DBLs for laboratory analysis to understand the wear track and characterise the wear morphology.

Characterisation of the damaged samples was carried out using field data, a stereo microscope, optical microscope (OM), and scanning electron microscope (SEM) equipped with energy-dispersive spectroscopy (EDS) to examine the worn-out surface morphology. A spark emission spectrometer was used to determine the elemental composition of the

DBLs, while the Innovatest Vickers hardness tester was used to evaluate the hardness of the DBL samples.

1.7 Significance of the study

This research investigates the root cause(s) of premature wear in dozer blade liners (DBLs) at the Orapa diamond mine. It focuses on identifying the dominant wear modes and mechanisms affecting DBLs, with the aim to recommend improvements in design and maintenance or operational practices. By addressing issues that contribute to the premature wear or failure of the DBLs, such as the abrasive nature of kimberlite, the study seeks to reduce operational costs, minimise downtime, and extend the service life of DBLs.

The initiative is expected to create employment opportunities, improve technical skills within the Botswana workforce, and significantly reduce costs associated with replacing worn-out dozer blade liners. In addition, Orapa diamond mine uses eleven track dozers, an effective solution for one unit can be applied across the fleet. Moreover, the findings may have broader relevance for other mining operations facing similar abrasive conditions, both within and beyond Botswana.

1.8 Thesis structure

The thesis is organised into six chapters, each focusing on the defined objectives. Each chapter starts with an introduction and concludes with a summary of the main findings. References are provided at the end of the thesis, along with appendices that include supplementary materials related to the study but not incorporated in the main text of the thesis. The structure of the thesis is outlined as follows:

- **Chapter 1:** Introduction

This chapter provides an overview of the problem and details the research objectives. It also explains the rationale behind the study.

- **Chapter 2:** Literature Review

This chapter provides a review of current literature relevant to the study. The literature

covers topics such as kimberlite tailings (KT), dozer blade liners (DBLs), the wear modes and mechanisms of DBLs, and a discussion of the environmental and operating parameters for the dozer blade liners, and the research gaps in the literature that are being addressed by the study.

- **Chapter 3:** Materials and experimental procedures

It outlines the approach taken for wear and failure analysis, the experiments performed, the methods of sample preparation, and the techniques for sample characterisation. Additionally, it includes all the standards applied in executing the various procedures.

- **Chapter 4:** Experimental wear and failure analysis results and discussion

Includes an analysis and discussion of the results from the experiments conducted on the wear and failure assessment of the damaged dozer blade liners (DBLs).

- **Chapter 5:** Downtime analysis and mitigation strategies for damaged Dozer Blade Liners (DBLs)

Discusses the costs incurred by the mine due to premature wear and failure of the DBLs, followed by proposed mitigation measures for the damaged DBLs, and a cost-benefit analysis (CBA) of the proposed mitigation measures.

- **Chapter 6:** Conclusion and Recommendations

Concludes the findings from this research thesis involving the root cause and measures to correct the cause. Recommendations for future work are also included in this chapter.

1.9 Conclusion

In this research study, chapter one has provided necessary information on the background of this research as well as the problem statement, aim, specific objectives, scope of the study, specific themes of the research as well as the thesis outline. The background in this chapter introduces the dozer blade liner and its use at the Orapa diamond mine in Botswana and the challenges it encounters. It further went on to introduce mitigation measures to combat the problem. The problem statement of the project is identified. It is then clearly stated that the

aim was to identify and investigate the root cause of DBLs premature wear/failure and propose relevant cost-effective mitigation measures to the mine. The research is narrowed to the experimental analysis of the wear and failure of DBLs.

2 Chapter Two: Literature review

2.1 Chapter summary

Chapter two reviews literature on kimberlite tailings (KT), dozer blade liners (DBLs) degradation, focusing on the nature of wear modes and mechanisms it encounters in service. It further went on to discuss environmental and operating parameters for the dozer blade liners. Thereafter, strategies to combat dozer blade liners (DBLs) wear and failures are presented. The chapter concludes with a summary of the literature review, highlighting gaps that informed the research objectives.

2.2 Kimberlite tailings (KT)

During diamond mining, a substantial quantity of kimberlite tailings is produced. Kimberlite rock typically contains only about 10 - 12 carats (roughly 2 to 2.4 grams) of diamonds per 100 tonnes (Chaurasiya & Markandeya, 2021b). As a result, most of the kimberlite that is processed ends up as tailings, which are then stacked into heaps near the mining site. According to Dunn (2004), when kimberlite rock is crushed and processed to extract diamonds, three different types of waste materials are produced, each classified by their size. The finest material, known as slimes slurry, consists of particles smaller than 0.3 mm. The next category, called grits, includes medium-sized pieces ranging between 0.3 and 1.5 mm. Finally, the largest waste material, referred to as coarse tailings, is made up of chunks between 1.5 and 8 mm in size. KT contains mainly silica, alumina, iron oxide, magnesia and a few traces of diamond for future recovery (Swami et al., 2007). The diamond extraction process involves crushing of the kimberlite, grinding in wet mills down to a particle size ranging between 0.075 and ~ 8 mm, screening, concentration, and recovery. KT typically do not contain any hazardous chemicals as the diamond extraction process involves mechanical process aided by potable water and ferrosilicon (Otieno & Ndoro, 2020). KT has a Mohs hardness range between 6 and 7 (Mat, 2023). **Table 2.1** presents typical kimberlite tailings weight percentage composition.

Table 2.1: Typical kimberlite tailings weight percentage composition (Mcnair, 2023).

Mineral	% weight composition range
SiO ₂	24.15-36.09
MgO	22.78-27.9
Fe ₂ O ₃	4.77-10.5
FeO	1.85-10.5
CaO	3.50-15.87
Al ₂ O ₃	2.03-4.9
TiO ₂	1.50-5.10
H ₂ O ⁺ (oxoniumyl)	5.9-13.05
CO ₂	0.72-12.04
P ₂ O ₅	0.65-2.31
K ₂ O	0.30-2.1
N ₂ O	0.19-0.32
MnO	0.10-0.1

These tailings exhibit a mix of angular and spherical particle shapes and typically contain about 11.5 wt% moisture content (Swami et al., 2007). The abrasive nature of KT, combined with its particle characteristics, accelerates wear on DBLs during operation, leading to frequent maintenance and replacement. **Plate 2.1** shows a picture of a track dozer pushing a pile of kimberlite tailings at the Orapa diamond mine in Botswana.



Plate 2.1: A track dozer pushing Kimberlite tailing particles at the Orapa diamond mine in Botswana.

2.3 Dozer Blade Liners (DBLs)

To protect the dozer blade from wear and tear, it is fitted with lining plates known as dozer blade liners (DBLs). Different track dozer blades use varying designs of DBLs, customised to the specific requirements of the mining operation. DBLs are typically manufactured through casting or hot rolling processes (Jere et al., 2025). Depending on the specific application, they may be made from materials such as the Hardox steel series, Arcoplate, Domex, Bisalloy 80, high-strength steel alloys, chromium-molybdenum steels, and other specialised alloys (Gates, 2003). **Plate 2.2** shows a Liebherr PR 776 Litronic track dozer with a blade protected by DBLs.

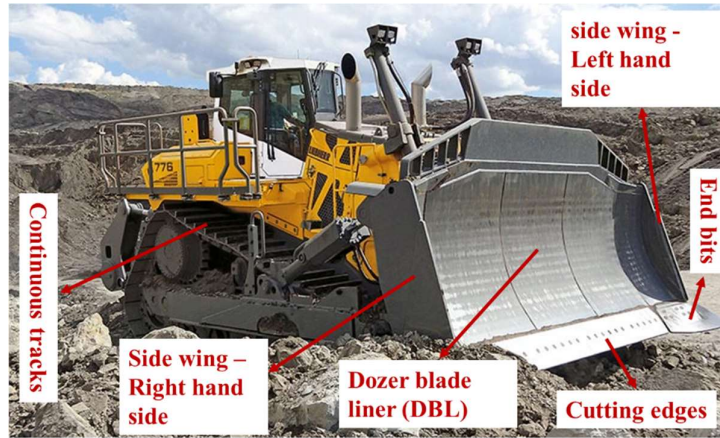


Plate 2.2: Liebherr PR 776 Litronic track dozer with DBLs on its blade (Power Equipment Company, 2017).

Most DBLs have a limited lifespan due to cracks and defects caused by harsh working conditions such as uneven and unstable terrain in open-pit mines, abrasive kimberlite environments in diamond mines, mud and waterlogged conditions in copper mines, among others (Metso Outotec, 2021). Once damaged, DBLs are often replaced with new lining plates or repaired using traditional methods like gas metal arc welding (GMAW) or manual metal arc welding (MMAW) (Barnes et al., 2015; Haynes International, 2025). However, when the economic value of the DBLs is high, repair efforts are prioritised. Unfortunately, repaired DBLs frequently do not meet performance expectations and tend to exhibit defects due to increased residual stresses and distortions as a result of the significant heat induced during the repair process (Kahhal et al., 2024).

In 2023, capital expenditure for the top 30 mining companies globally was estimated to increase by 6.2%, reaching approximately USD109.2 billion (Li, 2023). 30 - 50 % of this cost was directed towards equipment and maintenance, including DBLs, thereby, highlighting the impact of DBL's wear and failure to the mining industry (Grand View Research, 2023). Thus, there is growing interest in exploring the cause of premature failure of DBLs to come up with relevant cost-effective mitigation measure to counter the problem.

2.4 Environmental and operating parameters for the dozer blade liners

To maximise production, it is crucial to match a track dozer with the appropriate blade and lining plates (Gokhale, 2003). The first step is to examine the types of tasks the track dozer is expected to perform throughout its operational lifespan. Then an assessment of the materials it will be handling or dozing is performed, along with any limitations associated with the track dozer.

2.4.1 Materials to be moved and environmental considerations

Track dozers used in mining face some of the harshest working conditions, including abrasive wear from pushing through rocks and ores and heavy impact loads that lead to fatigue failure. Mines expose dozers to harsh conditions such as corrosion, extreme temperatures, and uneven terrain, which place additional strain on DBLs. In diamond mines, abrasive kimberlite and large rocks contribute to significant wear and tear on the DBLs, making efficient dozing challenging. For example, diamond mines in Orapa and Jwaneng use dozers to push abrasive kimberlite tailings, which promote a high wear rate of the DBLs (Mining Technology, 2004). In addition, waterlogged conditions, common in coal and gold mines, accelerate corrosion and wear on tracks and DBLs (Government of western Australian, 2015). These factors emphasise the need for highly wear-resistant materials for critical parts, such as DBLs, to ensure durability and high performance. Thus, most materials can be moved with dozers, but dozer performance will vary according to the characteristics of the materials, as outlined in **Table 2.2**.

Table 2.2: Factors influencing material movement and dozer blade efficiency (Caterpillar Inc., 2019).

Characteristics	Description
Particle size and shape	Larger particles are more difficult for the dozer blade cutting edge to penetrate. Sharp-edged particles resist the natural rolling action of a dozer blade, requiring more horsepower to move compared to the same volume of material with rounded edges.
Voids	When there are minimal or no voids, the particles are in close contact with one another, maximising surface area interaction. This creates strong bonds between particles that are difficult to break. A well-graded material with few voids tends to be dense and challenging to extract from its natural state.
Water content	In most materials, the lack of moisture strengthens the bond between the particles, making it harder to remove the material from its natural state. On the contrary, the high moisture content makes dozing difficult as the material becomes heavier, requiring more force to move. The optimal moisture content minimises dust and provides the best conditions for efficient dozing and operator comfort. The effect of freezing is influenced by moisture levels; as the moisture content increases and the temperature drops, the bonds between the particles become stronger. However, freezing a completely dry material does not alter its properties.

2.4.2 Dozer blade selection and operation

Dozer blade liners (DBLs) differ in size and design according to work applications. Factors such as soil characteristics, moisture content, compaction, and terrain will affect the choice of blade to optimise dozer productivity. Selecting the appropriate blade and DBLs for a given task can lead to fuel savings, increased productivity, and minimised wear and tear (Caterpillar Inc., 2019). For example, if the track dozer is used in kimberlite tailings

conditions, wear-resistant DBLs are required. If the environment is wet, corrosion-resistant DBLs are adopted, and so on. During dozing, the dozer blade is adjusted by hydraulic action to raise or lower it, and its pitch, tilt, and angle are also managed by hydraulic controls (Özdoğan & Özdoğan, 2021). The DBLs protect the blade from wear and tear as the blade pushes, shears, cuts, and rolls the material ahead of the tractor and/or pulls, shears, and rips the ground behind.

2.5 Dozer blade liners (DBLs) wear modes and mechanisms

This subsection explores the wear modes and mechanisms in dozer blade liners (DBLs). Understanding these common wear modes and mechanisms can aid in implementing preventive maintenance strategies, extending the life of the equipment, selecting a suitable remanufacturing technique, and reducing downtime. The discussion is further enriched with insights from related components, such as wheel loader buckets, ploughshares, and liner plates, which operate in comparable environments and are made from materials similar to those of DBLs, thereby providing a broader perspective on the wear behaviours of DBLs.

2.5.1 Abrasive wear mode and mechanism in DBLs

The material removal process in abrasive wear closely resembles the machining and grinding techniques used in manufacturing (Swain et al., 2021). According to Hylén et al. (2021), during the early stages of wear, the asperities penetrate the softer surface under normal pressure. As tangential motion occurs, the softer material is worn away due to various abrasive micro-mechanisms. This leads to the formation of grooves and scratches on the surface, while the wear debris typically appears as micro-cutting chips. Material removal can occur through mechanisms such as microcutting, microfracture, grain pull-out, or accelerated fatigue caused by repeated deformations, as shown in **Figure 2.1**.

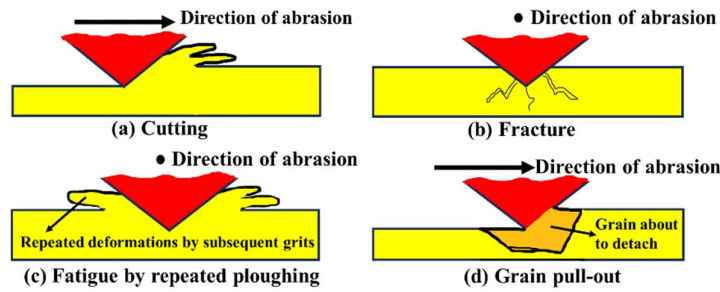


Figure 2.1: Abrasive wear mechanisms: (a) microcutting, (b) fracture, (c) fatigue by repeated ploughing and (d) grain pull-out (Stachowiak & Batchelor, 2005).

Alojali and Benyounis (2016) described the first mechanism, cutting (**Figure 2.1a**), as a classic model in which a hard asperity penetrates a softer surface, producing wear debris. In cases where the material is brittle, fractures may develop, as illustrated in **Figure 2.1b**. When a ductile material is abraded with blunt grit, cutting is less likely and the surface is repeatedly deformed, leading to wear debris from metal fatigue (**Figure 2.1c**). The final mechanism, shown in **Figure 2.1d**, illustrates grain detachment, where entire grains are lost as wear debris. From **Figure 2.2**, it is evident that the dozer blade liners experienced abrasive wear, as indicated by abrasive wear marks, cracks, deformations, and scratches.

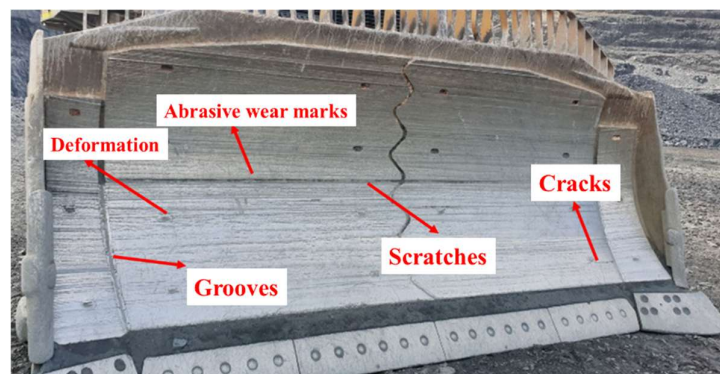


Figure 2.2: Abrasive wear in dozer blade liners (Cutting edges, 2020).

In another study which focused on minimising costs in the mining sector by applying hard surfacing to ground-engaging tools, Chippendale (2000) examined the dozer blades of four Caterpillar D11R machines, identifying blade sections prone to high wear rates. The analysis revealed that the dozer blade cutting edge experiences the most significant wear,

which also influences the cutting efficiency. The study found that the wear mechanisms that affect these edges include a combination of low-stress abrasion, high-stress abrasion, gouging abrasion, polishing wear, and impact erosion. However, Chippendale's work merely listed the wear modes and mechanisms observed on the dozer blade but did not detail the methodology used to reach these conclusions. Operational data from track dozers, along with fractography, optical microscopy, and scanning electron microscopy combined with energy dispersive X-ray spectroscopy (SEM/EDS) should have been utilised to examine microstructural alterations, fracture surfaces, and elemental composition in the worn regions. Incorporating these methods, along with micrographs, operational data, and macrographs, would have offered deeper insight into the root causes of failure. These would have allowed for more targeted material improvements and design optimisations, rather than simply identifying the wear types without a description of how the conclusion was reached.

Plate 2.3 shows parts of the CAT D11R dozer blade subjected to high wear rates.

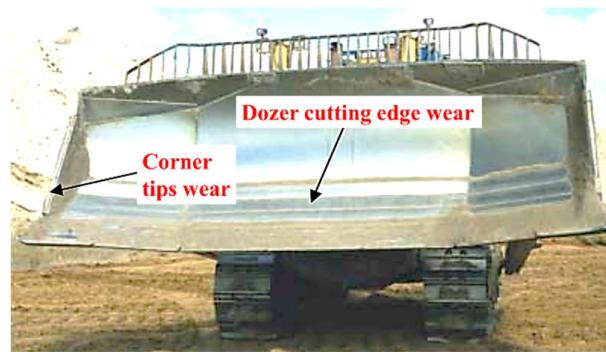


Plate 2.3: Parts of the CAT D11R dozer blade subjected to high wear rates (Chippendale, 2000).

Hylén et al. (2021) reviewed the impact of sliding abrasive wear on a bolt-on edge (BOE) section of a wheel loader bucket to understand the wear mechanisms and the application of wear-resistant steel. SEM image analysis (**Figures 2.3a** and **2.3b**) revealed significant ploughing, wedge formation, and grooves, indicating exposure to sliding abrasive wear. Furthermore, the SEM images (**Figures 2.3c** and **2.3d**) showed that the primary wear mechanisms responsible for material removal were micro-ploughing and micro-cutting. Some areas also exhibited weak fractures, suggesting that the wear mechanism also involved

impact forces. Furthermore, the black spots on both sides were probably due to corrosion, indicating the possibility of wet working conditions. Because the DBLs operate under comparable environmental and loading conditions, similar degradation and wear mechanisms are anticipated.

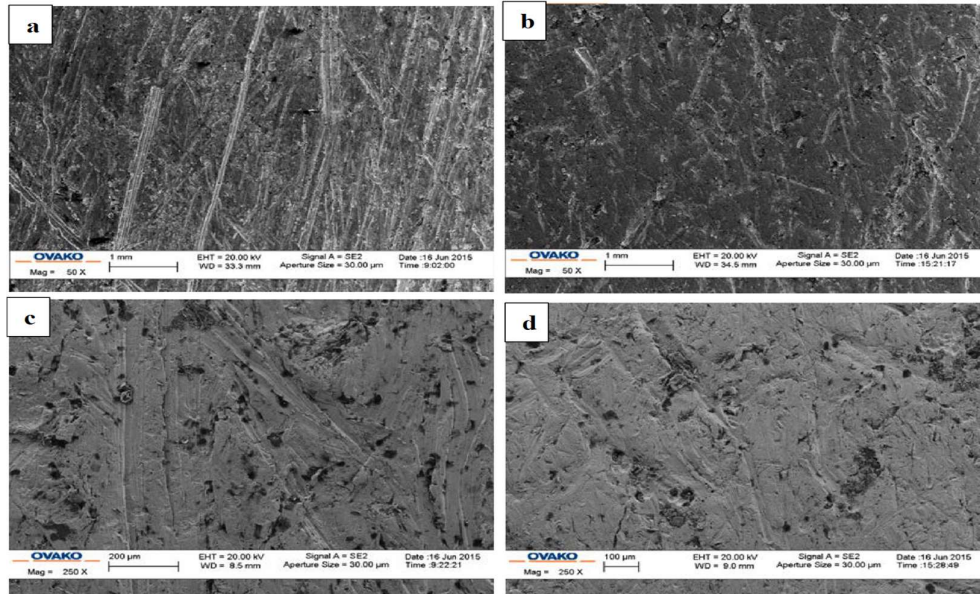


Figure 2.3: SEM micrographs of bottom surface (a), top surface (b) (at a magnification of 50X) and bottom surface (c), top surface (d) (at a magnification of 250X) of the BOE (Hylén et al., 2021).

