Multi-Edge Disc Cutters Wear and Damage Evaluation

By

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Abstract

The term "cutter wear" refers to a reduction in radial length. The fragmentation of rocks by disc cutters per revolution might result in the intermittently repeated wear of a given place on the cutter tip. Thus, the wear capacity of disc cutters can be determined by measuring the wear of a point on the cutter tip when crushing rocks, known as the radial wear coefficient; however, the wear of a disc cutter is caused by interaction between the disc cutter and its working objects, as seen macroscopically. This study evaluates the wear and damage of disc cutters that are now commonly used on cutter heads used in tunnel boring, raise drilling, and large-diameter blind drilling. Disc cutters are mounted on the cutter head for drilling purposes. Continuous use of the disc cutters over an extended penetrating time during drilling will lead the disc cutters to experience damage and wear, this wear will in turn influence drilling performance. It is therefore very important to evaluate the damage and wear of the drilling disc cutters. Wear is a significant cause of disc cutter failure. There is no current theory that provides a standard for predicting disc cutter wear.

This research is focused on wear and damage measurements of large-diameter disc cutters and drilling tools used for a mining operation at Baie Verte, north of Newfoundland, Canada. The field data compiled for wear and damage of the large diameter drilling disc cutters showed that the two methods (damaged score count and wear measurement) used to determine disc cutter wear give complimentary results. The objective for carrying out this project was met, although it is important to note that future research to carry out an expansive evaluation of wear and damage of the large diameter drilling cutters and drilling tools needs to be done as several drilling parameters influence the degree of wear and damage experienced by the disc cutters and drilling tools.

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Table of Contents

List of Figures

List of Tables

Nomenclature

A_B	Area of Bit
ASME	American Society of Mechanical Engineers
AR	Advance Rate
ASTM	American Society of Testing and Materials
AVS	Abrasive Value Steel
BHA	Bottom Hole Assembly
CAI	Che char Abrasivity Index
DE	Drilling Efficiency
DOT	Drill Off Test
DSM	Destructive Strength Method
DTL	Drilling Technology Laboratory
FTA	Fault Tree Analysis
FFT	Full Field Trial
FR	Fluid Rate
HHP	Hydraulic Horsepower
HV	Hardness Value
ITS	Indirect Tensile Strength
KN	Kilonewton
LD1	Large Diameter Hole 1
LDD	Large-Diameter Drilling
m	meter

m/hr	Meters Per Hour
MPa	Megapascal
MSE	Mechanical Specific Energy
MUN	Memorial University of Newfoundland
N	Rotary Speed
NDSM	Non-Destructive Strength Method
NTNU	Norwegian University of Science and Technology
OMAE	Ocean, Offshore and Arctic Engineering
P	Penetration
Pmax	Maximum Pressure
PLSI	Point Load Strength Index
PR	Penetration Rate
PVARD	Passive Vibration-Assisted Rotary Drilling
Qmax	Maximum Flow rate
Qmin	Minimum Flow rate
Qpump	Pump Flow rate
RDC	Research Development Company
RLM	Rock Like Materials
ROP	Rate of Penetration
RPM	Revolution Per Minute
SMD	Sustainable Mining by Drilling
SOP	Standard of Procedure
T	Bit Torque

TBM	Tunnel Boring Machine
Th	Thrust
TOB	Torque on Bit
Tq	Torque
μ	Friction Coefficient
UCS	Unconfined Compressive Strength
USGPM	US Gallon Per Minute
WOB	Weight on Bit
XRF	X-ray Fluorescence
Z	Thrust

Chapter 1: Introduction

1.1 Background of the Thesis

Wear is a significant cause of disc cutter failure. There is no current theory that provides a standard for predicting disc cutter wear. In the field, the most common wear prediction method is based on the excavation length of the tunnel boring machine (TBM) to predict disc cutter wear and its wear law, considering the location number of each disc cutter on the cutter head (Zhang et al., 2014).

The term "cutter wear" refers to a reduction in radial length. The fragmentation of rocks by disc cutters per revolution might result in the intermittently repeated wear of a given place on the cutter tip. Thus, the wear capacity of disc cutters can be determined by measuring the wear of a point on the cutter tip when crushing rocks, known as the radial wear coefficient; however, the wear of a disc cutter is caused by interaction between the disc cutter and its working objects, as seen macroscopically. Cutter consumption and parameters such as cutter ring wear play a significant role in drilling performance and cost predictions, particularly in hard rock conditions. Cutter wear is caused by a complex tribological system that interacts with the geological properties of the rock mass (Macias, 2016). The performance and efficiency of any disc cutter are heavily influenced by rock properties such as strength, hardness, and abrasion resistance. On the cutter head of a full-face hard rock boring machine, a disc cutter is the primary breaking rock tool. It comes into direct touch with the rock and is subjected to a great deal of wear and tear. When a disc cutter hits its wear limit, it loses its ability to break rock, therefore, predicting how much wear and tear it will experience can help enhance construction efficiency (Jianqin, 2020).