Abrasive wear occurs in two primary modes, which are determined by the type of contact involved (Hutchings & Shipway, 2017). These modes are referred to as two-body and three-body abrasion (**Figure 2.4**) (Saha, 2017). In two-body abrasive wear, the abrasive particles (protuberances) are either fixed or slide and/or roll freely, acting as a counterbody. In three-body abrasive wear, the abrasive particles are free to slide and/or roll between the two mating surfaces (Alpas et al., 2018). When a DBL operates on rough surfaces such as hard rock, compacted soil, or gravel, abrasive two-body wear is common. In this case, fixed abrasive particles act as cutting tools, creating grooves on the DBLs and causing high wear rates as the material is being removed. On the contrary, when working with loose materials, such as sand or soft soils, three-body abrasive wear occurs. Here, free-moving particles slide

or roll between the blade and the surface, causing milder wear. However, over time, this continuous movement can still result in significant material loss, especially with hard particles such as quartz or silica.

Kandeva-Ivanova et al. (2016) described a different abrasion classification system that divides it into three categories: high-stress (or grinding) abrasion, low-stress (or scratching) abrasion, and gouging abrasion. Gouging abrasion is characterised by the removal of large particles from a surface, creating deep grooves or pits. The stresses associated with this type of abrasion cause significant plastic deformation of the material. High-stress abrasion includes scratching and pitting, as well as plastic deformation resulting from the effect of embedded particles (Chippendale, 2000). In contrast, low-stress abrasion occurs under lighter loads, where the abrasive particles do not fracture, resulting in a worn surface with fine scratches (Vencl et al., 2010).

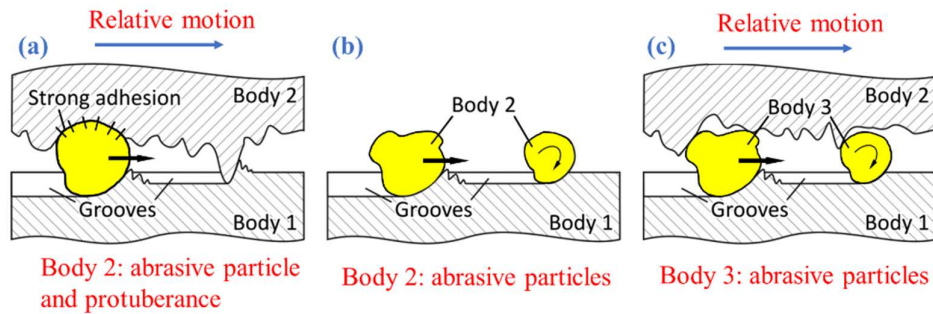


Figure 2.4: Illustration of the differences between (a) two-body abrasive wear, (b) three-body abrasive wear (Kandeva-Ivanova et al., 2016).

2.5.2 Surface fatigue modes and mechanisms in DBLs

Fatigue wear begins when cracks and fissures develop on the surface due to strains created by external influences such as sliding (Rigney & Hirth, 1979). Shear strains generated during sliding take place at varying depths below the surface, with their highest values at the surface. **Figure 2.5** shows the strain levels present in the deformed surface layer. This is also expected to be evident in DBLs, as their operation involves repeated and dynamic interaction with abrasive KT. During operation, KT particles impact the dozer blade and

slide both upward and downward along its surface as the track dozer pushes the tailings forward. These repeated sliding and impact actions generate severe plastic deformation on the blade surface, which leads to distinct patterns of subsurface microstructural evolution. As illustrated in **Figure 2.5**, this abrasive contact results in the formation of three deformation zones within the DBL: a top layer of very highly deformed material, a middle layer of moderately deformed material, and a lower region of bulk high deformed material. These zones form due to accumulated shear stress and strain caused by the constant friction and impacts (Alpas et al., 1993; Rigney et al., 1984). The topmost layer experiences the greatest deformation because of its direct exposure to the abrasive KT, often leading to micro-cracks, surface delamination, and eventual material loss.

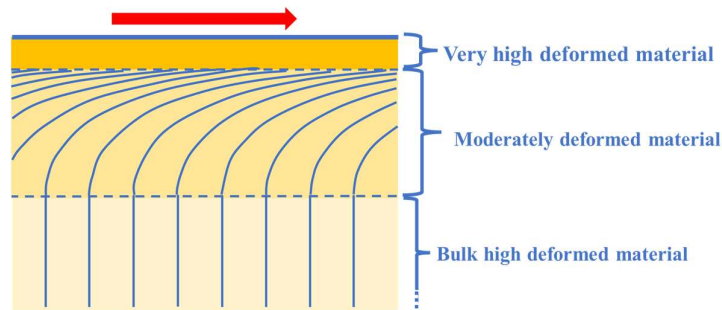


Figure 2.5: Strain measurements on a deformed surface (Stachowiak & Batchelor, 2005).

The area where strain-induced stress reaches its critical threshold is identified as the vulnerable point where cracks begin to form. Once a crack develops at this location, it tends to extend along the weak planes or boundaries of dislocation cells, ultimately resulting in the creation of the primary crack. The mechanism is depicted in **Figure 2.6**.

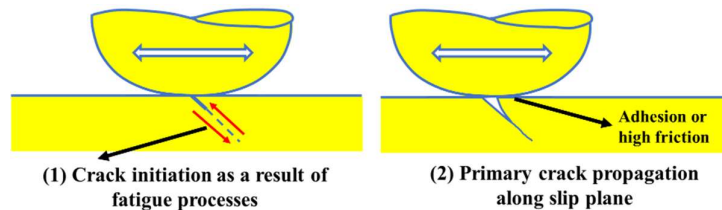


Figure 2.6: Diagram depicting primary crack initiation in fatigue wear (Stachowiak & Batchelor, 2005).

The primary crack, under continued stress from sliding contact at the interface, develops into secondary cracks by crack branching leading to multiple cracks forming. These secondary cracks propagate along weaker planes within the subsurface, eventually reaching the surface and forming wear particles. This mechanism is illustrated in **Figure 2.7**.

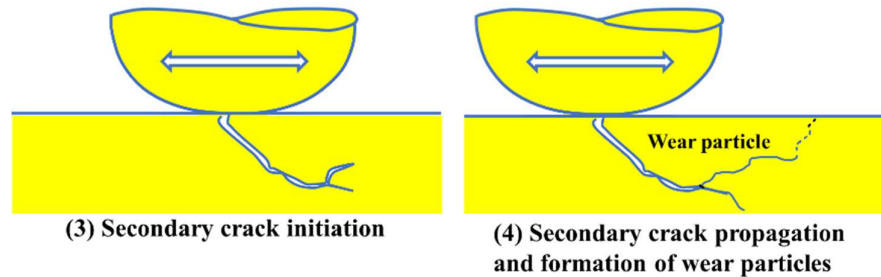


Figure 2.7: Diagram illustrating the initiation of secondary cracks due to fatigue wear (Stachowiak & Batchelor, 2005).

Fatigue wear on sliding contacts is significant on unlubricated surfaces and is exacerbated by the sliding motion at the material interface. Crack initiation occurs in weaker regions of the surface, such as areas containing non-metallic inclusions like alumina (Al_2O_3) and manganese sulfide (MnS), which act as stress raisers in steel (Bhadeshia & Honeycombe, 2017). In these regions, the planes tend to align parallel to the sliding direction. These cracks propagate from the surface to the subsurface, causing the formation of lamellar wear particles along the plane (Soda et al., 1975a). Lubrication is essential to reduce fatigue wear in sliding contacts, as it decreases surface friction. The delamination model of wear explains how lubrication decreases friction, which in turn reduces delamination and subsequent wear (Soda et al., 1975b). The fatigue wear process caused by sliding contact is illustrated in **Figure 2.8**.

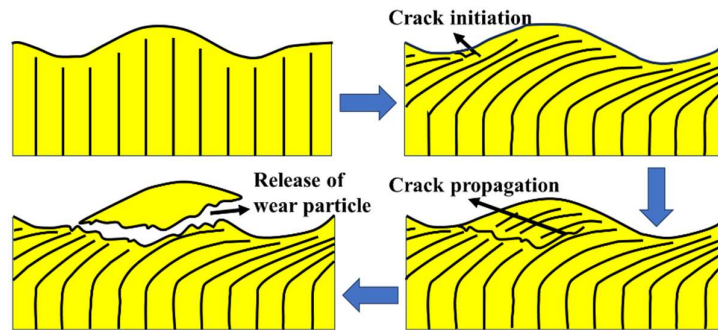


Figure 2.8: Diagram illustrating the initiation of fatigue wear in sliding contact (Stachowiak & Batchelor, 2005).

Bošnjak et al. (2018) studied the failure mechanisms of the SRs 470 bucket wheel excavator's buckets by employing ANSYS simulations to assess the operational stresses. The study revealed that the primary failure causes were "design-related defects," which originated from errors in geometric design and material selection. Additionally, increased residual stress and cold cracking at the welded joint between the knife and the bucket body highlighted the presence of "manufacturing-related defects." These combined design and manufacturing problems led to the initiation and propagation of fatigue cracks over time, eventually causing the buckets to fail. **Plate 2.4** shows damage to the bucket structure.

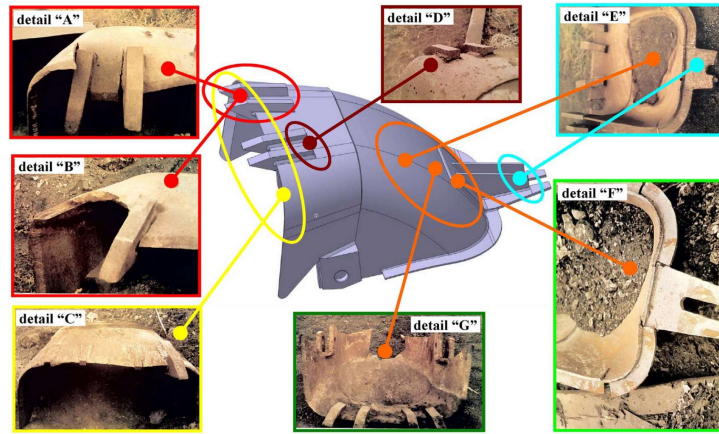


Plate 2.4: Failure of the buckets' structure: details A, B, C, D – failure of the teeth and knife; details E, F, G – failure of the buckets' back and zones of rear wedge fastening (Bošnjak et al., 2018).

Ligier et al. (2022) analysed the wear properties of various Hardox steels, including Hardox 500, Hardox 600, and Hardox extreme under different soil conditions, emphasising how soil composition affects wear mechanisms. In light soil, the main wear patterns observed for Hardox 500 steel (see **Figure 2.9a**) were characterised by scratching, ridging, and partial removal of material from grooves. Chipping occurred due to microfatigue induced by cyclic impacts of the sand grains, identified as fatigue wear, with some plastic deformation also observed. In medium and heavy soils (**Figure 2.9d** and **Figure 2.9g**), similar types of wear was present but with more intense damage, characterised by pronounced mechanical impact patterns. Hardox 600 steel, despite its increased hardness compared to Hardox 500, exhibited scratching, ridging, and fatigue wear in light soil (**Figure 2.9b**). In medium soil (**Figure 2.9e**), the wear patterns were similar, but the ridging intensity was notably higher. In heavy soil (**Figure 2.9h**), chipping, ridging, and microcutting dominated, driven by mechanochemical wear facilitated by the soil's composition. Hardox extreme steel in light soil (**Figure 2.9c**) showed deep and wide ridging traces, followed by plastic deformation and material tear-up. In medium soil (**Figure 2.9f**), the effects of ridging and microcutting were more pronounced than in other materials. In heavy soil (**Figure 2.9i**), wear was characterised by prominent wide and deep grooves, reflecting significant material loss. The

materials tested exhibit properties like those of commercial abrasion-resistant steels used in dozer blade liners (DBLs), making the results applicable to DBLs.

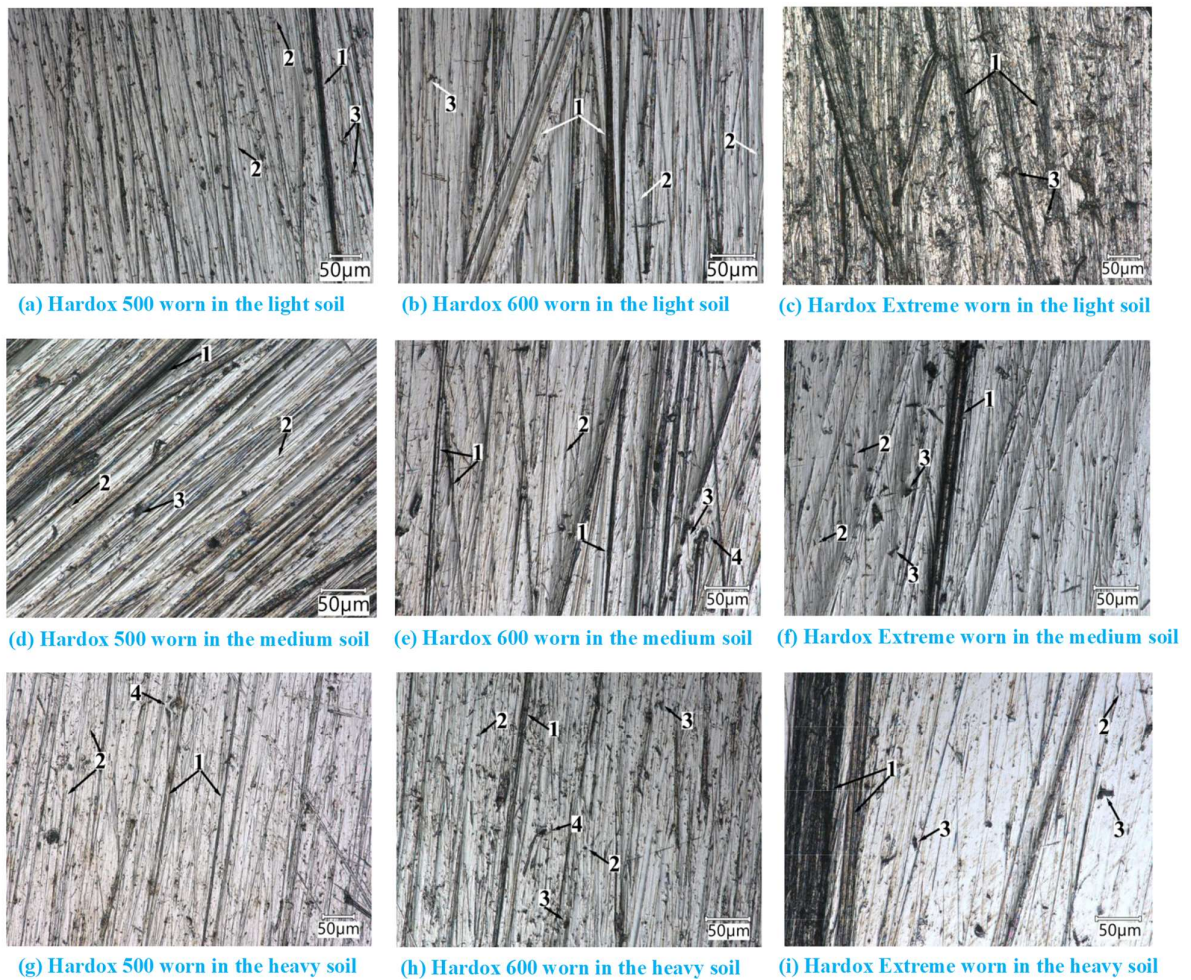


Figure 2.9: The surfaces of the Hardox steel samples subjected to wear in various soil types observed by light optical microscopy: (a) Hardox 500 worn in the light soil, (b) Hardox 600 worn in the light soil, (c) Hardox Extreme worn in the light soil, (d) Hardox 500 worn in the medium soil, (e) Hardox 600 worn in the medium soil, (f) Hardox Extreme worn in the medium soil, (g) Hardox 500 worn in the heavy soil, (h) Hardox 600 worn in the heavy soil, (i) Hardox Extreme worn in the heavy soil. The surface features are labeled as: 1 - ploughing, 2 - microcutting, 3 - chippings, and 4 - plastic deformation. (Ligier et al., 2022).

2.5.3 Corrosive and oxidative wear mode and mechanism in DBLs

Corrosive wear describes the damage to mechanical components resulting from the combined effects of mechanical wear and the removal of corrosion products from the metal surface due to environmental exposure (Xu et al., 2023). Because corrosion and wear interact, the overall wear rate becomes greater than if either process occurred independently (Zirari & Trabadelo, 2024). Corrosion-induced surface deterioration accelerates the wear process (Li, 2013). Zhao (2013) pointed out that corrosive wear can occur in different forms such as erosion-corrosion, cavitation-corrosion, abrasion-corrosion, and fatigue wear-corrosion. **Table 2.3** summarises the type of corrosive wear common in mining operations.

Table 2.3: Types of corrosive wear in mining equipment.

Type of Corrosive Wear	Description
Erosive-corrosive wear	Surface wear from fast-moving abrasive particles and chemical attack (Fernandez, 2025).
Abrasive-corrosive wear	Surface scratching and gouging by particles plus chemical corrosion (SSAB, 2025).
Fatigue wear-corrosion	Occurs when a mining equipment under cyclic stresses is also exposed to a corrosive environment. It differs from regular fatigue, which occurs without any corrosive influence (Cragolino, 2008).
Cavitation-corrosive wear	Occurs when vapor bubbles form in a liquid where pressure is low, then collapse violently, creating shock waves that damage mining equipment surfaces (Li, 2013).

Shibe and Chawla (2013) noted that during corrosive wear, the surfaces in contact interact with the surrounding environment and form reaction products on the surface asperities. These products are subsequently worn away by cracking and abrasion, which increases the

reactivity of the asperities as a result of variations in temperature and mechanical properties.

Table 2.4 discusses environmental factors influencing corrosive wear of mining equipment.

Table 2.4: Environmental factors influencing corrosive wear in mining operations.

Factor	Description	Impact on corrosive wear
Presence of corrosive agents	Acidic and alkaline solutions from mining processes; sulphide minerals reacting with oxygen and water.	Chemical attack on mining equipment surfaces; accelerated corrosion due to sulphide mineral byproducts (Fernandez, 2025)
Abrasive particles	Hard ore particles (e.g., quartzite, magnetite); slurry composition (particle size, hardness, concentration).	Mechanical wear removes protective layers, exposing fresh metal to corrosion; combined abrasive-corrosive wear increases material loss (Jiang et al., 2024).
Oxygen presence	Oxygen enhances electrochemical reactions, especially in the presence of sulphide minerals (Ma et al., 2024).	Higher corrosion rates, particularly during ore grinding in oxygen-rich environments.
High humidity and temperature	Moist environments (humidity) and elevated temperatures in mining operations.	Increased electrochemical corrosion; softened equipment material leads to greater abrasion and faster chemical reactions (Andrade, 2023).
Slurry characteristics	Rheological properties (viscosity, particle size distribution) and chemical composition (pH, ionic content).	High-viscosity slurries intensify abrasion; acidic or alkaline conditions increase chemical attack (Xu et al., 2018).
Operational conditions	Continuous operation coupled with inadequate maintenance.	Prolonged exposure accelerates wear; poor maintenance allows buildup of

		corrosive agents and delays repairs, worsening damage (Fernandez, 2025).
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Corrosion mechanisms involve the formation of protective films, sacrificial layers, and rapid corrosion (Stachowiak & Batchelor, 2005). According to Alojali and Benyounis (2016), presence of fine corrosive products on surfaces contribute to the generation of wear particles during corrosive wear. When these protective layers are disrupted or removed by sliding or abrasion, fresh metal is exposed, and a new layer begins to form, creating a continuous cycle of removal and formation. Corrosive agents such as water, seawater, oxygen, acids, and atmospheric gases like hydrogen sulphide and sulphur dioxide play a key role in these processes (Kalpakjian & Schmid, 2022). In corrosive wear, tribochemical reactions form a reactive surface layer that is gradually worn away by friction. The wear rate depends on the balance between the formation and removal of these reactive layers. **Figure 2.10** shows the corrosive and oxidation wear observed on a dozer blade liner from a Caterpillar D8 bulldozer.

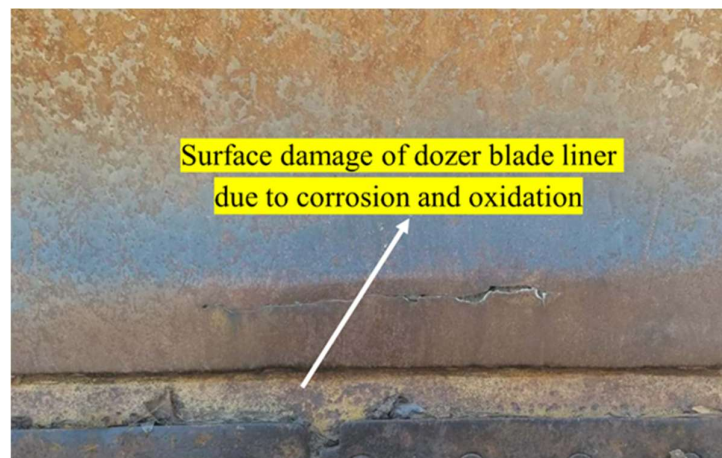


Figure 2.10: Corrosive and oxidation wear of a dozer blade liner for caterpillar D8 bulldozer (WeldingWeb artisan, 2021).

Swain et al. (2021) reported that an oxide layer on a metal surface can reduce wear, depending on the material properties and contact conditions. If the metal beneath the oxide is soft or subjected to high contact loads, wear through abrasion or adhesion becomes more pronounced. Conversely, if the underlying metal is sufficiently hard, oxidation wear occurs.

Frictional heating and plastic deformation during sliding accelerate oxidation, promoting the rapid growth of a thicker oxide layer that continuously replenishes itself, helping to protect the metal. Notably, oxidation wear does not occur in inert atmospheres or vacuums. When oxidation wear dominates, overall material loss is significantly reduced. **Figure 2.11** illustrates this mechanism.

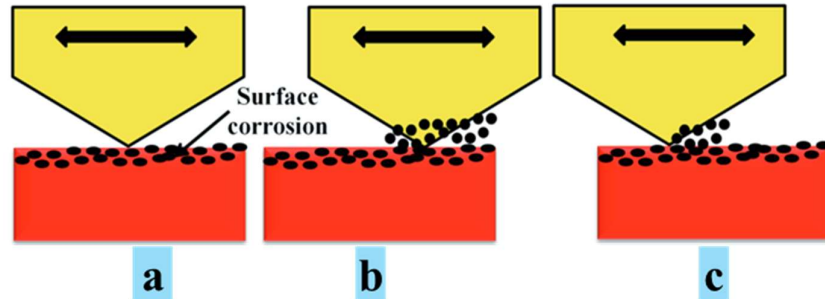


Figure 2.11: Corrosive wear mechanism: (a) oxide film formation, (b) film breakdown and debris generation, and (c) steady-state corrosive wear (Swain et al., 2021).

In this process (**Figure 2.11a**), frictional heating and plastic deformation initiate oxidation reactions, leading to the formation of a thin protective oxide film (Abdelbary & Chang, 2023). Continued sliding causes mechanical stresses that crack and spall parts of the oxide layer (Alojali & Benyounis, 2016) (**Figure 2.11b**). Detached oxide fragments accumulate as debris at the contact interface, exposing fresh metal surfaces and accelerating local corrosion. As sliding continues, a dynamic equilibrium is established where oxide film formation, breakdown, and debris removal occur cyclically, resulting in a steady wear rate (Ramteke et al., 2024) (**Figure 2.11c**).

In summary, mining environments subject equipment to severe corrosive wear due to the combined effects of mechanical action, abrasive particles, and chemical attack. Track dozers, particularly those operating in highly abrasive and moisture-laden conditions, such as in kimberlite tailings or wet overburden, are no exception. Given their direct engagement with mineral-rich soils, frequent exposure to water, and continuous mechanical loading, the DBLs are especially vulnerable to these corrosive wear mechanisms. Therefore, it is highly likely that the modes of corrosive wear observed in general mining equipment are also prevalent in DBLs during mining operations.

2.5.4 Factors affecting wear behaviour of dozer blade liners (DBLs)

Wear is commonly viewed as a material-related problem; however, it is, in fact, a characteristic of the system influenced by several factors. These include the properties of the abrasive material, the properties of the wear-resistant material, and the contact conditions between them. Understanding the interplay between these factors is crucial for developing effective strategies to improve the durability and performance of DBLs in harsh operational environments. **Table 2.5** summarises the factors that influence the wear behaviour of materials - DBLs inclusive.

Table 2.5: Factors that affect wear behaviour of a dozer blade liners (Abbas, 2009).

Abrasive Properties	Wear Material Properties	Contact Conditions
Particle size	Hardness	Force/impact level
Particle shape	Yield strength	Velocity
Hardness	Elastic modulus	Impact/impingement angle
Yield strength	Ductility	Sliding/rolling motion
Fracture properties	Toughness	Temperature
Concentration	Work-hardening characteristics	Presence of moisture
	Fracture toughness	pH levels
	Microstructure	
	Corrosion resistance	

2.6 Strategies to combat dozer blade liner (DBL) wear and failures

The literature review reveals that combating wear and failure of DBLs in diamond mines involves a multifaceted approach, including selecting wear-resistant materials like Hardox

steel and chromium carbide, maintaining equipment through regular inspections and lubrication, and applying protective coatings or liners (Patel & Lyman, 2015; Tyrrell, 2023). These strategies, supported by industry practices and research, can significantly enhance the durability and efficiency of DBLs, reducing operational costs and downtime in the challenging environment of kimberlite tailings.

For example, Chippendale (2000) examined wear-related problems and hardfacing applications on four Caterpillar D11R dozer blades operating at the BHP Gregory mine. To reduce the effects of wear on the dozer blade, an unknown hardfaced wear package developed by Abrasion Resistant Materials (ARM)* Pty Ltd was used. Numerous field trials were carried out to assess the durability of the hardfaced and unhardfaced cutting edges of the dozer blade. The results of these field trials indicated that the hardfaced dozer blades led to a total savings of USD 100,480 for a fleet of four dozers over 6000 hours of usage.

Eduardo et al. (2017) conducted field trials to characterise and assess the performance of Iron niobium carbide (FeNbC), a metal matrix composite, applied as a hardfacing coating using laser cladding (LC) on low-alloy carbon steel bucket teeth from an ore wheel loader operating at the Companhia Brasileira de Metalurgia e Mineração (CBMM) mine in Araxá, Brazil. Their findings indicated that the FeNbC hardfacing layer exhibited strong adhesion to the carbon steel teeth, effectively preventing spalling during intense operations. After field tests, the coating maintained the same morphology and phase composition as the originally applied FeNbC particles. The laser-clad teeth had a service life of 2200 hours, reflecting a 64% improvement compared to the best previous performance and approximately 80% longer than the average service life of standard carbon steel teeth. Furthermore, coated teeth experienced 21% to 31% less weight loss, and their length reduction was 16% to 18% lower compared to uncoated teeth after the same duration. **Plate 2.5** shows steel teeth of a Volvo wheel loader before (a) and after coating with FeNbC in images (b), (c), and (d).

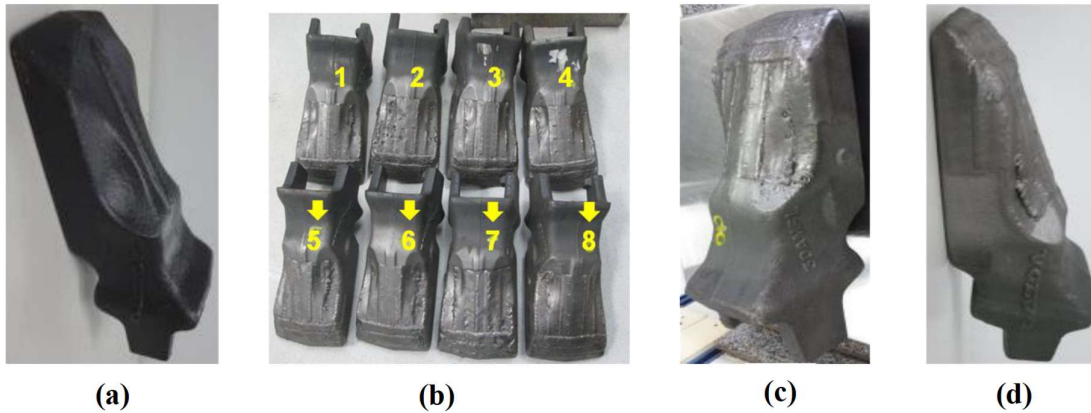


Plate 2.5: Steel teeth of a Volvo wheel loader shown before (a) and after coating with FeNbC in images (b), (c), and (d) (Eduardo et al., 2017).

2.7 *Gaps in the literature*

This study addressed the following key gaps in the existing literature.

- There is limited research analysing the specific wear modes and failure mechanisms that dozer blade liners (DBLs) experience in harsh mining environments, particularly in diamond mining operations.
- There's a noticeable lack of in-depth research on how DBLs actually fail while in use, which makes it difficult to properly diagnose failures and predict how long these components will last in the field.
- The influence of kimberlite tailings (KT) on the degradation and failure behaviour of DBL materials remains poorly understood, especially in relation to failure mechanisms such as abrasion, surface fatigue, or plastic deformation, which are common in DBLs.
- Few studies have applied engineering failure analysis to develop corrective measures that could extend DBLs service life, such as identifying root causes and recommending design or material changes based on failure modes.

2.8 Conclusion

This section began with a review of kimberlite tailings (KT) and dozer blade liners (DBLs). It then described the environmental and operational parameters affecting DBLs used in diamond mines for pushing KT. The wear modes and mechanisms of DBLs in harsh mining conditions were reviewed. Factors affecting the wear behavior of DBLs were discussed, followed by a detailed explanation of the gaps in the currently available literature and mitigation measures to combat wear of dozer blade liners.

3 Chapter Three: Materials and methodology for implementing experimental wear and failure analysis for damaged DBLs:

3.1 Chapter summary

This chapter outlines the procedures and techniques adopted to achieve the objectives of the project. The research methodology was developed to investigate typical wear, its causes, modes, and mechanisms in dozer blade liners (DBLs) through experimental analysis. The experimental approach included visual inspection; stereo and optical microscopy; scanning electron microscopy (SEM) coupled with energy dispersive spectroscopy (EDS); chemical analysis; and macro- and micro-hardness testing. These methods, along with the materials, standards, sample preparation procedures, and characterisation techniques used, are described here to identify the wear modes and mechanisms affecting the worn DBLs. **Figure 3.1.** shows experimental concept evaluation for root cause of the DBLs premature wear or failure.

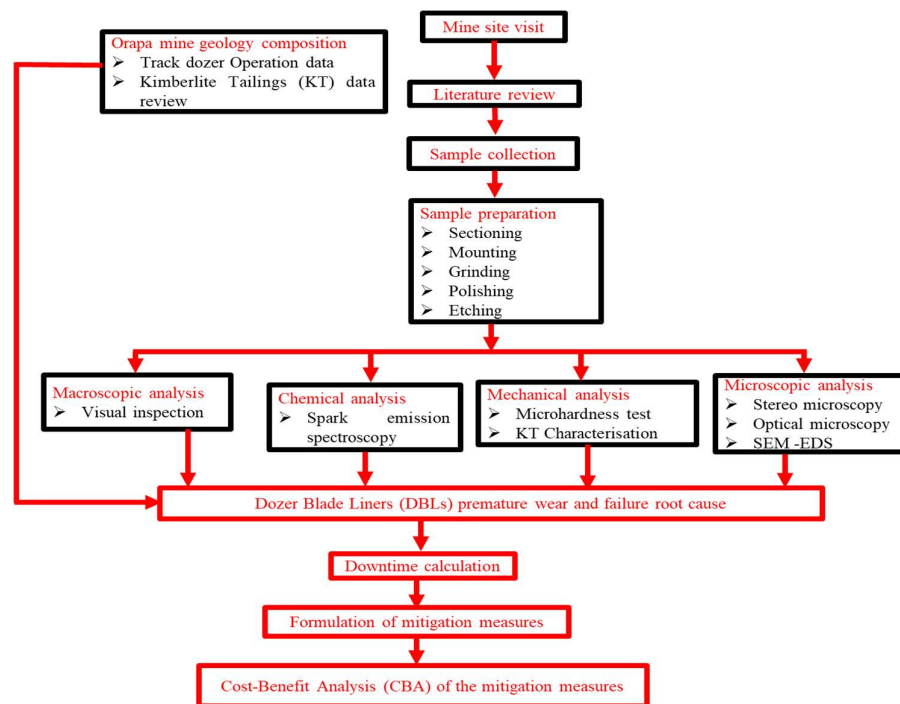


Figure 3.1: Flow chart of experimental procedure.

3.2 Kimberlite tailings characterisation

Kimberlite tailing (KT) particles were collected and analysed to determine their abrasiveness and hardness. The analysis revealed the presence of silica, magnesia, traces of diamond, and other hard rock bands (Chaurasiya & Markandeya, 2021a). These characteristics were incorporated into the methodology for evaluating their influence on the wear resistance and service life of the DBLs. To evaluate the suitability of the DBL material for pushing or leveling kimberlite tailings, the mechanical properties of the kimberlite tailings provided by the mine were compared to those of AISI 1513 (Putra et al., 2021), the material used for the DBLs, as listed in **Table 3.1**.

Table 3.1: Mechanical properties of the kimberlite tailings and the DBL (AISI 1513) at the Orapa diamond mine in Botswana.

Material	Density (g/cm ³)	Modulus of elasticity (GPa)	Poisson's ratio	Tensile strength (MPa)	Yield strength (MPa)	Hardness
AISI 1513	7.85	210	0.27	585	450 (Putra et al., 2021)	218 HV ₁₀
Kimberlite tailings	2.66	100 (Poudjom Djomani et al., 2005)	0.25 (Poudjom Djomani et al., 2005)	-	-	(6 - 7 Mohs) $\approx$ (714 - 1100 HV ₁₀) (McNair, 2023)

It was observed at the mine that a 10.98% average moisture content (see **Appendix B**) in the kimberlite tailings (KT) increases adhesion, causing the material to stick to DBL surfaces and leading to greater resistance during movement, friction, and wear. Moisture also increases the cohesiveness of KT, leading to agglomeration that creates a more abrasive

interface against the DBL surface, further accelerating wear. This clumping contributes to operational inefficiencies and places additional stress on the blade, exacerbating wear. This observation was also confirmed by (Abu Bakar et al., 2018), who found that wear can increase with moisture up to 10% and then decrease, suggesting variability based on rock type and moisture level. However, the moisture content in the tailings does not cause corrosion of the liners, as the continuous sliding of KT up and down the blade acts like a wiper. This motion constantly removes any material that may adhere to the blade surface, preventing corrosive media from remaining in contact with the liner for an extended time. As a result, corrosion is effectively minimised.

3.3 Sample collection and Visual inspection of the dozer blade liner samples

A field investigation was conducted at the Orapa diamond mine in Botswana to fully understand the nature of the problem and the operating environment of the track dozer blade liners. The track dozer runs continuously for three non-stop 8-hour shifts per day and pushes or levels the kimberlite tailings for sun drying prior to stockpiling. Based on the wear patterns observed during the visual examination, portions of the damaged DBL samples were cut from the failed DBL for further investigation. The wear patterns were found to be similar across all the dozer blades; therefore, it was decided that sampling a single dozer blade would be representative of all the eleven track dozers. Four damaged samples were collected from the marked areas labelled S1, S2, S3, and S4 (see **Plate 3.1a**) to ensure representative coverage of different wear regions on the blade. The sampling was carefully conducted to capture all the observed wear modes and mechanisms without affecting the surface integrity of the collected samples. The intact DBL, labelled S5, which corresponds to an undamaged section of the blade, was used as the control sample, while the others were identified as worn-out plates (samples S1, S2, S3, and S4), as shown in **Plate 3.1b**. These were further visually examined to identify observable wear characteristics. The selected sampling areas were identified as the regions exhibiting the highest wear mechanisms and failure occurrences, making them critical for analysing DBLs material degradation and optimising mitigation measures.

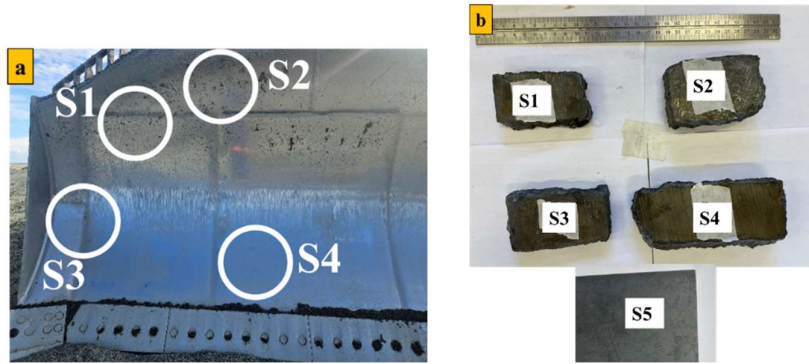


Plate 3.1: (a) Dozer blade covered with lining plates, highlighting the sampling areas. (b) Extracted DBL samples S1, S2, S3, S4, and S5.

3.4 *Metallographic preparation of DBLs samples for characterisation*

Metallographic preparation of samples was carried out before microstructural analyses. The sample preparation procedure involved cleaning, cutting, hot mounting, grinding, polishing, etching, and viewing under an optical or scanning electron microscope. **Figure 3.2** shows samples after the grinding process.

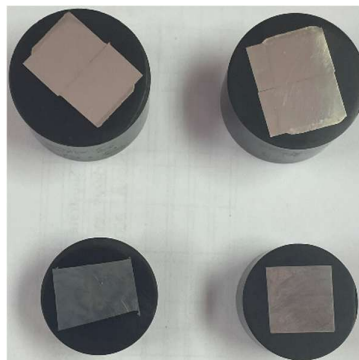


Figure 3.2: A picture of ground and polished specimen mounted on conductive resin.

3.4.1 *Cutting of Specimens*

Before cutting, the DBLs samples were cleaned in an ultrasonic cleaner using a 5% acetic acid for 30 minutes to remove any contamination. Subsequently, they were rinsed in ethanol to prevent rusting. A Struers Labotom-12 cutting machine (shown in **Figure 3.3a**) and a V-Multicam water jet machine (**Figure 3.3b**) were used to cut the specimens transversely.

Subsequently, a 10 x 10 mm piece was cut out for characterisation, as shown in **Figure 3.4**. Both the Struers Labotom-12 and the Multicam V-series waterjet machines are equipped with water-cooling systems, which were turned on during operation to cool the sample and prevent structural alteration during sectioning.

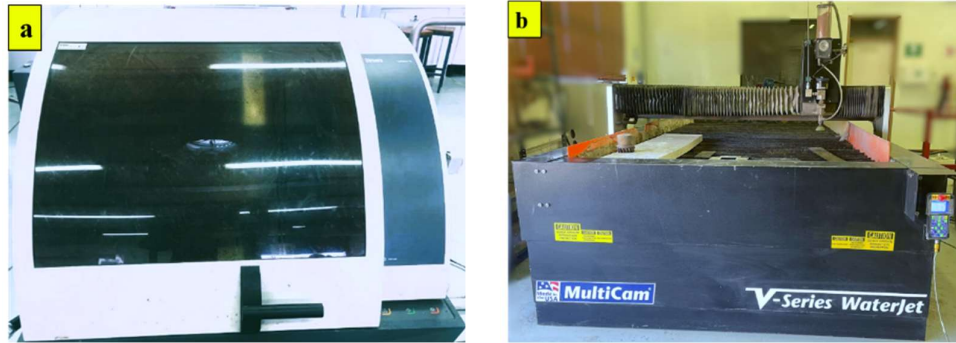


Figure 3.3: Struers Labotom-12 cutting machine (a), and Multicam V-series CNC waterjet machine (b).

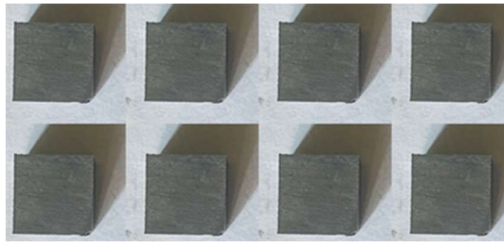


Figure 3.4: Cut specimens before mounting.

3.4.2 Specimens Mounting

The specimens were mounted using a Struers CitoPress-5 hot mounting machine (shown in **Figure 3.5**) with black conductive phenolic resin with carbon filler (Polyfast). This choice allows viewing under a scanning electron microscope because Polyfast has low emissions in a vacuum chamber (Nyadongo et al., 2021). The specimens were mounted facing downward and lowered into the chamber, then 15 ml of Polyfast resin was added. A 25mm mount was obtained for the specimens in this study. The machine was set to a pressure of 325 bars, 180°C, and a total processing time of 5 minutes (3.5 minutes for heating and 1.5 minutes for cooling).



Figure 3.5: Struers CitoPress-5.

3.4.3 Specimens Grinding and Polishing

Specimens were ground and polished using a Qualitest Qualipol-VTD-SA (**Figure 3.6**) machine with consumables detailed in **Table 3.2**. Abrasive silicon carbide (SiC) paper with grit sizes from 120-1200 μm was used for sample preparation prior to viewing under optical microscope and SEM. The goal was to eliminate all scratches and marks, ensuring results reflect only the true microstructural features of the DBL surface. Polishing involved rotating samples with diamond suspension up to 9 μm on a satin woven acetate cloth and a finer porous neoprene cloth with a colloidal suspension up to 1 μm .



Figure 3.6: Qualitest Qualipol-VTD-SA machine used for grinding and polishing.

Table 3.2: Grinding and polishing consumables.

Grinding consumables	Abrasive SiC grinding paper: P120, P220, P320, P500, P800, P1000, P1200
Polishing consumables	Polishing Cloths: Struers MD-Largo disc, MD-Dac disc, MD-chem polishing cloth. Polishing Chemicals: MD-Largo 9 µm, MD-Dac 3 µm, Water-based diamond suspension.