Many factors influence drill bit wear, including drilling and rock properties, as well as the properties of the materials used to make the bit. The type and amount of wear is determined by several complicated factors that must be considered when predicting wear rates in field and laboratory conditions, such as the geometry of the bit, drilling parameters, and mechanical properties of the materials used to form the drill bit. There have been numerous descriptions of bit wear quantification technologies. To estimate the bit wear condition, each method relies on available measured data and prudent interpretation. Furthermore, each approach is premised on assumptions that limit its applicability.

1.2 Research Objectives

The primary goal and objective of this research work is focused on wear and damage measurements of large-diameter disc cutters and drilling tools used for a mining operation at Baie Verte, north of Newfoundland, Canada.

The evaluation of disc cutters was conducted to measure the damage and wear of the large-diameter drilling disc cutters utilized during the FFT#1 of a mining field situated at Baie Verte, Newfoundland, Canada. Another objective is to understand dynamic factors such as vibration, torque and drag, WOB, rock strength and hardness, ROP etc. that go on to influence wear and failure of the disc cutters, and to also gain insight into major contributing causes of the disc cutter and drilling tool wear and damage. The objective was to minimize wear and overall failure of the disc cutters, thereby maximizing the rate of penetration (ROP), increase the span life of the disc cutters, and optimize drilling efficiency (DE).

Several forensic analyses were carried out at the Drilling Technology Laboratory as well as the technical services at the Memorial University of Newfoundland, to determine how several parameters such as drilling operation parameters (vibration, torque, thrust etc.), manufacturing conditions of the multi-edge disc cutters affect the operation and performance of drilling.

1.3 Thesis Outline

This thesis consists of 7 chapters. See below the description of each chapter's content.

Chapter 1 entails the introduction of the thesis which gives an overview and compound summary of the whole work that's comprised in the thesis.

This chapter contains the background of the thesis, the research objective, and the thesis outline that was employed in building up the thesis. The thesis outline describes the content of each chapter of the thesis (a comprehensive literature review, research methodology, OMAE paper publications, a DTL quarterly report, and the conclusion of the work.

Chapter 2 is a comprehensive literature review of the drilling performance optimization related to the evaluation of wear and damage of disc cutters and drilling tools. Covers the literature on methods and procedures that were employed during this research.

Chapter 3 gives an insight into the research methodology used to conduct the research for the subsequent chapters 4, 5, and 6. The methodology includes the Drilling Technology Laboratory (DTL) standard of procedure (SOP) for wear and damage evaluation for sustainable mining by drilling full field trial one, the equipment used to conduct the wear evaluation, and methodology utilized in the bit cutters reconfiguration experiments**.**

Chapter 4 discusses a yet-to-be-published technical paper titled "Evaluation of Wear and Damage on Large-Diameter Disc Cutters", expected to be presented at the upcoming ASME 2023 42nd International Conference on Ocean, Offshore, and Arctic Engineering OMAE 2023 June 11-16, 2023, in Melbourne, Australia. The paper details the wear evaluation methodology that has been adopted for utilization in the ongoing SMD project and the objective of the paper is to shed light on a qualitative way of recording the wear and damage of disc cutters.

Chapter 5 discusses a technical report “Forensic Analysis of Damaged Multi-Edge Disc Cutters” for ongoing research by the MUN-DTL group. The objective of this report was to disassemble damaged disc cutters used in FFT#1 and to analyze how they influence cutter wear.

Chapter 6 discusses the analyses of operating drilling parameters used during the drilling operation to determine how they influence wear and caused the damage of the disc cutters.

Chapter 7 summarizes and concludes the research work that has been conducted during my research journey with the DTL group.

Chapter 2: Literature Review

2.1 Overview of Disc Cutter Wear

The theory of the disc cutter's wear and damage mechanism serves as a foundation not only for assessing overall wear and damage but also for predicting the impact of wear and damage on drilling efficiency and performance. As a result, scholars both at home and abroad have put a lot of effort into characterizing disc cutter wear. Several analytical or judgmental methods have been used by numerous competent researchers, these methods can be summarized as analyzing cutter load empirical formulae, engineering data fitting analyses, experimental parameters derived from rock grinding, and qualitative cutter wear analysis. Wear is a significant cause of disc cutter failure. According to several literature, there is no current theory that provides a standard for predicting disc cutter wear. Despite the importance of cutter wear and its significant impact on drilling performance, little attention has been paid to establishing realistic models for estimating cutter wear and associated costs.