3.4.4 Etching

Etching is used in metallography primarily to reveal the microstructure of a specimen under a microscope (Vander Voort, 2004). Etching was carried out on the specimens using a 3% Nital solution, prepared by mixing 3% nitric acid (HNO_3) with 97% ethanol ($\text{C}_2\text{H}_5\text{OH}$). The etchant was swabbed onto the polished surfaces of the specimens. During the process, the surfaces were carefully observed for visual changes, with a matte or frosted appearance indicating that etching was occurring. After approximately 15 seconds, once the desired contrast was achieved, the reaction was immediately halted by rinsing the specimens with distilled water. This was followed by rinsing in ethanol to facilitate drying and prevent oxidation or rust formation.

3.5 Chemical composition analysis

The chemical composition of the DBL samples was determined using a spark spectrometer (ENT8002 - SpectroMAXx LMM04) (see **Fig 3.7**). The sample was first ground to obtain a clean, flat surface, free from oxides and contaminants. The sample was then placed on the spark stand, and a high-voltage spark was generated in an argon atmosphere to excite the atoms. The emitted light from the excited atoms was analysed by the spectrometer, which identified and quantified the elements based on their characteristic wavelengths. The resulting chemical composition was reported as weight percentages of key alloying elements (see **Table 4.1**).



Figure 3.7: Spectrometer (ENT8002 - SpectroMaXx LMM04).

3.6 Dozer blade liner (DBL) material hardness testing

To assess changes in the hardness of the DBLs material, which could indicate strain hardening or material degradation, a microhardness test performed on the cross-sections of worn DBLs (samples S1, S2, S3, and S4) as well as the control sample (S5). The test was carried out transversely from the surface to the core of each sample using an EMCO Test indenter (Indenter No: ENT5010-01) in accordance with ASTM E384 standards (ASTM international, 2009). A Vickers hardness test was employed with a 0.3 kg load, 200 μm indentation spacing, and a 15-second dwell time. **Figure 3.8a** shows the Vickers hardness testing machine used in this study, while **Figure 3.8b** displays the transverse indentation line extending from the contact surface to the core of the DBL sample.

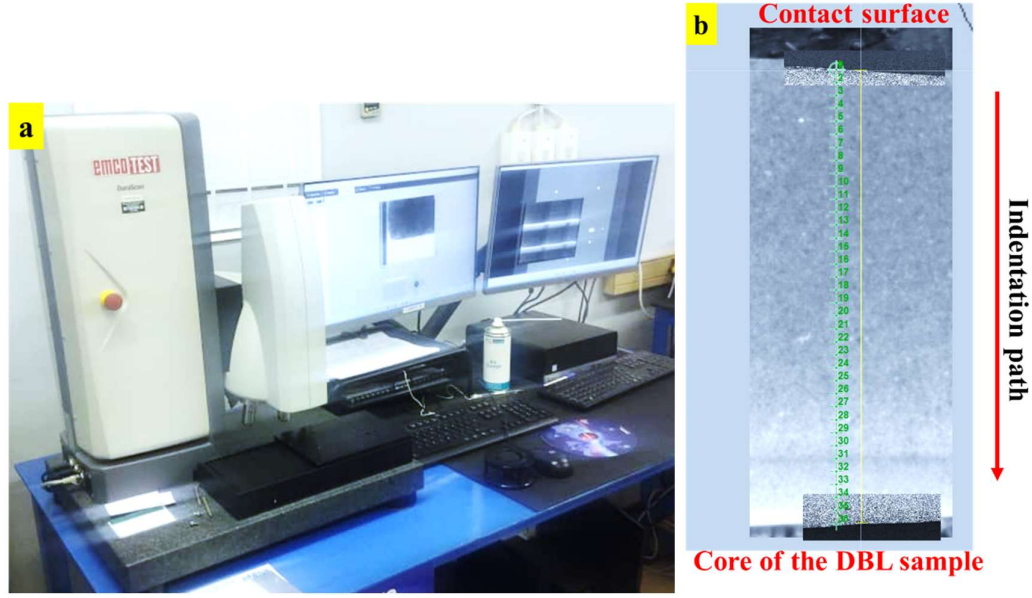


Figure 3.8: (a) Vickers hardness tester and (b) Vickers microhardness indentation profile taken transversely across the DBL sample, from the contact surface to the core.

3.7 *Microscopic and wear track analysis*

Based on the wear modes identified in **Table 4.2**, a detailed microscopic examination was performed to study the morphologies and origins of these wear modes. For this analysis, an Olympus SZX7 stereo microscope (**Figure 3.9a**) and an Olympus BX53M optical microscope (**Figure 3.9b**), both equipped with PRECiV imaging software and a camera, were used to examine the control sample and cross-sections near the worn surfaces of the damaged samples. Microstructural and wear track analysis of the worn samples were conducted using a scanning electron microscope (SEM) (JSM-IT100 series) equipped with energy-dispersive X-ray spectroscopy (EDS) (**Figure 3.10**) to determine the wear mechanism and the root cause. The damaged samples were cleaned with 5% acetic acid in an ultrasonic cleaner to remove rust residue from the surface. After 30 min, the samples were removed and rinsed in ethanol. Without polishing, the damaged surfaces were observed in a SEM facility. Additionally, cross-sections close to the damaged surfaces were analysed.



Figure 3.9: (a) Olympus SZX7 stereomicroscope and (b) BX53M optical microscope (OM).



Figure 3.10: SEM; JSM-6010PLUS/LA, JEOL Ltd.

3.8 Conclusions

This chapter describes the methodology used to investigate the premature wear and failure of the damaged DBLs. It began with the characterisation of the kimberlite tailings, followed by the collection and macroscopic visual inspection of samples. Metallographic sample preparation was then carried out to enable further analysis using a spectrometer, Vickers hardness tester, scanning electron microscope (SEM) equipped with energy dispersive X-ray spectroscopy (EDS), as well as optical and stereo microscopy.

4 Chapter Four: Experimental wear and failure analysis results and discussion

4.1 Chapter summary

Chapter four discusses the wear modes and mechanisms encountered by the dozer blade liners (DBLs) in the field. Spark emission spectrometry was used to reveal the chemical composition of the dozer blade liners (DBLs). To study the wear track, stereo and optical microscopes were used, along with scanning electron microscopy (SEM) equipped with energy-dispersive X-ray spectroscopy (EDS). EDS spectra were used to analyse the presence of inclusions in the microstructure of the DBLs. Finally, the evolution of failure modes in DBLs was discussed to identify the first wear or failure mode to manifest in the DBLs.

4.2 Chemical Analysis of Dozer Blade Liner sample

The results of spark emission spectrometry revealed that the dozer blade liner (DBL) is a low-carbon, low-alloy steel (containing a total of less than 5% alloying elements) with a carbon equivalent of 0.25, calculated using **equation 4.1**. **Table 4.1** shows the chemical composition of the DBL and its identified related grade material. The DBL is consistent with AISI 1513 (Putra et al., 2021), which has a carbon equivalent content of 0.22 (use **equation 4.1**). Alloying elements like manganese in the DBL are crucial, as manganese forms manganese sulphide (MnS), which prevents the formation of brittle iron sulphide (FeS) that causes hot shortness (brittle failure at high temperatures) (Liu, 2016). Manganese also strengthens steel, lowers the eutectoid transformation temperature, which in turn improves toughness and wear resistance (Kutz, 2002). The DBL was compared to AISI 1513 because its primary alloying elements (C, Mn, S, P, and Si) fall within the specified ranges for AISI 1513, which are essential to the steel's core properties. The trace elements in the DBL (Cr, Ni, Cu, Al, V, Nb, B, Ti, and Co) are not listed in AISI 1513, as they are either impurities, residuals from steelmaking, or minor additions not required for the steel's intended purpose. AISI standards focus on the major elements that define the properties of the steel, while modern production and analysis reveal trace elements that were not controlled in older specifications such as AISI 1513.

$$CE = C + \frac{Si}{25} + \frac{Mn+Cu}{16} + \frac{Ni}{40} + \frac{Cr}{10} + \frac{Mo}{15} + \frac{V}{10} \quad (\text{equation 4.1})$$

Table 4.1: Comparison of the chemical compositions (wt.%) of the dozer blade liner (DBL) sample and its corresponding reference steel.

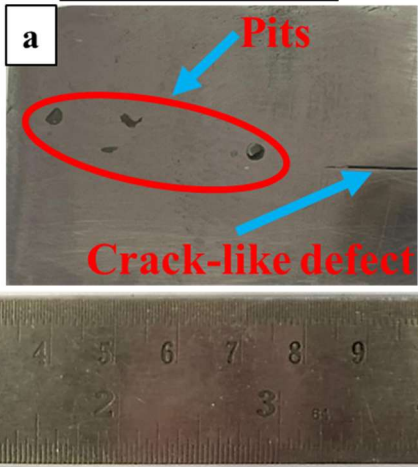
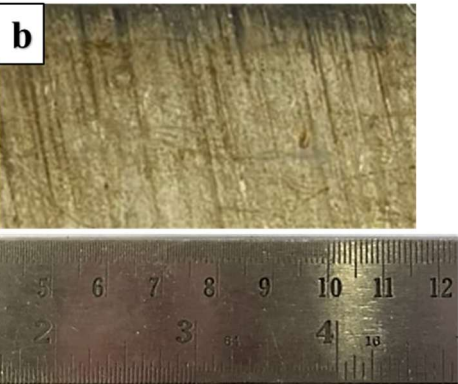
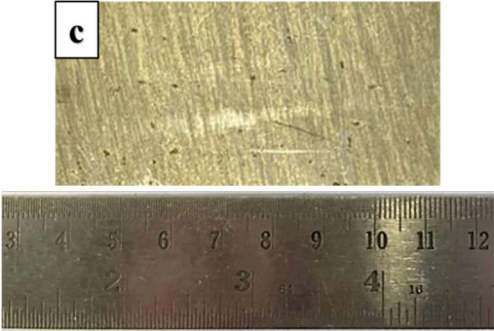
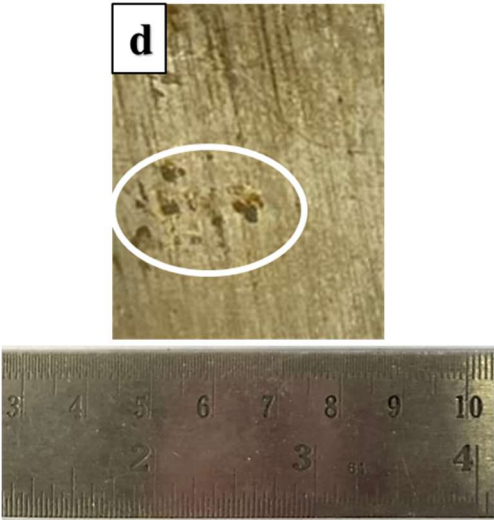
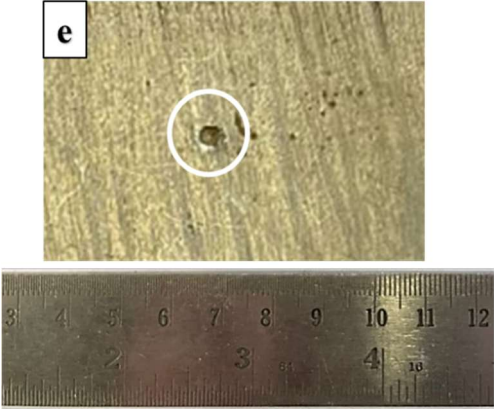
Element	DBL sample	AISI 1513
C	0.12	0.10 - 0.16
Mn	1.32	1.10 - 1.40
S	0.009	≤ 0.05
P	0.024	≤ 0.05
Si	0.30	0.20 - 0.40
Cr	0.03	-
Mo	≤ 0.01	-
Ni	0.02	-
Cu	≤ 0.01	-
Al	0.024	-
V	≤ 0.014	-
Nb	≤ 0.005	-
B	0.0018	-
Ti	≤ 0.026	-
Co	≤ 0.005	-
Fe	Matrix	Balance

4.3 Identification of failure modes in DBLs via macroscopic analysis

Visual examination of the worn DBL samples (seen in **Plate 3.1b**) revealed the following failure modes, detailed in **Table 4.2**: abrasive wear (failure mode A), pitting (failure mode B), deformation (failure mode C), and spalling (failure mode D). Control sample S5, when cut crosswise, revealed inherent defects such as pits and cracks, which may indicate inherent manufacturing defects. Examination of the control sample S5 at both macroscopic and microscopic levels is crucial for setting a reference point, allowing differentiation between manufacturing defects and those caused by operational conditions. This analysis is essential

because it confirms the steel's microstructure and composition while also revealing the surface and subsurface characteristics. The insights gained helped in refining DBL material and implementing preventive measures to reduce the risk of future DBLs failure or wear.

Table 4.2: Findings from the macroscopic wear analysis of dozer blade liners: Worn samples S1, S2, S3, S4, and control sample S5.

Failure mode	SAMPLE ID / Image	Macroscopic appearance and morphological characteristics	Causative factors
Inherent defect in the control sample S5	Control sample a 	Large visible internal pits and possibly inclusions. Crack-like defect (more likely a ‘lap’ defect) characterised by a crevice that runs lengthwise on the DBL.	Presence of inclusions and errors during the manufacturing process.
Abrasive wear (failure mode A in sample S1)	b 	Abrasive wear marks and scratches on the surface.	Quartz, diamond and other abrasive materials in kimberlite tailings which are harder than the liners.
Pitting (failure mode B in sample S2)	c 	Presence of small cavities or pits on the surface. Roughened surface.	Repeated stresses from sliding of KT on the DBL.
Deformation (failure mode C in sample S3)	d 	Dent/s on the dozer blade liner’s surface.	High impact load as the DBL comes in contact with the tailings.
Spalling (failure mode D in sample S4)	e 	Chipping or flaking of the surface.	Wet tailings. High impact stresses. Surface cracking.

4.3.1 Macroscopic/microscopic analysis of the control sample S5 and its relationship to other failure modes

Visual inspection of control sample S5 when cut crosswise revealed some inherent defects, such as pits and a large internal crack-like feature (see **sample ID a** in **Table 4.2**). Pits in the control sample are likely due to manufacturing defects, such as inclusions. Thus, these defects were present from the production process, given the expected standard condition of the control sample. These defects act as stress raisers, and as such, acts as a nucleation point for other defects, and the coalescence and growth of existing defects (Lindsay et al., 2023). This claim is supported by Zerbst et al. (2019), who observed such defects as the root cause of fatigue failure in metallic components. Similarly, a study by (Ma et al., 2002) demonstrated that inclusions during heavy forging can lead to internal cracks, which may propagate to the surface. As a result, the pre-existing defects in the as-received DBL liner compromise its structural integrity and increase the risk of premature failure or wear during service. **Figure 4.1.** shows a stereo micrograph of control sample S5, which contains pits.

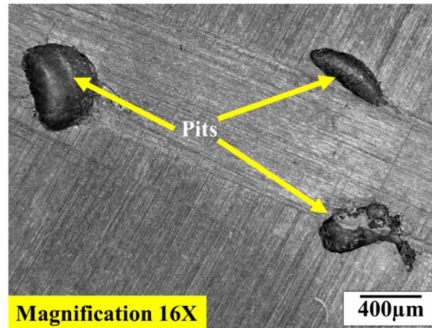


Figure 4.1: Stereo microscope micrograph of the control sample S5 showing pits.

SEM analysis of the microstructure indicates defects such as cracks, pits and inclusions, as shown in **Figure 4.2**. These defects, Pits, inclusions, and microcracks serve as nucleation sites, accelerating the formation of pores in the material (Noell et al., 2018). EDS analysis of the inclusions identified elements such as carbon, oxygen, aluminium, silicon, sulphur, and manganese (**Figures 4.2c** and **4.2d**). Therefore, confirming the presence of aluminium oxide and silicon oxide inclusions. Under high stress, inclusions gradually separate from the metal matrix grains, leading to micro-damage, primarily in the form of micro voids (Kyekyere et al., 2024). Additionally, stresses within the metal are transferred to the softer inclusion (SiO_2), causing microcrack formation within the inclusions and subsequent crack propagation along their interface with the metal matrix.

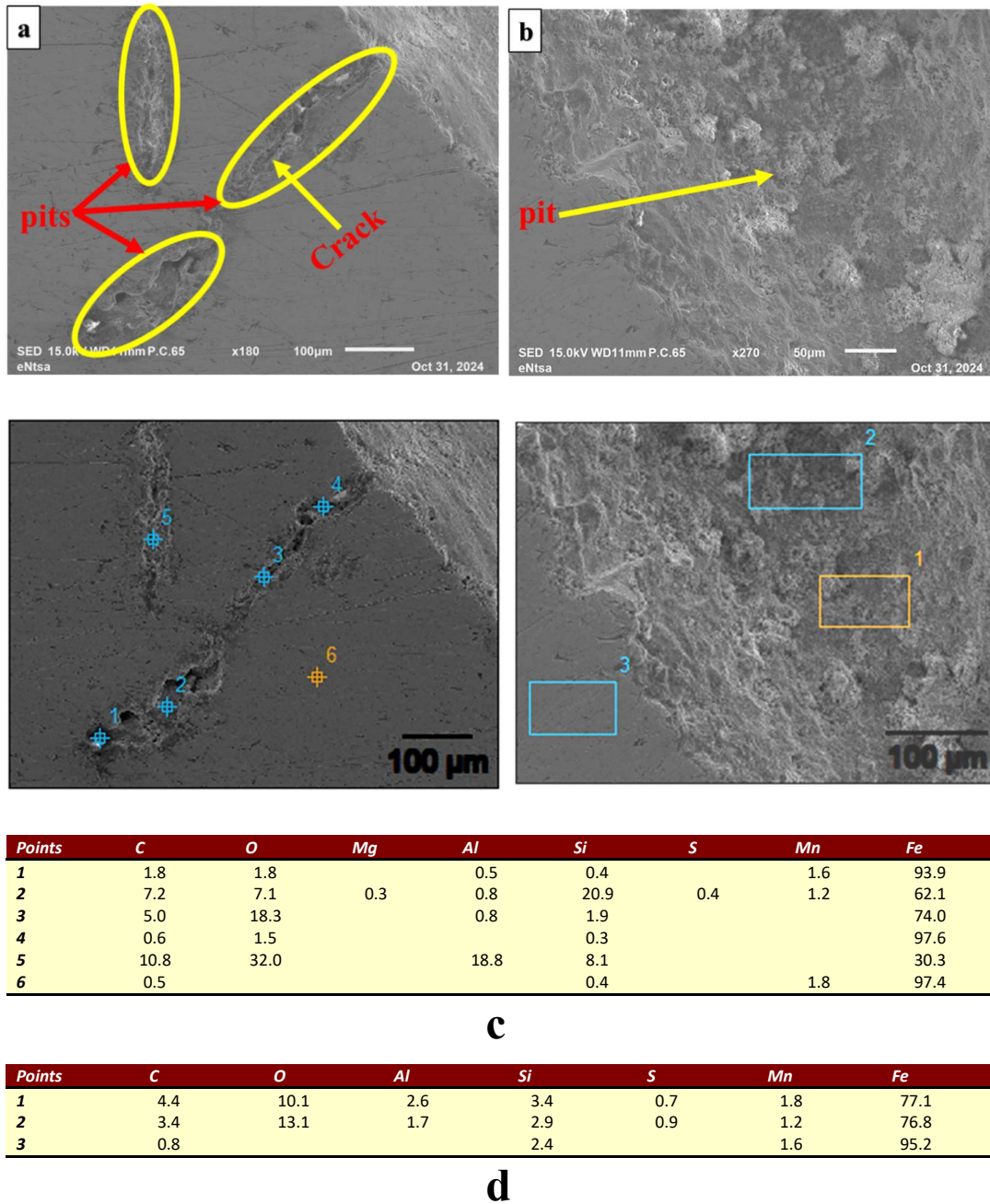


Figure 4.2. SEM micrographs of the control sample S5: (a) pit (1), (b) pit (2), (c) EDS spectrum of pit (1), and (d) EDS spectrum of pit (2).

The optical micrograph of control sample S5 (**Figure 4.4a**) shows a predominantly ferritic and pearlitic microstructure, typical for low-carbon steels with the given chemical composition (see **Table 4.1**). Ferrite, which appears as light regions, is soft, ductile, and has a body-centered cubic (BCC) structure (Vander Voort, 2015). The low carbon content (0.12%) promotes a significant amount of ferrite. The darker regions represent pearlite, a

lamellar mixture of ferrite and cementite (Fe_3C), present in limited quantities due to the small carbon content of 0.12%. Phase analysis using PRECiV imaging software revealed an average microstructural composition of 86.7% ferrite and 13.3% pearlite, based on area fraction measurements from optical micrographs (**Figure 4.4a**). Given the assumption of a randomly oriented and homogeneous microstructure, these area fractions are representative of volume fractions. Cross-verification using the lever rule (**equations 4.2** and **4.3**), considering a carbon content of 0.12%, the eutectoid composition of 0.76% for pearlite, and 0.022% for ferrite at 298 K, yielded a phase fraction of 86.7% ferrite and 13.3% pearlite by volume. This is visualised in **Figure 4.3**.

$$\text{Fraction of ferrite } (\alpha) = \frac{C_{(\alpha+\text{Fe}_3\text{C})} - C_0}{C_{(\alpha+\text{Fe}_3\text{C})} - C_\alpha} \quad (\text{equation 4.2})$$

$$\text{Fraction of pearlite } (\alpha + \text{Fe}_3\text{C}) = \frac{C_0 - C_\alpha}{C_{(\alpha+\text{Fe}_3\text{C})} - C_\alpha} \quad (\text{equation 4.3})$$

Where: C_0 = carbon content of the DBL steel; C_α = carbon content of pure ferrite; and $C_{(\alpha+\text{Fe}_3\text{C})}$ = carbon content at eutectoid composition.

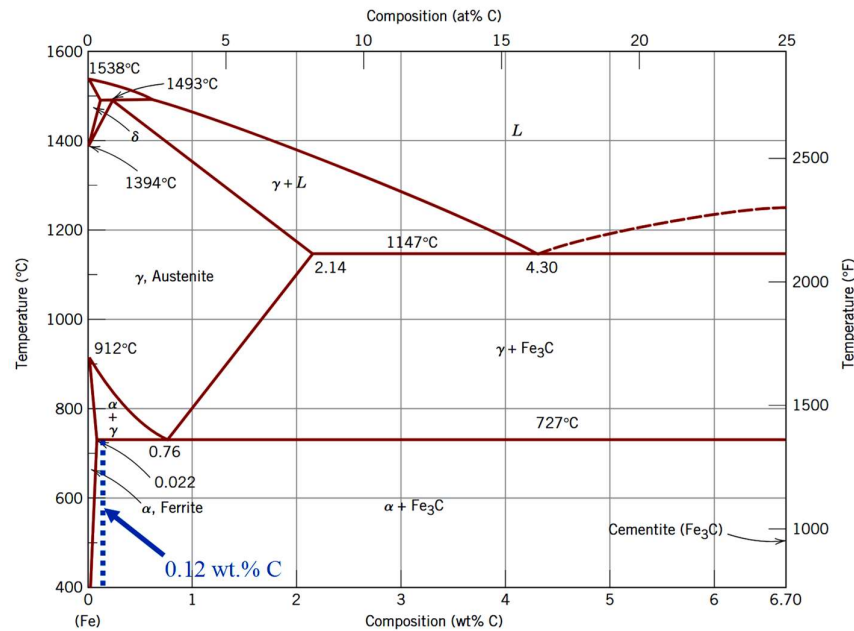


Figure 4.3: The iron-iron carbide phase diagram (Callister, 2007).

The expected microstructure is primarily ferrite with some pearlite; however, a minor amount of uniform auto-tempered lath martensite was observed in certain regions, likely

due to rapid cooling from austenite. **Figure 4.4(b)** shows the microstructure of control sample S5, which consists of a uniform tempered martensitic structure characterised by a homogeneous distribution of fine acicular (needle-like) features, typical of wear-resistant steels (Bayram et al., 1999). This structure enhances toughness and hardness (Callister, 2007). The martensitic transformation (**Figure 4.4b**) resulted from rapid quenching and tempering, which improve hardness and wear resistance (Gharbi et al., 2021). This is because the steel plates are produced through casting, followed by hot rolling. (He, 2015). These findings align with (Militzer, 2014), who reported that sufficiently fast cooling (quenching) of ferrite-pearlite steels promotes martensite formation. However, the demanding operating conditions of the DBLs, combined with the significant sliding abrasion on the DBLs, lead to premature wear, as indicated by the wear modes outlined in **Table 4.2**. Consequently, the performance is compromised, and its quality deteriorates. Therefore, an alternative material with an optimal balance of superior hardness and adequate abrasion resistance is required for this application.

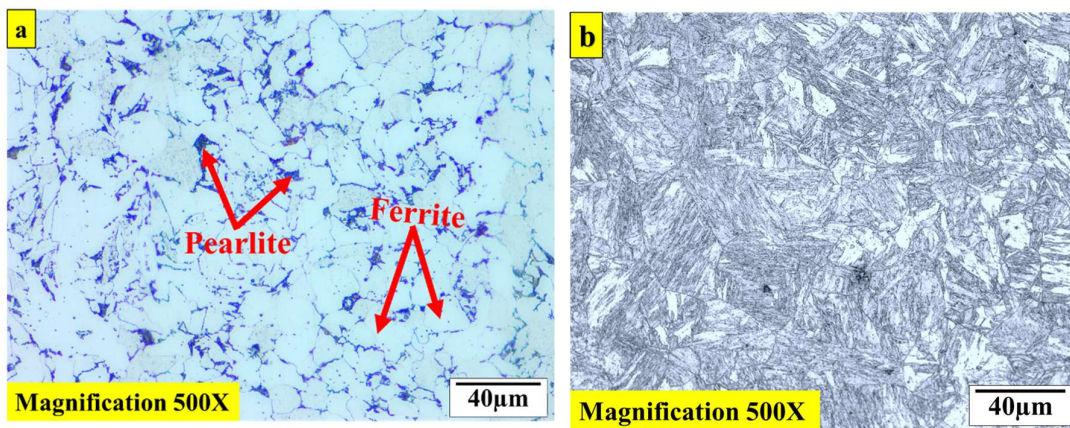


Figure 4.4: Microstructural analysis of control sample S5: (a) Optical micrograph at 500X reveals ferrite and pearlite structure; (b) Optical micrograph at 500X reveals a uniform tempered martensitic structure in rapidly quenched regions.

4.3.2 Macroscopic analysis of failure mode A: Abrasive wear

Abrasive wear marks observed in failure mode A result from kimberlite tailings that contains hard mineral particles such as diamond, silica, and alumina repeatedly sliding over the DBL's surface. This movement gradually roughens the surface, creates scratches, and removes small pieces from the DBL's surface (see **sample ID b** in **Table 4.2**). At the macroscopic level, abrasive wear marks appear as parallel or semi-parallel scratch lines

running in the direction the kimberlite tailings slide on the DBL surface. Over time, these scratches deepen and widen, leading to gradual loss of material (Saha, 2017). As a result, the DBL becomes thinner, eventually leading to significant wear or failure. Furthermore, cracks and pits from manufacturing defects disrupt the normal abrasive wear process by creating weak points where stress builds up and abrasive particles get trapped (Scott, 2008). As a result, more material wear away faster, and the wear mechanism can change from mild to severe (ASTM International, 2016).

4.3.3 Macroscopic analysis of failure mode B: Pitting

At the macroscopic scale, failure mode B, the pitting on a DBL used to push kimberlite tailings appears as numerous small, localised pits across the blade surface (see **sample ID c** in **Table 4.2**). These pits develop primarily because of repeated loading and high-intensity contact with abrasive particles in the kimberlite tailings (e.g., diamond and alumina). As the blade pushes the tailings, hard sharp particles in the tailings strike the DBL surface repeatedly. Each impact can dislodge tiny fragments of material or initiate microcracks that later grow into visible pits on the surface (Chintha, 2019). Over time, this repeated contact and abrasive action leads to small cavities on the surface called pits. Sometimes, slight surface imperfections or existing microcracks become stress concentrators under load (Eryürek et al., 2007). Repeated loading and unloading (pushing, backing up, and pushing again) causes these cracks to propagate just below the surface. Eventually, sections of the material break away, leaving behind a ‘pitted’ appearance (Chowdhury, 2019). Visually, the blade surface shows scattered, often round, or irregular pits (**Table 4.2(b)**) rather than uniform wear. Pitting reduces the overall smoothness, increasing friction and potentially accelerating further wear. It has been confirmed in literature that rougher surfaces tend to exhibit higher wear rates (Kubiak et al., 2011; Leso et al., 2023; Yuan et al., 2024). If left unchecked, deep pits join together or become crack initiation sites, leading to more surface fatigue (Fatoba & Akid, 2022).

4.3.4 Macroscopic analysis of failure mode C: Deformation

From a macroscopic standpoint, the dents (see **sample ID d** in **Table 4.2**) indicate that abrasive particles in the tailings hit the DBL surface with enough force to deform it plastically. Each dent is effectively an ‘impact crater’, where the material has been compressed beyond its yield point and has become plastically deformed (Karimi

Bakhshandi et al., 2022). Repeated collisions with kimberlite tailings cause small permanent indentations on the DBL. Under the push action of the track dozer blade, these particles can concentrate force on contact areas, creating very high local stresses that lead to denting. Although, the dents themselves are mainly plastic deformation, repeated high-stress impacts can initiate microcracks at the edges of these indentations (Qi et al., 2015). Over time, this may lead to spalling, which is loss of material. Additionally, internal cracks detected in **sample ID a** in **Table 4.2** compromise the steel's ability to undergo uniform plastic deformation, reducing its ductility and toughness (Hosford, 2005). In addition, track dozer operators sometimes allow tailings to accumulate into large piles before pushing and spreading them in a single operation. This approach increases the force required by the blade, potentially leading to vibrations in both the track dozer and the blade. Over time, these vibrations could contribute to stress concentration in the blade liner, which may influence deformation, characterised by dent formation (see **sample ID d** in **Table 4.2**).

4.3.5 Macroscopic analysis of failure mode D: Spalling

At the macroscopic scale, spalling (see **sample ID e** in **Table 4.2**) on a DBL is essentially small chunks of material that have broken away from the surface due to repeated, high-impact stresses. In a diamond mine environment, kimberlite tailings create intense localised stresses as they collide or grind against the liners of the dozer blade. The blade is subjected to repeated impacts from hard, abrasive tailings. These particles concentrate force in tiny contact regions, creating very high local stresses. Over many cycles, these stresses can initiate subsurface cracks that gradually propagate (Azevedo & Neto, 2004). When the cracks break through the surface, a small piece of steel ‘pops out’ leaving a characteristic pit. This detachment of tiny metal flakes or chips from the DBL surface is called spalling (Craig, 2005). Over time, multiple spalling sites can develop, weakening the surface and potentially leading to larger-scale damage or the need for dozer blade liner replacement. As discussed earlier, sometimes pits and cracks from manufacturing defects propagate to the surface. Once they reach the surface, they locally weaken the DBLs, making it more susceptible to spalling failure (see **sample ID e** in **Table 4.2**).

4.4 Relationship between failure modes, damaged sample's microhardness of AISI 1513 DBLs and kimberlite tailings (KT) characterisation

The microhardness analysis aimed to determine the level of degradation that the damaged DBLs have been subjected to after wear, and the results are summarised in **Figure 4.5**. The microhardness of the damaged samples showed a different trend from that of the control sample S5. The control sample S5 (blue curve) maintains stable microhardness across the entire distance from 0 to 7.2 mm. The values fluctuate slightly within the 285-264 HV_{0.3} range, and show no significant upward or downward trend. This consistency suggests that the control sample maintains uniform material properties throughout its depth, serving as a reliable reference for comparison.

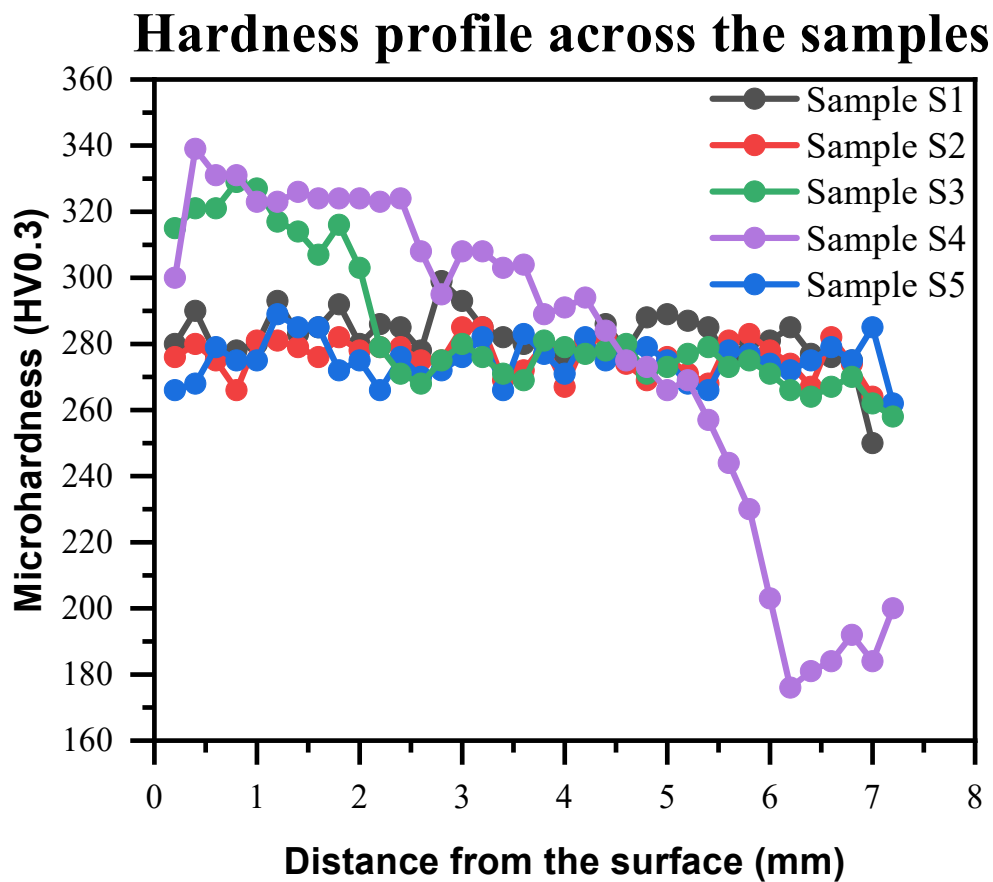


Figure 4.5: Microhardness profile across the DBL samples.

Damaged samples (S1, S2, S3, and S4) show different degrees of degradation as a result of wear. Sample S4 initially hardens (300-339 HV_{0.3}) due to work hardening from repeated impact and sliding against kimberlite tailings (KT). However, its hardness drops sharply 2.8

mm from the surface, though it remains higher than that of the control sample (S5). This may be attributed to potential microstructural changes. At 4.6 mm from the surface, the hardness of sample S4 falls below that of the control sample (S5), indicating severe wear, material softening, and potential microstructural changes, such as phase transformations, leading to material failure (see **Figure 4.12a**). This was also evident in the work of Lindroos et al. (2015) which investigated wear behaviour and work hardening of high strength steels under high stress abrasion. While work hardening can temporarily improve the hardness and wear resistance of steel components, continuous exposure to high-stress abrasive environments can lead to microstructural degradation and eventual failure (Olawale et al., 2013). Sample S4 was extracted from a region closer to the cutting edges (metal plates at the bottom of the blade that make direct contact with the ground) where stress levels are high (see **Plate 3.1a**). This explains the increased hardness values observed across all samples and the severe wear behaviour of sample S4. (Mahto & Mastorakis, 2016) confirmed that stress levels are highest at the dozer blade cutting edges and the areas adjacent to them compared to other portions of the blade. On the contrary, samples S1 and S2 exhibit relatively stable hardness (299-250 HV_{0.3}) and (289-266 HV_{0.3}), slightly above control sample S5, suggesting strain hardening has slightly improved wear resistance. This pattern highlights the progressive wear of the dozer blade liner, with some areas experiencing accelerated degradation due to high-stress abrasion and material loss. The reduced hardness variation in S1 and S2 can be attributed to their location, which is closer to the top of the dozer blade and farther from the cutting edges (see **Plate 3.1a**).

However, sample S3 undergoes work hardening (335–279 HV_{0.3}) from 0 to 2.2 mm due to the sliding action of kimberlite tailings, which roughens its surface. Beyond 2.2 mm, the hardness decreases from 279 to 258 HV_{0.3}, indicating that the core of the DBL remains unaffected, while the area closer to the region of contact with the KT particles has been work-hardened. Sample S3 was extracted from the middle portion of the blade (see **Plate 3.1a**); hence, it has a higher hardness than Sample S1 and S2 but a lower hardness compared to Sample S4. This observation is supported by the works of (Chippendale, 2000; Mahto & Mastorakis, 2016), who observed that the highest stress intensity occurs at the dozer blade's cutting edge and its surrounding areas. These are the primary zones where wear rate and stress levels are high, as most interaction with the material (kimberlite tailings) occurs in this region compared to the top part of the blade. Additionally, a bulk hardness test using a

10 kgf (kilogram-force) load was performed on the DBL control sample, and the average value was 218 HV₁₀.

Figure 4.6 shows the particle size distribution (PSD) for kimberlite tailings (KT) at the Orapa diamond mine in Botswana, as provided by the mine ore processing department. The data was gathered in 2023 at the Orapa diamond mine in Botswana through sieve analysis, where kimberlite tailing samples were systematically screened using sieves of varying mesh sizes to determine the particle size distribution (see **Appendix B**).

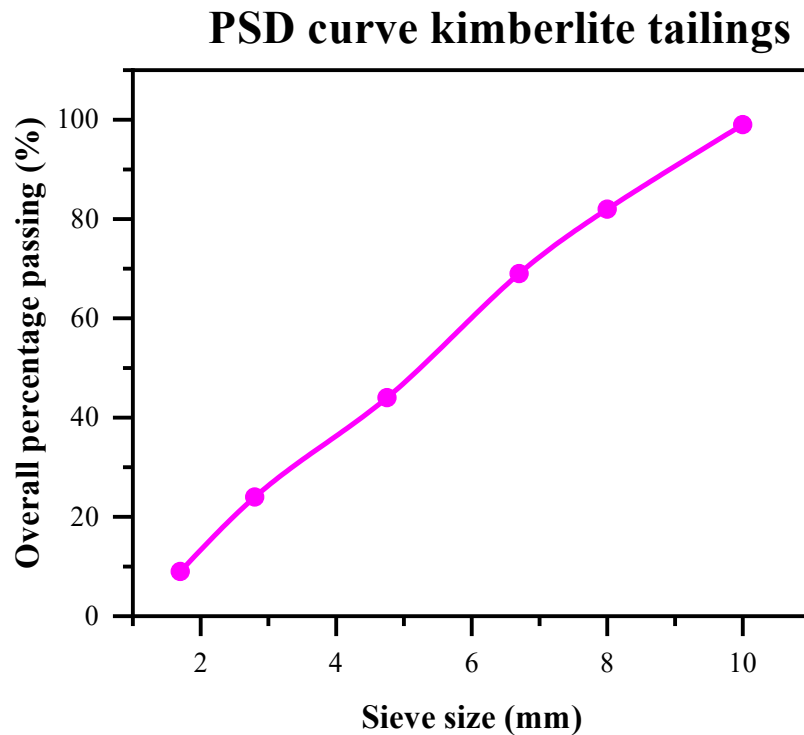


Figure 4.6: Particle size distribution (PSD) of kimberlite tailings (KT).

Data in **Figure 4.6** imply that 98% of the particles are smaller than 10 mm; 82% of the particles are smaller than 8 mm; 69% of the particles are smaller than 6.7 mm; 44% of the particles are smaller than 4.75 mm; 24% of the particles are smaller than 2.8 mm, and 9% of the particles are smaller than 1.7 mm. This distribution indicates that a significant portion of the kimberlite tailings is relatively coarse, as 91% of the particles have a size greater than 1.7 mm. Coarse kimberlite tailings are defined as waste materials produced during diamond extraction from kimberlite rock, with a particle size greater than 1.6 mm (Copeland & Teixeira, 2019; Dunn, 2004). Coarse abrasives remove material quickly, but leave deep

scratches (HUB Industrial Supply, 2025) (see failure mode A for **sample ID b** in **Table 4.2**). Studies in soil mechanics and tribology, by Malvajerdi (2023), indicate that wear rates increase with larger particle sizes, due to their higher kinetic energy and ability to induce scratching and impact wear. Similarly, (Królicka et al., 2020) showed that larger soil particles intensify the wear of tillage tools, which interact with the soil similarly to DBLs. These particles contribute to micro-delamination and spalling in hard, brittle components, further accelerating wear. Larger particles enhance wear by increasing the probability of cutting and scratching actions (Yazıcı, 2024). Extensive wear is attributed to higher impact forces (Malvajerdi, 2023). In contrast, finer particles generally cause less wear, but under certain conditions, harder fine particles can embed into the blade surface, acting as micro-cutting tools (Hutchings & Shipway, 2017).

4.5 Fractographic and wear track analysis of damaged samples using stereo, optical and SEM microscopy

It is essential to recognise that while the failure mode refers to the observable physical characteristics, the failure mechanism explains the process that leads to the failure (Akintunde et al., 2023). The following section discusses the failure mechanisms which resulted in the macroscopic failure modes discussed in **section 4.3** of **chapter 4**. This is accomplished by examining the failed surfaces and cross-sections near these surfaces using SEM, stereo, and optical microscopes.