(Hassanpour, 2018) created an empirical model for estimating disc cutter wear in sedimentary and low to medium-grade metamorphic rocks. Based on the data from the shield excavation parameters, (Li, and Su, 2010) predicted overall cutter wear using the Elman neural network model. (Chen et al., 2011) investigated the cause and form of disc cutter wear and described a series of disc cutter wear-reduction measures. Built on a mechanical analysis of the disc cutter, (Wang et al., 2012) developed the energy method for predicting disc cutter wear extent. Based on a previously developed model, (Frenzel, 2012) created a statistical model for performance and wear prediction. (Rostami and Ozdemir, 1993) developed a model for the cutting force estimation of disc cutters based on the intact rock properties.

(Mouritz and Hutchings, 1991) investigated the wear rates and abrasive wear mechanisms of the materials used in the teeth of rotary drill bits. Using testing, (Parviz, (1975) demonstrated that wear would impair the cutting performance of disc cutters. Models developed at the Colorado School of Mines (Rostami and Ozdemir, 1993); (Rostami, 1997) and the Norwegian University of Science and Technology (Bruland, 1998) were proposed to predict the force on the cutter based on many statistical data. The fragmentation of rocks by disc cutters per revolution can result in the intermittently recurrent wear of a specific point on the cutter tip. Thus, the wear capacity of disc cutters can be determined by measuring the wear of a point on the cutter tip when they crush rocks, i.e., radial wear coefficient; whereas, macroscopically, disc cutter wear is the result of interaction between the disc cutter and its working objects and emerges during the TBM excavation process in the field (Zhang et. al. 2011). Figure 2-1 shows different types of cutter wear.

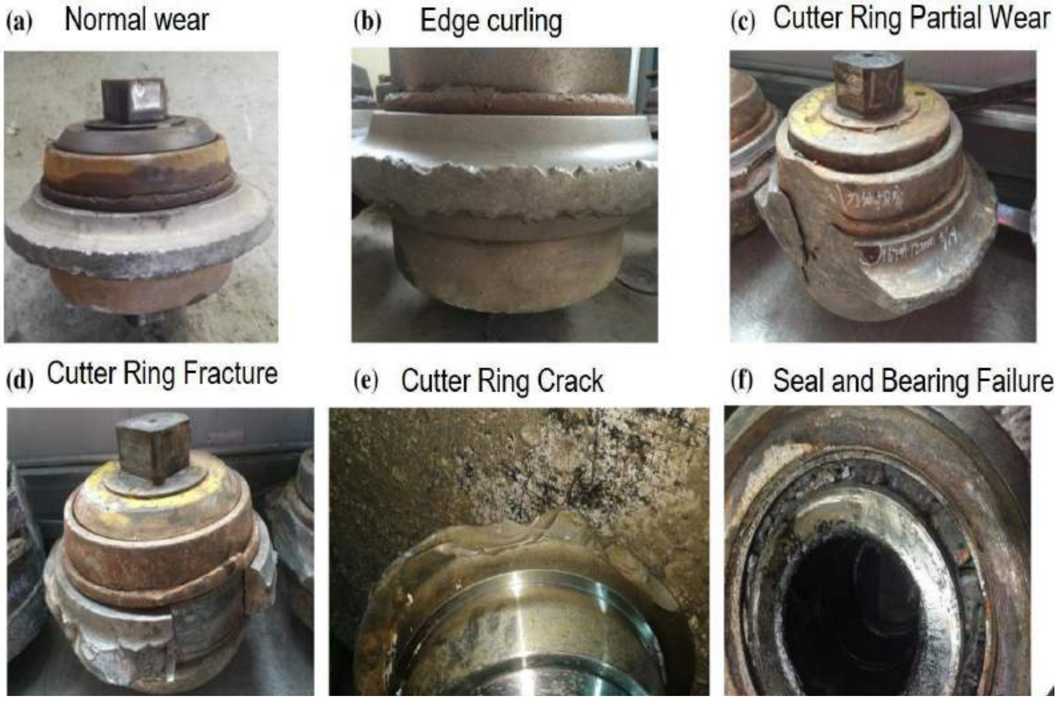


Figure 2-1. Different types of disc cutter wear

Wear can also be calculated by measuring the wear of a cutter within a unit excavation length, which is known as the axial wear coefficient. The analysis of disc cutter rock fragmentation, on the other hand, reveals that in the excavation process, in terms of one disc cutter, the boring trajectory track of the continuously rolling rock fragmentation is in the form of a spatial spiral. As a result, the cutter wear can also be determined by measuring the wear of a cutter that rolls on the spatial spiral, i.e., trajectory wear coefficient, and a cutter within a unit excavation length, i.e., axial wear coefficient (Zhang et. al. 2011).