4.5.1 Mechanism of occurrence of failure mode A: via optical, stereo and SEM micrographs.

Stereo microscope micrographs of sample S1 revealed the presence of scratches, cutting, ploughing, wedge formation, and pitting (see **Figure 4.7**). The scratches (**Figures. 4.7a, 4.7b, 4.7c, and 4.7d**) on the surface indicate abrasive wear, where the kimberlite tailing particles, which have sharp edges, have been dragged across the lining plate, gouging out material. Under high stresses, repetitive interaction between the DBLs and the tailings causes scratches to develop into cutting marks. The cutting marks (**Figures. 4.7a and 4.7c**) indicate that harder kimberlite tailings particles have likely penetrated the surface of the lining plate, removing material as the track dozer blade liner interacts with it. Sometimes sliding of the constrained abrasive kimberlite tailings occurs without material being removed from the wearing surface in the primitive stages of contact, but it is shifted to the

sides of the wear groove, forming ridges or furrows (**Figure 4.7c**) along the direction of the sliding motion (**Figures 4.7a, 4.7b, 4.7c, and 4.7d**). Although the detached material on the sides will be removed by additional abrasive contact (Hylén et al., 2021). This mechanism is mainly governed by plastic deformation and is called ploughing. The deeper grooves (**Figure 4.7d**) could be the result of larger or more angular kimberlite tailing particles being dragged across the plate, leading to significant material removal. This shows the impact of larger or more aggressive particles in the tailings. Groove formation creates a plastically deformed region, forming side ridges along the groove (Kato, 1992). This may have contributed to the higher hardness observed in sample S1 compared to control sample, S5 (see **Figure 4.5**).

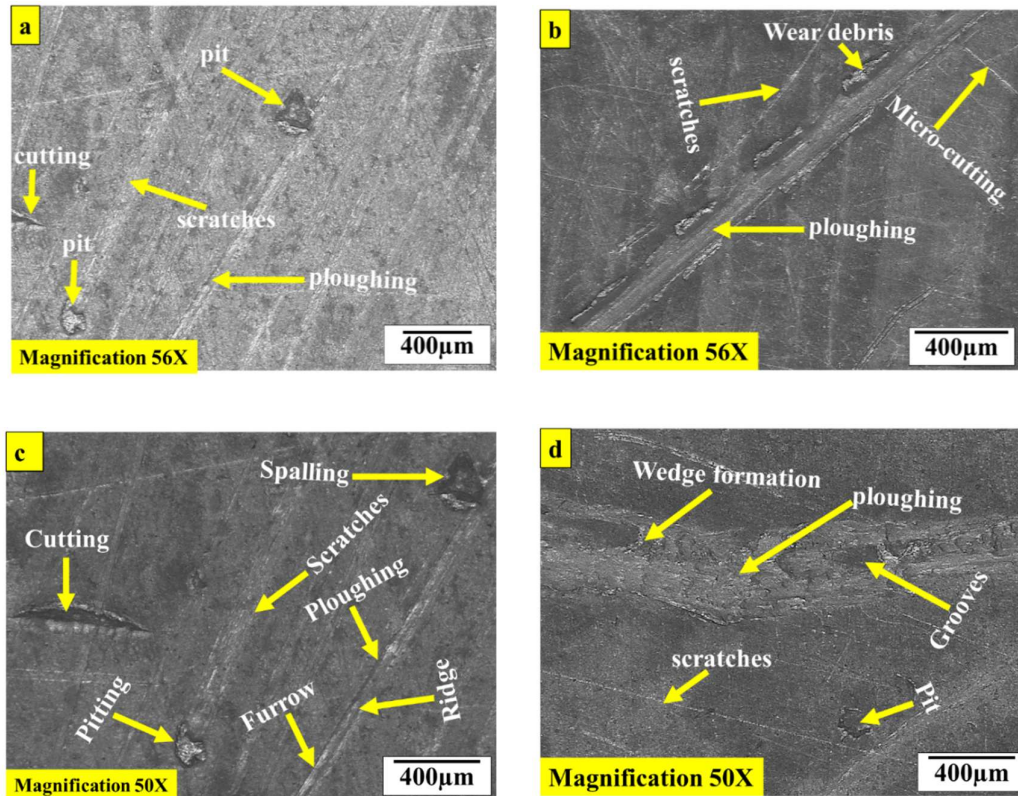
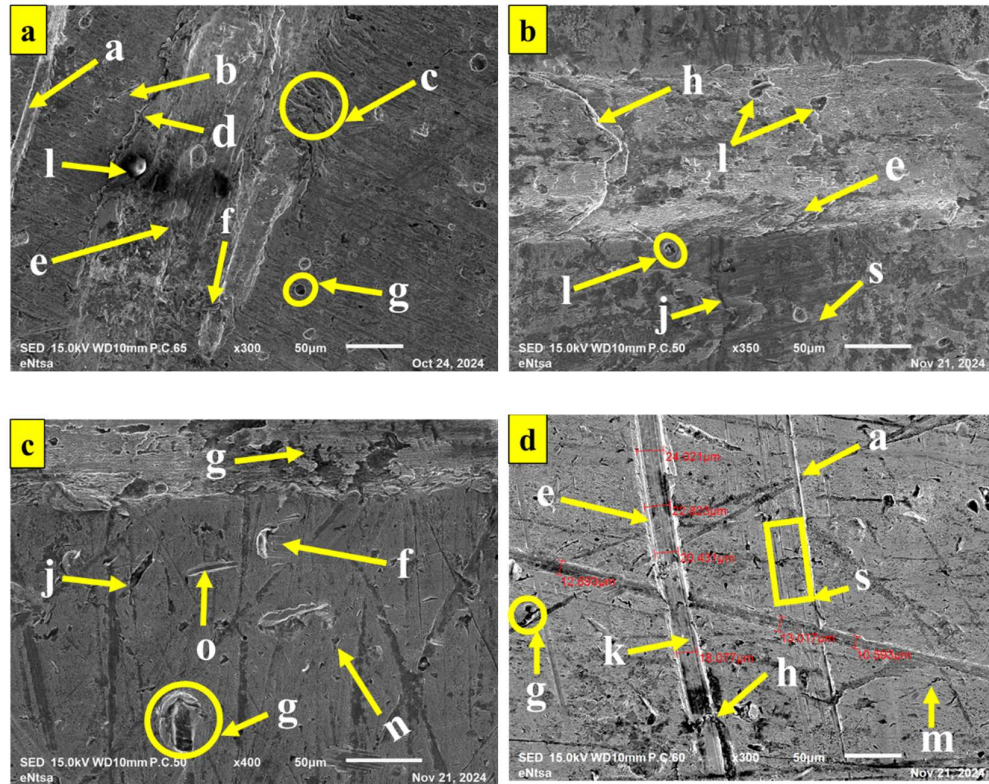


Figure 4.7: Stereo microscope micrographs of damaged sample S1 showing abrasive wear mechanisms that led to failure mode A.

In addition, wedge formation also occurs. The material may be pushed to the front of the grit to form a wedge-like shape (**Figure 4.7d**), which grows until its eventual detachment and then the process begins again. Wedge formation is an intermediate mechanism between cutting and ploughing (Hylén et al., 2021). The samples were then evaluated using the SEM

to observe the various mechanisms at a higher magnification than that of the stereo microscope. The same mechanisms observed in **Figure 4.7** were also seen using the SEM, as shown in **Figure 4.8**.



- | | | | |
|-----------------------|-------------------------|-------------------|----------------|
| (a) = Micro-ploughing | (e) = Grooves | (s) = Scratches | (m) = Crack |
| (b) = Micro-cutting | (f) = Micro-indentation | (j) = Micro-crack | (n) = Spalling |
| (c) = Shear bands | (g) = Pit | (k) = Ploughing | (o) = Abrasion |
| (d) = Wedge forming | (h) = Indentation | (l) = Void | |

Figure 4.8: SEM micrograph of damaged samples S1 showing abrasive wear mechanisms in DBLs.

The minor ploughing (grooves) observed on the worn surface (as seen in **Figures 4.8a, 4.8b,** and **4.8d**) suggests that the abrasion process was primarily driven by abrasive sliding of kimberlite tailings (KT) particles-two-body abrasive wear. Two-body abrasive wear is caused by abrasive particles or asperities that are rigidly attached to the second body. Due to this, the abrasive particles in a two-body mechanism can penetrate deeply into the workpiece material (Marinescu et al., 2013). In this case, the higher hardness of the KT particles compared to that of DBLs results in deep cuts or scratches on the DBLs, resulting

in sliding abrasion. Few traces of diamond and quartz in the KT, probably caused the minor surface grooves since they are harder than the DBLs.

The SEM micrograph (**Figure 4.9a**) taken from sample S1 highlights an elongated manganese sulphide (MnS) inclusion, which affects mechanical properties and wear resistance of steels. The shape of MnS inclusions in low carbon, low alloy steels is typically elongated as MnS stringers (Mahmutović et al., 2017). Using SEM EDS, it was confirmed that the inclusion was manganese sulphide as shown on **points 3 and 4** in **Table 4.3**. Manganese sulphide inclusions have been found to be softer than the steel matrix, and they act as stress raisers, resulting in higher stress concentrations and leads to crack initiation sites under loading (Arreola-Herrera et al., 2018).

Since the dozer blade liner (DBL) used at the Orapa Diamond Mine in Botswana has a carbon content of 0.12% (see **Table 4.1**) and the kimberlite tailings (KT) contain trace amounts of diamonds, an increased carbon composition, as observed in spectra point 1 (11.9%), point 2 (9.0%), point 3 (2.4%), and point 4 (2.1%) in **Table 4.3**, could potentially indicate the presence of diamond particles embedded in the DBL's surface. Diamonds, which are crystalline forms of carbon, have a high hardness (10 on the Mohs scale), allowing them to become trapped within surface asperities during abrasive interactions with the KT (Mat, 2024). This phenomenon corresponds to the high carbon content detected by elemental analysis and suggests interaction between the DBL and diamond-rich tailings. The embedment of the diamond particles into the DBL may result in areas of high stress concentration, hence an area where cracks will grow and propagate. Furthermore, the presence of C, Al, Ti, Mn, S, and O (see **Table 4.3**) suggests the formation of Al_2O_3 , TiC, and MnS inclusions, thereby confirming their presence in the DBL. Due to their high hardness and low toughness, Al_2O_3 inclusions and TiC inclusions tend to form hard, brittle particles that act as stress concentrators within the microstructure, leading to localised strain accumulation under mechanical loading (Murakami, 2019). As a result, they serve as preferential sites for crack initiation, particularly under cyclic loading, thereby adversely affecting toughness and fatigue strength if the inclusions are not properly controlled (Juvonen, 2004).

Under high stress, inclusions gradually separate from the metal matrix grains, leading to micro-damage, primarily in the form of micro-voids (Kyekyere et al., 2024). Additionally, stresses within the metal are transferred to the softer inclusions (MnS), causing microcrack

formation within the inclusions and subsequent crack propagation along their interface with the metal matrix. **Table 4.3** shows the EDS spectra for **Figure 4.9b**, an SEM micrograph indicating regions (1–6) sampled for elemental composition analysis.

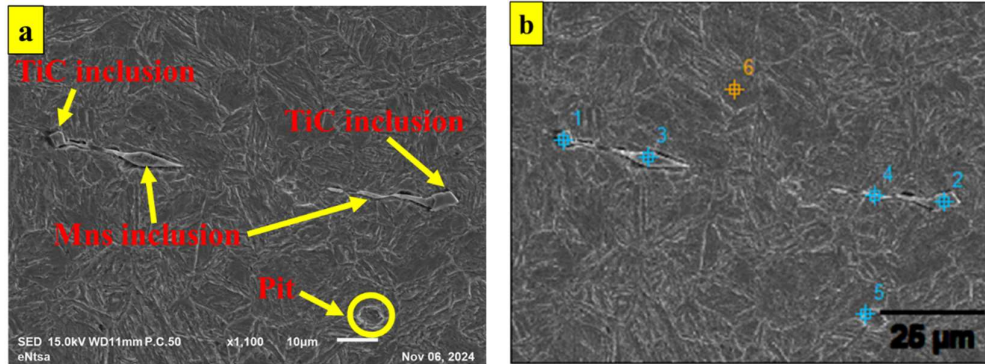


Figure 4.9: (a) SEM showing MnS and TiC inclusions within the microstructure, (b) SEM micrograph indicating regions (1-6) sampled for elemental composition analysis.

Table 4.3: Elemental composition of regions marked in Figure 11b indicating regions (1–6) sampled for elemental composition analysis.

Points	C	O	Al	Si	S	Ti	Mn	Fe
1	11.9					63.0		25.0
2	9.0					62.9		28.2
3	2.4	11.1	13.3		27.0		46.3	
4	2.1				30.6		56.6	10.7
5	0.6						1.8	97.6
6	0.7			0.4			2.0	96.9

4.5.2 Mechanism of occurrence of failure mode B: via optical, stereo and SEM micrographs.

The small, localised cavities, depressions, or irregularities on the surface of samples S2 and S4, called pits (**Figures 4.10a** and **4.10b**), observed on the surface of failure mode B, are likely the result of localised impact from hard kimberlite tailing particles. Kimberlite tailing is known to contain abrasive minerals like diamonds and quartz that are harder than the steel materials used in the liners, which can cause localized material removal or detachment of localised material. Pits act as crack nucleation sites, which may lead to surface fatigue (Hashim, 2020).

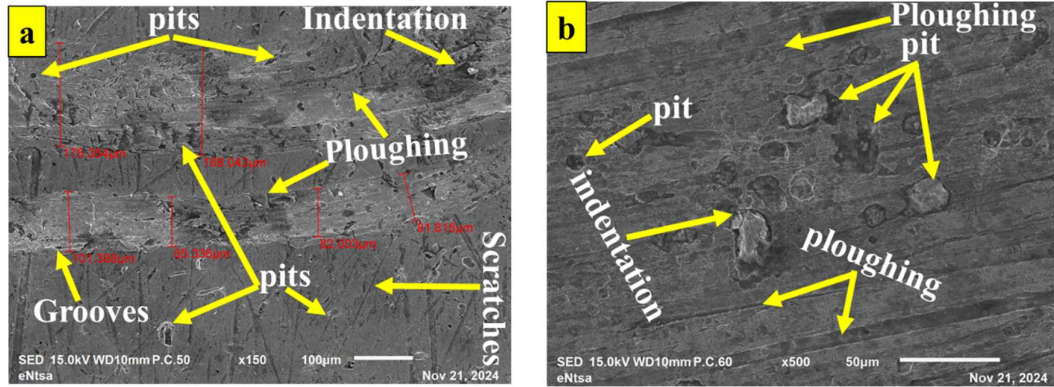


Figure 4.10: SEM micrograph of damaged samples S2 showing pits in DBLs.

Furthermore, SEM and EDS analysis (**Table 4.4**) of sample S2 revealed the presence of Al_2O_3 inclusions (see **Figure 4.11a** and **Figure 4.11b**). Al_2O_3 inclusions (globular shape) are generally considered harmful because they have low toughness, therefore, brittle and act as crack initiation sites (Kumar Sarna, 2021; Lecomte-Beckers et al., 2001).

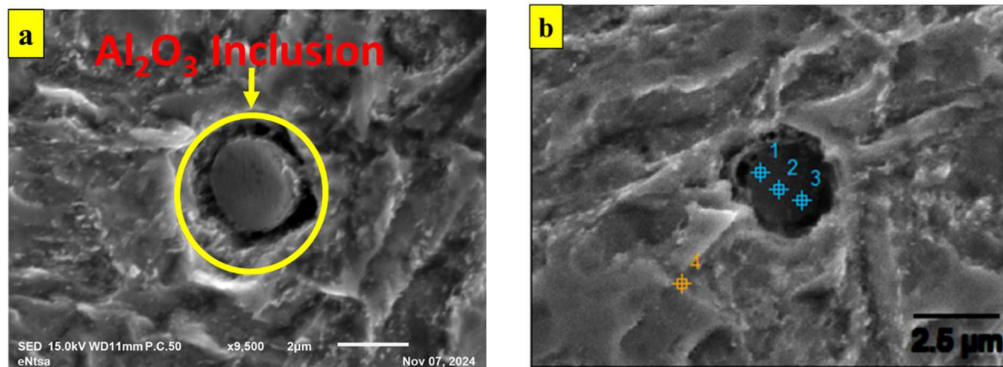


Figure 4.11: (a) SEM micrograph of sample S2 showing Al_2O_3 inclusion and (b) SEM micrograph of distinct areas (1-3) analysed for compositional variation.

Table 4.4: EDS spectra of Al_2O_3 inclusions showing elements present at different points (1-4).

Points	C	O	Al	Si	S	Cr	Mn	Fe
1	1.3	26.3	40.8		0.8		1.3	29.4
2	1.7	33.9	49.8		1.0			13.6
3	0.5	5.1	14.4				2.0	78.1
4	1.1			0.3		0.3	1.8	96.5

4.5.3 Mechanism of occurrence of failure mode C: via optical, stereo and SEM micrographs.

Figure 4.12a shows alternating microstructural bands of pearlite and ferrite in the microstructure of worn sample S3. The inhomogeneous stress-strain distribution at the pearlite/ferrite interface within the banded structure affects crack nucleation (Isavand & Assempour, 2021). The Ferrite/Pearlite banded structure makes steel deform unevenly during the early stages of wear and promotes micro-crack initiation at the boundaries between ferrite and pearlite (Zhang et al., 2020). The ferrite bands, which are soft, tend to wear down faster than the pearlite bands. Micro-segregation during the solidification of ferritic-pearlitic steels causes banding, where alloying elements like manganese (Mn) become unevenly distributed, leading to regions with varying Mn content (Majka et al., 2002). The extent of banding depends significantly on the cooling rate post-austenitisation (Isavand & Assempour, 2021). High cooling rates (e.g., air cooling) prevent banding by rapidly cooling the steel, thereby avoiding significant segregation. Low cooling rates promote intense banding due to prolonged cooling, allowing for more pronounced segregation of elements (Kyekyere et al., 2024). Additionally, while heat treatment can prevent or erase the banded structure, it may reappear upon further heating or deformation (Samuels, 1999; Shi et al., 2014; Zhang et al., 2020).

During sliding wear, severe plastic deformation at the contact surface induces localised recrystallization, phase transformations, and carbide alignment, leading to a banded structure (Mazilkin et al., 2019) (**Figure 4.12a**). Additionally, the grain refinement (**Figure 4.12b**) near the worn surface forms ultrafine or nanocrystalline layers, contributing to the observed martensitic banding (Ebrahimzadeh et al., 2024) (**Figure 4.12a**). This banded microstructure causes anisotropy in the steel's tensile, bendability and impact properties, leading to reduced impact toughness, bendability, and tensile strength in the transverse direction. Bendability, tensile strength, and impact toughness along the banding direction are better than those in the transverse direction (Isavand & Assempour, 2021). Furthermore, during severe plastic deformation, high contact stresses and strain localisation can cause local redistribution of alloying elements, which may result in banding. Similar observations were reported in the work of (Zayed et al., 2023), where they reviewed the deformation behaviour and properties of severe plastic deformation techniques for bulk materials.

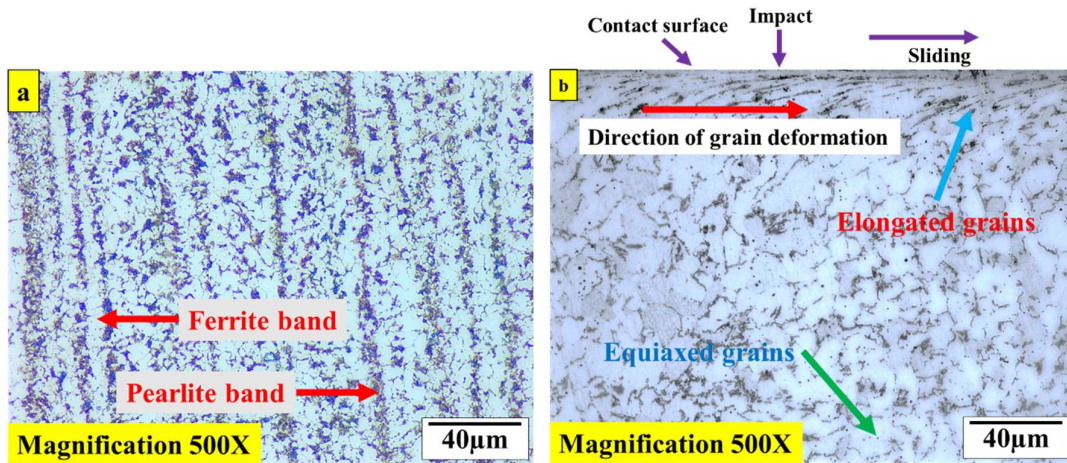


Figure 4.12: Optical micrograph of the dozer blade liners (DBLs) sample S3 (a) is the micrograph the worn samples showing a banded structure, and (b) grain deformation in the DBL.

SEM analysis of sample S3 revealed a banded structure of the surface to complement the optical microscopy results (see **Figure 4.13a**). **Figure 4.13b** shows the SEM micrograph of sample S3 banding region, showing distinct areas analysed for microstructural and compositional variation (regions 1–8). **Table 4.5** shows the EDS spectrum of Sample S3, banding region #4, highlighting the elemental composition with peaks for Fe, Mn, Cr, Si, and C.

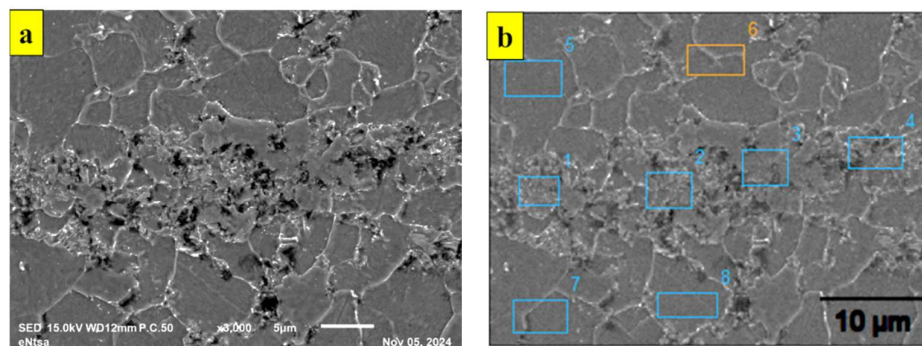


Figure 4.13: (a) SEM micrographs of sample showing banded structure of sample S3, (b) SEM micrograph of distinct areas analysed for microstructural and compositional variation

Table 4.5: EDS spectrum of Sample S3, banding regions confirming the steel's composition.

<i>Points</i>	<i>C</i>	<i>Si</i>	<i>Cr</i>	<i>Mn</i>	<i>Fe</i>
1	0.8	0.4	0.3	2.4	96.2
2	0.9	0.3	0.5	1.7	96.7
4	0.9			2.5	96.6
4	1.1	0.3	0.4	1.6	96.7
5	0.6	0.3	0.3	1.6	97.2
6	0.5	0.2	0.3	1.6	97.4
7	0.7	0.3		1.4	97.6
8	0.5	0.3	0.3	1.4	97.5

Figure 4.12b shows the optical micrograph of the grain deformation in the dozer blade liner (DBL) sample S3. The breakdown of martensite into ferrite (α) and globular cementite (Fe_3C) requires a certain amount of energy, which can be supplied through deformation and heat (Callister, 2007). In wear-intensive environments, such as kimberlite tailings localised heat generation due to friction can reach temperatures high enough to induce phase transformations (Hutchings & Shipway, 2017) (see **Figure 4.12b**). It is possible that the wear mechanism led to sufficient localised heating to cause the decomposition of the pearlite phase, resulting in structural changes within the DBL.

In addition, the grains at the top of the micrograph (**Figure 4.12b**) (closer to the contact area) appear elongated, indicating that this region likely experienced higher stress or strain during operation hence being plastically deformed. This could be due to repeated direct sliding contact with abrasive kimberlite tailings particles. The deformation in this area may have caused strain hardening, and the breakdown of the pearlite phase indicates that the material experienced significant heat, leading to grain refinement (see **Figure 4.12b**). During hot rolling ($\sim 900 - 1100^\circ\text{C}$), low carbon steels such as AISI 1513 steel undergoes severe deformation, causing dislocation buildup (Peng et al., 2022). Once a critical threshold is reached, dynamic recrystallization refines the grain structure, improving strength, toughness, and wear resistance (Peng et al., 2022).

The average grain diameter near the contact area, observed at 500X magnification, was $7.5\ \mu\text{m}$. This measurement was determined using PreCiV software and verified using the line intercept method. On the contrary, the grains farther from the contact area were more equiaxed, indicating that this region was less affected by service conditions and maintained a more uniform and original microstructure. The average grain diameter in this region is approximately $10\ \mu\text{m}$. This area is likely to exhibit better ductility than the contact area, which has experienced more significant work hardening.

SEM subsurface analysis beneath the abraded areas of sample S3 revealed plastic deformation of the grains within the microstructure (**Figure 4.14a**). This deformation was characterised by grain elongation and realignment in the martensitic microstructure, orientated in the direction of abrasion (**Figure 4.14a**). The plastic deformation was also confirmed by a microhardness test across the depth of the specimen (**Figure 4.14b**), which showed an increase in hardness towards the contact surface compared to the undeformed region with an average deformation depth of approximately 30 μm . Similar findings were reported by Kyekyere et al. (2024) during failure analysis of screen plates used in coal separation and classification processes.

Cyclic sliding of the KT on the DBLs surface induces significant stress, causing localised plastic deformation on both the surface and the subsurface (**Figure 4.14**). These deformations initiate surface and subsurface cracks stemming from pre-existing manufacturing defects such as cracks, voids, and inclusions in the as-purchased DBLs. These cracks eventually merge, resulting in local fractures that lead to pitting which later results in loss of material by spalling (**Figure 4.15**).

Furthermore, the continuous abrasion caused by KT and its hard mineral content creates microindentation, microcutting, and microcracks on the DBL surface. These combined mechanisms lead to material loss, manifesting itself as two-body abrasive wear. A plot of the microhardness variation between the deformed and undeformed region is shown in **Figure 4.14b**. The deformed region has a higher hardness compared to the undeformed region. This signifies that the DBL has indeed undergone work hardening closer to the area of contact, as first revealed under an optical microscope (**Figure 4.12b**).

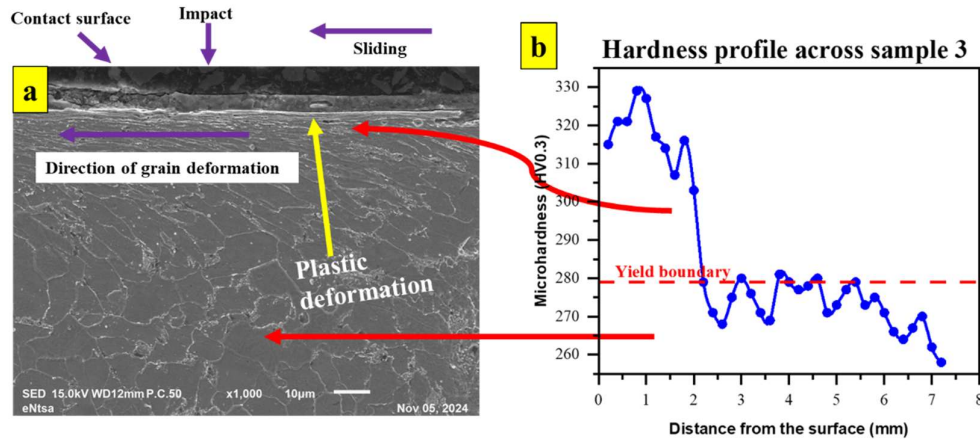
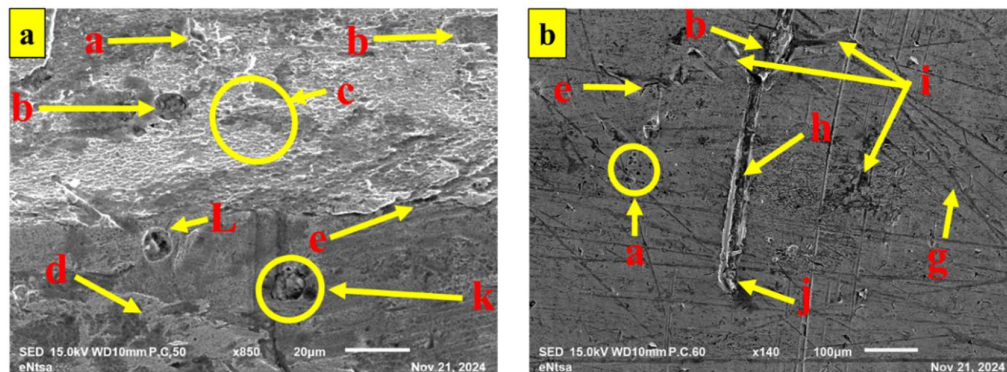


Figure 4.14: (a) SEM micrograph of sample S3 cross-section near the failed surface and (b) hardness plot of sample S3.

4.5.4 Mechanism of occurrence of failure mode D: via optical, stereo and SEM micrographs.

The spalling observed in this micrograph (**Figure 4.15a**) suggests that repetitive impact from kimberlite particles has caused small cracks to form and propagate, eventually leading to the flaking off material. This wear mechanism is often associated with surfaces that have undergone deformation and have been work-hardened.



a = Void , b = Spalling, c = Layered delamination, d = Plastic deformation, e = Micro-crack, g = Scratches, h = Ploughing, i = Indentation, j = Material pile up, K = Pits/voids, L = pit

Figure 4.15: SEM micrograph of damaged DBLs samples S4 showing spalling and other wear mechanisms.

The micrographs (**Figure 4.16a** and **Figure 4.16b**) corresponding to sample S4 highlight areas of material displacement and embedded particles, with regions showing intact and heavily eroded zones. This reflects localised variations in resistance to mechanical wear. The high carbon content in **Table 4.6** could imply the presence of diamond in the pit as discussed in **Table 4.3**. EDS spectrum at point 1 confirms the presence of aluminium and oxygen, indicating an aluminium oxide inclusion (**Figure 4.16a**). The presence of aluminium oxide inclusions as discussed earlier can act as stress concentrators, leading to crack initiation and propagation under cyclic sliding (Arreola-Herrera et al., 2018). Additionally, these hard inclusions may contribute to abrasive wear, accelerating material degradation.

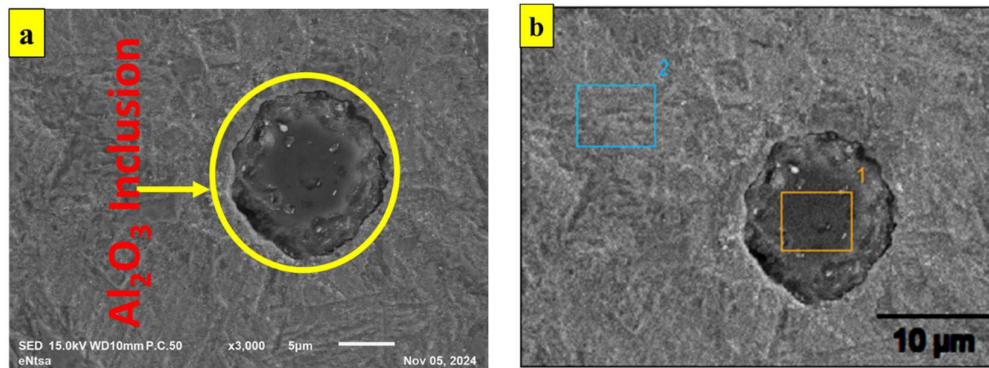


Figure 4.16: (a) SEM micrograph showing Al_2O_3 inclusion within the microstructure of sample S4, (b) SEM micrograph indicating regions (1-2) sampled for elemental composition analysis.

Table 4.6: EDS spectra of sample S4 establishing presence of Al_2O_3 inclusion.

Points	C	O	Al	Si	Mn	Fe
1	7.1	30.5	53.2			9.1
2	1.2			0.1	2.4	96.2

4.6 Failure mode evolution in Dozer Blade Liners (DBLs)

Dozer blade liners (DBLs) used in kimberlite tailings environments at diamond mines experience various failure modes, as outlined in **Table 4.2**. However, a key gap remains in identifying which specific wear mode most significantly accelerates wear or failure by exacerbating other modes. Addressing that failure mode early will help prevent the occurrence of other failure modes. Therefore, this analysis examines the interactions between failure modes and mechanisms that contribute to the progressive deterioration of

DBLs. This section investigates the sequential development of wear-related damage to the DBL, emphasising how abrasive sliding wear initiates surface degradation and its potential role in propagation of pitting, deformation, surface cracking, and spalling. These failure mechanisms collectively compromise the structural integrity of the liner, reducing its operational lifespan.

The as-purchased dozer blade liners (DBLs), which contain manufacturing defects within an acceptable limit, are installed onto the track dozer blades. During operation, the blade pushes kimberlite tailings with particle sizes ranging between 10 mm and 1.7 mm. These tailings impact and slide across the DBL surfaces, leading to the development of abrasive wear marks and scratches, - characteristic features of abrasive wear, here in referred to as **failure mode A**. The abrasive wear marks, combined with pits and crack-like feature ‘lap defects’ present from manufacturing phase, further weaken the DBLs surface. These defects tend to propagate under repeated abrasive contact, creating localised weak spots that eventually initiate pitting, referred to as **failure mode B** in **Figure 4.17**. A surface that is continuously subjected to abrasion by kimberlite tailings while also exhibiting pitting becomes increasingly vulnerable to plastic deformation, leading to the formation of dents, this progression was classified as **failure mode C**. Subsequently, the plastically deformed surface, already compromised by cracks from abrasion and pre-existing manufacturing defects, begins to lose small chunks of material. This chipping or flaking is referred to as **failure mode D**, commonly known as spalling. Ultimately, at a macroscopic level, these progressive failure mechanisms result in a visibly worn and severely degraded dozer blade liner (DBL) surface **Figure 4.17** illustrates a schematic representation depicting the occurrence of different modes and DBL failure mechanisms and their interconnections.

5 Chapter Five: Downtime analysis and mitigation strategies for damaged Dozer Blade Liners (DBLs)

5.1 Chapter summary

This chapter focuses on the analysis of downtime caused by damaged DBLs and explores practical strategies to mitigate its impact. It begins with a brief discussion on the calculation of DBL-related downtime, evaluating the associated monetary costs using field data collected from the mine, maintenance department records, and relevant literature. This was followed by a set of proposed cost-effective and environmentally friendly mitigation strategies for the mine to adopt in order to reduce premature wear and failure of DBLs at the mine. In the end, a cost-benefit analysis of the proposed mitigation measures was carried out to determine their profitability for the Orapa diamond mine.

5.2 Dozer blade liners (DBLs) downtime calculation

To assess the financial impact of replacing dozer blade liners (DBLs), data from the machinery maintenance department at the Orapa diamond mine was analysed. This section presents a step-by-step breakdown of the information, calculating downtime costs and estimating the company's losses due to premature blade failures. The analysis draws on data from Appendices C and D, which detail dozer blade liner performance and maintenance records at the mine, and is based on the assumption that these records accurately represent dozer performance over the study period.

Key Information from Appendices C, and D:

- Expected lifespan: The supplier expected the blade to last 15000 hours of operation.
- Actual lifespan: The blade failed after 11125 hours, falling short of expectations.
- Operating schedule: The dozer works 18 hours per day and 6570 hours per year.
- Failure shortfall: The blade stopped working 3875 hours earlier than expected

$$\text{Failure shortfall} = 15000 \text{ hours} - 11125 \text{ hours} = 3875 \text{ hours} \quad (\text{equation 5.1})$$

- Replacement details: From the maintenance records, replacing the blade liners took 5 hours on 27th October, 2017.
- Blade cost: The replacement cost of the blade is BWP 80000 ($\approx$ USD 5600), as noted in the component changeout schedule.

The blade's early failure means the company had to stop the dozer to fix it, losing valuable operating time, and had to replace the blade sooner than planned, costing extra money.

a) Understanding the blade's operating time

$$\text{Yearly operation} = 18 \frac{\text{hours}}{\text{day}} \times 365 \text{ days} = 6570 \text{ hours/year} \quad (\text{equation 5.2})$$

This assumes the dozer runs daily without breaks, which is standard for heavy mining equipment, aside from minor downtime.

- Expected life in years: If the blade lasted 15000 hours:

$$15000 \text{ hours} \div 6570 \frac{\text{hours}}{\text{year}} \approx 2.28 \text{ years} (\approx 2 \text{ years and 3 months}) \quad (\text{equation 5.3})$$

- Actual life in years: It lasted 11125 hours:

$$11125 \text{ hours} \div 6570 \frac{\text{hours}}{\text{year}} \approx 1.69 \text{ years} (\approx 1 \text{ years and 8 months}) \quad (\text{equation 5.4})$$

- Lost time: The dozer blade liners failed about 7 months earlier than expected.

This indeed confirms that the dozer blade liners didn't perform as expected, forcing Orapa diamond company to address the issue much sooner than anticipated.

b) Implications of the dozer blade liner's premature failure

The DBLs were installed on February 28, 2019, when the dozer had already accumulated 11125 hours (from **Appendix C**). This likely means 11125 hours was the dozer's total operating time at installation, and the blade itself started at 0 hours (it was new). When it failed, the dozer stopped working until the blade was replaced. **Appendix D** shows a replacement on October 27, 2017, taking 5 hours (from 08:00 to 13:00). This is best clue about the downtime duration.

c) Downtime duration

- Replacement time: This is the time the dozer was out of service for that specific event. In practice, downtime might include extra time for diagnosing the failure or waiting for parts, but since the record shows the job was completed in 5 hours on the same day, therefore, 5 hours was used as the immediate downtime caused by the failure.

d) Financial Impact

The company lost money in two main ways:

- Lost productivity during downtime: The dozer couldn't work for 5 hours while being repaired.
- Premature replacement cost: The blade didn't last as long as expected, so the company had to buy a new one sooner than expected.

e) Cost of premature replacement

Cost per hour: 80000 pula ÷ 15000 hours ≈ BWP 5.33/hour (equation 5.5)

- But actual hours used: 11125 hours.

Expected value used: 11125 hours × 5.33 $\frac{\text{pula}}{\text{hour}}$ ≈ BWP 59296.25 (equation 5.6)

- Value lost: The blade should have lasted 15000 hours, so the unused portion is:

Value lost = 3875 hours × $\frac{5.33\text{pula}}{\text{hour}}$ ≈ BWP 20653.75 (equation 5.7)

This means the company lost about BWP 20654 because the blade didn't deliver its full value.

f) Downtime Cost

The exact cost of the dozer sitting idle as a result of premature DBLs failure was not given by the mine, but it represents the value of the work it could have done such as moving kimberlite tailings or mining diamonds. However, an estimate was made. In mining, a large track dozer such as the Komatsu D475A-5E0 might generate USD 1000 - 2000 (BWP 14300 - 28600) per hour in productivity (based on material moved and ore value) (Boltstress Ultrasonics, 2018; Creamer Media, 2022). For illustration purposes, a midpoint estimate of BWP 21450 per hour is considered a reasonable approximation.

Downtime Loss: 5 hours × BWP $\frac{21450}{\text{hour}}$ = BWP107250 (equation 5.8)

This is the money lost because the dozer was not working for 5 hours.

But, total estimated loss = Premature replacement + Downtime (equation 5.9)

$$\therefore \text{Total estimated loss} = 20654 + 107250 = \text{BWP } 127904$$

5.2.1 Summary of key finding from the downtime calculations

The dozer blade failed early, at 11125 hours instead of its expected 15000 hours, leading to unplanned downtime and extra costs. This caused a 5-hour work stoppage and a direct loss of BWP 20654 in blade value. But the bigger concern is the cost of lost production during that downtime. Assuming the mine loses about BWP 21450 per hour, the total estimated loss comes to BWP 127904 (USD 8950). However, this is just an estimate, the actual cost could be higher or lower depending on the mine's operation expenses. For a more accurate assessment, Orapa diamond mine would need to provide their specific hourly downtime rate. This analysis highlights how a single DBLs failure can quickly lead to significant financial losses for the mine.

5.3 Mitigation measures for dozer blade liner plate damage

According to Raj (2023) mining equipment maintenance generally falls into two main categories: proactive and reactive. In many industries, reactive maintenance is the most commonly practiced approach, where action is only taken once machinery breaks down or malfunctions. However, adopting a predictive or proactive strategy is significantly more effective to ensure the long-term operability and lifespan of equipment. While reactive maintenance is not ideal, an even less favourable option for addressing equipment issues is full replacement.

Replacing machinery often results in greater downtime compared to repairing or remanufacturing, as operators must wait for new parts or equipment, sometimes sourced from neighbouring countries or even overseas (Tyler et al., 2015). Additionally, equipment replacement is not aligned with sustainable practices, which are becoming increasingly important as society places greater emphasis on sustainability and decarbonisation. For this reason, businesses that focus on repair over replacement, especially when dealing with high-value machinery such as DBLs, are better positioned to extend asset life, lower long-term costs, and meet environmental, social, and governance (ESG) objectives. A proactive maintenance approach, strengthening and optimising critical machinery and components, plays a vital role in maximising efficiency and overall productivity. Therefore, to address premature wear of dozer blade liners (DBLs) used in diamond mines, several cost-effective

and environmentally friendly mitigation strategies, which are proactive and reactive are proposed:

- Material Selection:
 - The mine should use structurally stable and wear-resistant materials with improved hardness, toughness, and fine microstructures, such as WC-reinforced H13 tool steel, can be utilised to manufacture DBLs. These improved material properties can better withstand abrasive interactions with kimberlite tailings.
 - Orapa diamond mining company should explore surface treatments that increase resistance to abrasive wear, such as coatings and surface hardening treatments.
- Manufacturing Technologies:
 - The mine should adopt advanced manufacturing technologies to improve bonding among constituent materials without degrading their mechanical properties. Techniques such as laser cladding or other advanced hardfacing can improve the durability of DBLs.
- Inspection and Maintenance:
 - Orapa mining company should implement regular inspections of DBLs before and after each operational shift to detect early signs of wear or damage, such as abrasive wear marks, pitting, cracking, or spalling. This will enable timely interventions and reduce downtime.
 - The mine should develop a maintenance schedule that includes the reconditioning of worn liners to extend their lifespan.
- Operational Adjustments:
 - The mine should provide refresher courses to train operators on identifying and avoiding operating conditions that accelerate wear, such as excessive loading or long waiting for tailings to pile-up before pushing.