However, in this study, measurements were carried out at a mining operation site located at north of Newfoundland, Baie Verte, Canada, to determine the degree of damage and wear on large-

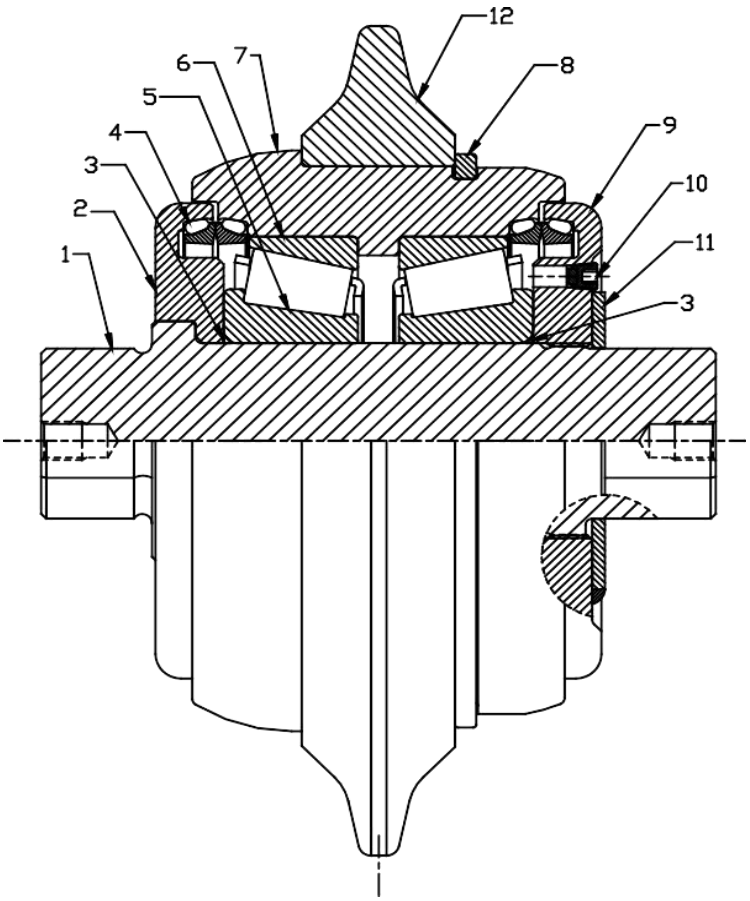


Figure 2-2. Single disc cutter (Frenzel, 2011).

1. Shaft 2. Seal retainer 3. O-ring 4. Seal set 5. Bearing cone 6. Bearing cup 7. Hub 8. Split ring 9. Seal retainer 10. Plug 11. Tab plate 12. Cutter ring

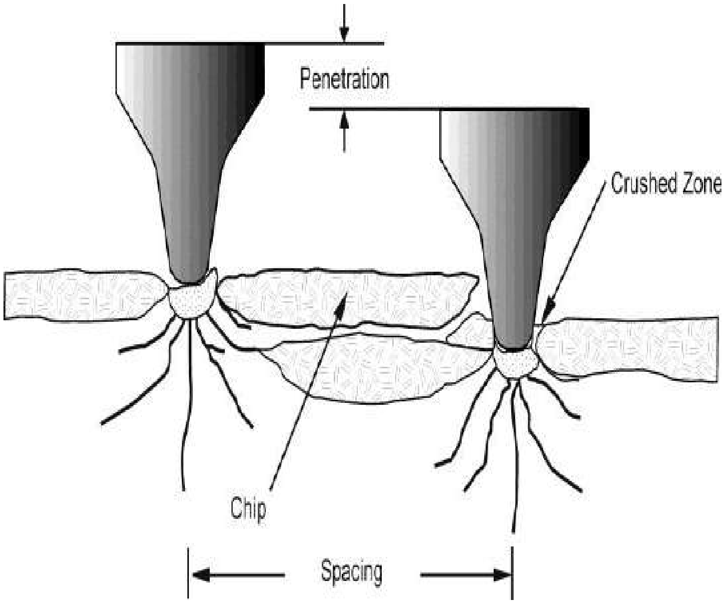


Figure 2-3. Chipping process of a disc cutter (Frenzel, 2011).

diameter drilling disc cutters as well as drill string components. Figure 2-2 depicts a standard single disc cutter that is 17 inches long (432 mm). The actual cutting of the rock is being done by the cutter ring (number 12).