- They should implement a strict operational guideline that require dozer operators to manage tailings continuously rather than waiting for large accumulations, ensuring efficiency and reducing operational delays.

5.4 *Cost-benefit analysis of mitigation measures for dozer blade liner plate damage*

This section presents a cost-benefit analysis (CBA) that compares the costs of implementing these measures against the benefits they are expected to deliver. Costs include direct expenses, such material purchases and operator training, while benefits encompass savings from reduced maintenance, fewer replacements, and reduced operational downtime. Since detailed financial data from the Orapa mine was not provided, the analysis relies on industry standards and case studies to estimate the associated costs and benefits. **Table 5.1** outlines the estimated cost categories for each mitigation measure proposed in **Section 5.3**, based on general industry practices and relevant literature.

Table 5.1: Estimated cost categories for mitigation measures based on industry standards.

Mitigation measure	Cost components	Estimated cost range
Materials selection	Purchase of WC-reinforced H13 tool steel; application of surface treatments (coatings, hardening).	High initial cost; potentially 2-3 times higher than standard steels (Lindsay, 2024).
Manufacturing technologies	Investment in laser cladding equipment or outsourcing; training for skilled personnel.	Significant upfront cost; equipment may cost USD 100,000 to ≥ USD 400,000 (Guosheng Laser, 2024).
Inspection and maintenance	Labour for shift-based inspections; consumables and labour for reconditioning.	Moderate recurring cost; labour costs depend on inspection frequency (Small Business Expert, 2023).
Operational adjustments	Refresher courses for track dozer operators; resources for tailings management	Low to moderate cost; training may cost R4500 (~ USD 240) per 7- 10 days session (Gautech Training

	(e.g., fuel, procedures, reinforcement guidelines).	Institute, 2023; ZTC, 2025).
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- **Manufacturing technologies and materials selection:**

The economic feasibility of laser cladding (LC) for remanufacturing dozer blade liners (DBLs) and other high-value heavy duty mining equipment lies in its ability to offset high upfront costs with significant long-term savings. While LC systems range from USD 100,000 to $\geq 450,000$, more expensive than thermal spraying (USD 50,000–200,000) and arc welding (USD 10,000–50,000), they offer considerable lifecycle benefits (Guosheng Laser, 2024; Laura, 2022; Spraywerx technologies, 2021). LC recovers 85 to 90% of energy and material inputs, significantly reducing machining requirements and cutting lifecycle costs by 20 to 40% compared to thermal spraying, due to improved durability (Swinson, 2020). For example, Titanova inc (Swinson, 2020) successfully repaired a 8,000 lb bull gear (see **Plate 5.1**) in a single day using LC, avoiding the need for costly replacements and extended downtime. Thermal spraying, in contrast, incurs higher material costs (~USD 319–329 / kg) and additional finishing work due to its mechanical bonding process (Focus Technology Co., Ltd, 2025; HTS Coatings, 2020). The LC metallurgical bond improves wear resistance and reduces maintenance frequency (Akintunde et al., 2025). Arc welding, although initially cheaper, often results in higher labour costs due to manual rework (Das, 2012). Its high heat input, up to 70% more than LC, also causes distortion, further increasing repair expenses (Kyekyere et al., 2025). Advanced LC coatings, such as WC-reinforced alloys, provide exceptional wear resistance, but come at a higher material cost, necessitating careful selection based on application requirements (Da Silva et al., 2025). Although LC requires advanced diagnostics and programming, its ability to extend DBL service life and minimise maintenance supports its economic viability in mining applications.



Plate 5.1: Laser refurbished bearing surface on bull gear (Swinson, 2020).

Laser cladding offers both environmental and economic sustainability. Improvements that reduce their environmental impact, such as material efficiency and waste minimisation, also contribute to lower production costs (Islam, 2021; Jung et al., 2023). LC enables the fabrication of complex components more quickly and efficiently than traditional methods.

- **Inspection and maintenance, and operational adjustments**

Regular inspections allow for early intervention, preventing costly failures. A case study from FLS Wear Solutions indicates that proactive maintenance with wear-resistant solutions can reduce maintenance costs by up to tenfold (FLS Wear Solutions, 2025). This suggests that similar wear-resistant solutions for DBLs could yield comparable savings. On the contrary, refresher courses to train dozer operators to use wear-reducing practices can decrease wear rates by 10-30%, while effective tailings management minimises abrasive exposure, reducing downtime by 5-15% (Gautech Training Institute, 2023; Jindal Infrastructures PVT LTD, 2025; Richer-Lanciault, 2025; SEO, 2025). The benefits of the proposed mitigation measures are supported by industry evidence (outlined in **Table 5.2**), which suggests the potential for significant savings.

Table 5.2: Industry evidence supporting the benefits of proposed mitigation measures.

Mitigation measure	Expected benefits	Estimated impact
Materials selection	Extended DBL lifespan; reduced replacement frequency.	Lifespan may double and improve overall performance, saving 50 - 70% on replacement costs (Amado et al., 2009; Laserbond, 2024).(Belbağ & Belbağ, 2023; Walsh et al., 2015)
Manufacturing technologies	Improved durability; fewer premature failures.	30 % reduction in maintenance costs (Senfeng, 2024).
Inspection and maintenance	Early detection of wear; prevention of major failures.	15 - 25 % reduction in repair costs; 20 - 40% less downtime (MCH Parts, 2023).
Operational adjustments	Reduced wear from better practices; less tailings-related wear.	Reduction in wear rate of the DBLs; decreased downtime (Gautech Training Institute, 2023).

5.5 Summary of findings from the Cost-Benefit Analysis (CBA) of the proposed mitigation measures

The cost-benefit analysis suggests that the proposed mitigation measures for track dozer blade liners at Orapa Mine are economically viable. The use of wear-resistant materials, advanced manufacturing techniques, regular inspections, and operational adjustments is likely to extend DBL lifespan, reduce maintenance costs, and minimise downtime. While initial investments are significant, industry evidence indicates that these costs will be offset by long-term savings, potentially halving replacement frequency and reducing maintenance

expenses by up to tenfold in some cases. To confirm these benefits, Orapa mine should conduct a detailed financial assessment and consider a pilot implementation to validate the effectiveness of the measures.

5.6 Conclusion

This chapter began by analysing the monetary losses associated with track dozer downtime due to premature failure of the DBLs. At the Orapa diamond mine, a single track dozer incurs a loss of approximately BWP 127904 ($\approx$ USD 8950) in just five hours of idling caused by premature DBL failure. This significant cost underscores the urgent need for effective mitigation strategies to address the premature wear or failure of DBLs. Consequently, mitigation measures were developed (Section 5.3), based on the downtime cost analysis and the experimental wear and failure analysis results and discussion from **Chapter 4**. In the end, a Cost-Benefit Analysis (CBA) of the proposed mitigation measures was performed to ascertain the profitability of adopting the mitigation measures at the Orapa diamond mine.

6 Chapter Six: Conclusions and future work

6.1 Chapter summary

This chapter reaffirms the study's objectives and summarises the key findings related to the dozer blade liners (DBLs) used to push kimberlite tailings at the Orapa diamond mine in Botswana. It concludes with recommendations and outlines directions for future research.

6.2 Conclusions

The study aimed to address the premature failure/wear of the dozer blade liner through the following objectives which were established in **subsection 1.4.2 of chapter 1**:

- a) Investigate of the operational and environmental conditions contributing to the wear and failure of DBLs at the Orapa diamond mine.
- b) Conduct experimental analysis of worn DBLs, including macro- and microstructural characterisation to uncover the root cause of premature wear/failure of the DBLs.
- c) Correlate observed failure modes with field conditions and DBLs material properties.
- d) Develop and recommend mitigation strategies to the mine based on the results of the analysis of wear/failure modes of the DBLs.

6.3 Key Research Findings

6.3.1 Findings from the Literature Review

- Track dozers used in mining operations, particularly in diamond mines, face some of the harshest working conditions. These include abrasive wear from pushing through kimberlite tailings (KT) and large rocks, heavy impact loads, extreme temperatures, corrosion, and uneven terrain. Such environments place significant mechanical and environmental stress on dozer blade liners (DBLs), leading to frequent maintenance and replacement.
- Kimberlite tailings typically contain about 11.5% moisture, which causes the tailings to agglomerate into larger particles. This agglomeration makes dozing more difficult, increases wear on DBLs. The tailings also exhibit mixture of angular and spherical particles. This abrasive material accelerates the wear on DBLs during operation, contributing significantly to equipment fatigue and component failure.

- DBLs differ in size, design, and material depending on the specific mining task. They are typically manufactured through casting or hot rolling processes and made from wear-resistant materials such as the Hardox steel series, Arcoplate, Domex, Bisalloy 80, high-strength steel alloys, and chromium-molybdenum steels. These materials are chosen based on their performance under abrasive and impact conditions.
- Selecting the appropriate blade and DBLs is critical for maximising dozer productivity and efficiency. The process begins with assessing the expected tasks over the dozer's lifespan, evaluating the materials to be handled, and considering operational limitations. Factors such as soil characteristics, compaction, moisture content, and terrain influence the optimal blade and liner configuration. Proper selection can lead to reduced wear, increased fuel efficiency, and longer component life.
- The common wear modes and mechanisms in DBLs include: abrasive, surface fatigue and corrosive wear.
- While often viewed as a material-centric issue, wear is a system-level phenomenon influenced by the properties of both the abrasive and wear-resistant materials, as well as the contact conditions. A comprehensive understanding of these interactions is essential to improving DBL performance in mining environments. Insights from similar components such as wheel loader buckets, ploughshares, and liner plates—help broaden the understanding of wear behaviours, as these components operate under comparable conditions and use similar materials.
- Literature and industry practices support a multifaceted approach to combating wear in DBLs. Effective strategies include: selecting high-performance wear-resistant materials (e.g., Hardox, chromium carbide); applying protective coatings or liners; conducting regular inspections and maintenance (e.g., lubrication) and implementing preventive maintenance programs and suitable remanufacturing techniques. Together, these measures can significantly improve the durability and efficiency of DBLs, reducing downtime and operational costs in abrasive mining environments.

6.3.2 Findings from the experimental wear and failure analysis of DBLs

Investigating the wear mechanisms of dozer blade liners (DBLs) used at the Orapa diamond mine in Botswana revealed several critical findings which are summarised below:

- Premature wear is primarily driven by abrasive sliding contact with kimberlite tailings (KT), which contain hard minerals such as silica and diamond. The abrasive nature and angularity of the KT particles, combined with their high hardness, exacerbated the loss of material.
- The predominant wear mechanisms include abrasive sliding wear, pitting, ploughing, surface cracking, plastic deformation, and spalling. Repeated impact stresses intensified spalling and pitting, further reducing the service life of the DBL.
- The damaged DBLs exhibited banded ferrite-pearlite microstructures which cause anisotropy in the steel's tensile, bendability and impact properties, leading to reduced mechanical properties, particularly impact toughness, bendability, and tensile strength in the transverse direction.
- Plastic deformation during operational cyclic sliding contact contributed to increased hardness near the wear surface but led to microcracks and eventual material loss.
- Pre-existing manufacturing defects, such as microvoids, inclusions, and cracks, acted as stress concentrators, further accelerating wear.
- The total estimated production loss was BWP 127904 (approximately USD 8950) during a 5-hour period. This highlights the critical importance of proactive maintenance and timely replacement of damaged DBLs to minimise financial losses and ensure consistent productivity.
- This study underscores the need for improved DBL materials and manufacturing processes to combat wear mechanisms. Optimising microstructures, eliminating banding, and addressing manufacturing defects are essential to improve the wear resistance. Additionally, operational strategies such as controlling the moisture content of the KT and reducing contact stresses can complement material improvements. These insights provide a foundation for developing robust solutions to extend DBL service life and reduce maintenance costs in the mining industry.

6.4 Recommendation for future work

While the study has successfully achieved its objectives and addressed several existing knowledge gaps, there remains scope for additional investigation. The following recommendations are proposed for future research, though they are not exhaustive.

- There is a need to perform numerical analysis of DBL failure modes and wear mechanisms under KT conditions, using the finite element method (FEM) or discrete element method (DEM), in order to identify areas of stress concentration on the blade, validate wear modes, and optimise loading conditions for blade liners.
- The incorporation of condition-monitoring sensors (such as strain gauges, acoustic emission sensors, or vibration monitors) into dozer blade liners should be considered. This can provide real-time data on wear progression and potential imminent failures.
- The damaged DBLs should be remanufactured using advanced laser-based manufacturing techniques, such as laser cladding. This will restore the damaged DBLs to at least 'as-new' performance at a lower cost than purchasing new ones.
- There is a need to use the findings from the failure analysis to identify the most suitable material and remanufacturing process parameters for restoring damaged DBLs, by evaluating the consolidation mechanisms, microstructural evolution, and mechanical properties of the remanufactured layer.

This study contributes to a deeper understanding of the failure mechanisms affecting dozer blade liners in challenging mining environments. The insights and recommendations provided here lay the groundwork for developing more resilient and cost-effective solutions for the Orapa diamond mine.

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Appendices

Appendix A: Total Particle Size Distribution (PSD) of kimberlite tailings at the Orapa diamond mine in Botswana.

Month	Sieve size	10mm	8mm	6.7mm	4.75mm	2.8mm	1.7mm
9-Jan-24	Overall percentage of kimberlite tailing particles passing through the sieves (%)	98%	85%	70%	44%	20%	6%
16-Jan-24		98%	85%	73%	50%	25%	7%
24-Jan-24		96%	71%	57%	35%	21%	13%
30-Jan-24		97%	80%	67%	42%	30%	17%
6-Feb-24		97%	80%	68%	40%	28%	16%
13-Feb-24		97%	85%	75%	52%	27%	9%
19-Feb-24		96%	72%	57%	35%	22%	13%
27-Feb-24		98%	84%	73%	48%	23%	7%
4-Mar-24		98%	86%	73%	47%	23%	5%
12-Mar-24		98%	85%	73%	50%	25%	7%
21-Mar-24		97.40%	80.02%	65.86%	36.02%	21.06%	5.73%
30-Mar-24		97.61%	78.20%	62.91%	37.95%	27.63%	16.63%
4-Apr-24		98.66%	86.23%	73.62%	42.49%	23.79%	4.67%
10-Apr-24		98.10%	80.38%	64.96%	40.64%	19.87%	6.68%
17-Apr-24		98.87%	87.67%	76.63%	55.60%	32.47%	14.59%
22-Apr-24		98.8%	83.0%	70.9%	47.2%	21.6%	4.2%

1-May-24		98.7%	83.2%	71.6%	47.2%	21.4%	4.5%
8-May-24		97.5%	81.9%	69.3%	42.3%	20.6%	6.2%
14-May-24		99.1%	87.8%	73.9%	48.2%	23.5%	7.1%
22-May-24		99%	84%	71%	43%	20%	4%
Average		99	82	69	44	24	9

Appendix B: Monthly tailings moisture content data collected at the Orapa diamond mine, Botswana in 2024.

Production month	week	Date	Tailings moisture				
			Wet mass	Dry mass	Moisture content	Average	Target
Jan-24	1	19 Dec 2023	12.45	11.19	10.12	11.79	10%
	2	26 Dec 2023	12.69	11.19	11.82		10%
	3	02 Jan 2024	11.55	10.03	13.16		10%
	4	09 Jan 2024	10.86	9.55	12.06		10%
Feb-24	5	16 Jan 2024	12.63	11.19	11.40	10.12	10%
	6	23 Jan 2024	15.64	14.88	4.86		10%
	7	30 Jan 2024	10.47	9.12	12.89		10%
	8	06 Feb 2024	14.85	13.21	11.04		10%
	9	13 Feb 2024	13.47	12.07	10.39		10%
Mar-24	10	20 Feb 2024	14.98	13.25	11.55	10.49	10%
	11	27 Feb 2024	10.66	9.30	12.76		10%

	12	05 Mar 2024	10.99	10.16	7.55		10%
	13	12 Mar 2024	12.48	11.22	10.10		10%
Apr-24	14	19 Mar 2024	12.45	11.19	10.12	11.92	10%
	15	26 Mar 2024	12.69	11.19	11.82		10%
	16	02 Apr 2024	12.83	11.17	12.94		10%
	17	09 Apr 2024	15.84	13.81	12.82		10%
May-24	18	16 Apr 2024	12.42	10.82	12.88	12.34	10%
	19	23 Apr 2024	13.61	12.08	11.24		10%
	20	30 Apr 2024	7.02	6.14	12.54		10%
	21	07 May 2024	12.89	11.32	12.18		10%
	22	14 May 2024	12.42	10.82	12.88		10%
Jun-24	23	21 May 2024	13.61	12.08	11.24	11.91	10%
	24	28 May 2024	7.02	6.14	12.54		10%
	25	04 Jun 2024	12.83	11.17	12.94		10%
	26	11 Jun 2024	15.84	13.81	12.82		10%
	27	18 Jun 2024	17.48	15.73	10.01		10%
Jul-24	28	25 Jun 2024	12.89	11.5	10.78	9.78	10%
	29	02 Jul 2024	10.78	9.81	9.00		10%
	30	09 Jul 2024	13.8	12.4	10.14		10%
	31	16 Jul 2024	13.59	12.34	9.20		10%
Aug-24	32	23 Jul 2024	12.88	11.74	8.85	7.74	10%
	33	30 Jul 2024	9.04	8.41	6.97		10%

	34	06 Aug 2024	12.94	11.91	7.96		10%
	35	13 Aug 2024	8.63	8.01	7.18		10%
Sep-24	36	20 Aug 2024	15.64	14.28	8.70	10.28	10%
	37	27 Aug 2024	12.5	11.22	10.24		10%
	38	03 Sept 2024	13.13	11.81	10.05		10%
	39	10 Sept 2024	13.23	11.9	10.05		10%
	40	17 Sept 2024	10.91	9.564	12.34		10%
Oct-24	41	24 Sept 2024	10.66	9.27	13.04	12.43	10%
	42	01 Oct 2024	10.68	9.46	11.42		10%
	43	08 Oct 2024	9.42	8.15	13.48		10%
	44	15 Oct 2024	9.78	8.63	11.76		10%
Nov-24	45	22 Oct 2024	11.98	10.53	12.10	12.58	10%
	46	29 Oct 2024	10.82	9.61	11.18		10%
	47	05 Nov 2024	13.5	11.63	13.85		10%
	48	12 Nov 2024	12.31	10.77	12.51		10%
	49	19 Nov 2024	12.92	11.21	13.24		10%
Dec-24	50	26 Nov 2024	12.53	11.28	9.98	10.41	10%
	51	03 Dec 2024	12.6	11.13	11.67		10%
	52	10 Dec 2024	13.38	11.83	11.58		10%
	53	17 Dec 2024	13.58	12.44	8.39		10%
Average						10.98	

Appendix C: Komatsu D475A-5E0 track dozer changeout schedule at the Orapa diamond mine in Botswana.

Description	Name/Value
Machine	Komatsu D475A-5E0 (Unit: D475-17)
serial number	30339
Estimated operating hours/day	18
Equivalent operating hours/annum	6570
Dozer Blade Liners (DBLs) details	
Date of installation	28-Feb-2019
Current machine hours	11125
DBLs hours at installation	15000
DBLs current hours	0
DBLs hours not used	3875
DBLs changeout hours	15000
Remaining hours to changeout	11125
Remaining days to changeout	795
Projected DBLs replacement date	05-June-2020
Unit price (BWP):	80000
Previous DBLs change history	
31-March-2014	OK
30-June-2014	OK

30-September-2014	OK
31-December-2014	OK
Projected second replace (days)	6548

Appendix D: Maintenance contract and premature DBLs failure refurbishment confirmation summary - Orapa diamond mine in Botswana.

Category	Field	Value
Project / Order	Order number	11005/05132
	Project title	Blade refurbishment
	System status	TECO, GMCO, GMPS, IMAT, PRC, TEG
	Planner group	001 / 3020
	Person responsible	(Anonymised)
	Basic start date	07-09-2018
	Basic finish date	23-09-2018
	Priority	Break-in
Equipment	Functional location	OE-EMV-Hling-KOMATSU TRACK DOZER D475-17
	Equipment number	10027725
Operation	Operation number	0010
	Operation description	Fit blade

	Work Centre (Planning)	Q999 (example)
Confirmation	Confirmation number	5313425
	Operation / Activity	0010 / Fit blade
	Personnel number	10
	Wage type	(Not shown / Anonymised)
	Posting date	21-10-2017
	Work centre (Actual)	OHEMC2 (Mechanic Komatsu)
	Final confirmation	Yes
	Confirmation text	Replaced blade; ref: 731201,4555
Additional Details	Activity type	120
	Actual work	10 (Hours)
	Remaining work	0 (Hours)