Due to the rotation of the cutterhead, a set of tapered roller bearings are used to connect the cutter ring to the shaft (number 1). A pair of face seals (number 4) are employed to keep debris and the lubrication for the disc cutter's bearings out and the interior clean. Together with the seal retainers (numbers 2 and 9), the hub (part number 7), creates the disc cutter's envelope (Frenzel, C. 2011).

2.1.1 Cutting Process

Because rock often has a significantly lower tensile strength than compressive strength, disc cutting makes use of this feature.

Compressive failure as shown in Figure 2-3, occurs in the contact region because of a high point load. There is a crushed zone formed. Tensile failure also induces cracks into the region surrounding the crushed zone. Between two-disc cutter locations, the cracks begin to cross, forming a rock chip that is released (Frenzel, C. 2011).

2.2 Insert Tooth Cutter Wear and Damage

Insert tooth cutter wear and damage is characterized by the condition of the tungsten carbide inserts after a drilling operation. The inserts are then classified into blunt, chipped, fractured, and missing, and a damage score is then attributed to each insert condition. A damage score of 0 for blunt inserts, 1 for chipped inserts, 2 for fractured inserts and 3 for missing inserts. There is a standard for dull grading drilling bits in the oil and industry, but there isn't one for disc cutters. As a result, an extrapolation that since each insert's vertical height and slope are 5mm and 3.54mm, respectively, each 1mm represents 20% of the insert's height. Table 2-1 below can be used to grade the dullness of the disc cutter insert (Q2 2021 DTL report, 2021).

Table 2-1. Disc Cutter Insert Dull Grading (Q2 2021 DTL report)

Insert Condition	Insert Material (%)	Insert Slant/Vertical Height (mm)
Excellent	80-100	4-5/2.83-3.54
Good	60-80	3-4/2.12-2.83
Fair	40-60	2-3/1.41-2.12
Bad	20-40	1-2/0.71-1.41
Critical	0-20	0-1/0-0.71
Completely worn	<0-0	0

2.3 Wear and Drilling Performance Efficiency

Drillability estimation is crucial for drilling rocks. Two essential factors for determining an operation's duration and cost are drilling performance and tool wear. The fundamental definition of "drillability" is the ability of a rock mass or rock to resist being penetrated by drill bits (Thuro, 1996). This metric can be expressed using drill rig measurements of drilling (or penetration) rate and drill bit application measurements of tool wear. In rock engineering, the drilling process is the most expensive, and early on in an operation, predicting drilling performance is crucial.

Planning a drilling operation is more effective with an accurate drillability estimate. Planning a rock excavation project is more effective when drillability is accurately estimated (Bruland, 1998); (Dahl et al., 2012); (Kivade et al., 2015).

Rock drilling rate and tool wear depend on a number of variables that can be divided into the fields of geology (i.e., soil, rock, and rock mass), tool (i.e., type, weight, power of the machine, and shape, size, and geometry of the head), and logistics (i.e., mode of operation, transport, and maintenance) (Thuro, 1996). Due to this, numerous researchers have been examining the effects of various geological and geotechnical characteristics of rock mass and rock on drillability for decades. According to, (Gstalder and Raynal's, 1966), the drilling rate declines with rising Schreiner hardness and sonic velocity, respectively. (Thuro and Spaun, 1996), looked into the relationship between drilling rates and rock mechanical characteristics. They suggested a metric they called "destruction work," emphasizing that it could be more closely connected to drilling rate than uniaxial compressive strength, Young's modulus, and indirect tensile strength.

Drilling efficiency can be increased by predicting drill bit wear without having to remove the bit from the hole. However, due to several circumstances, including bit balling and an increase in rock hardness, a decrease in the rate of penetration is insufficient proof of bit wear. There have been proposed mathematical models for the rate of penetration (ROP) with the bit wear factor (Bourgoyne and Young, 1974). These models, however, cannot be used for real-time bit wear analysis (Rashidi and Hareland, 2010). The mechanical specific energy (MSE) technique makes the most extensive use of the drilling bit's efficiency. Teale first proposed the idea of MSE for effect on bit performance as the energy needed to pulverize a unit volume of rock (Teale, 1965).

2.3.1 Methodology of MSE

The definition of mechanical specific energy (MSE), which can be used as a competitive tool to detect changes in drilling efficiency and indicate real-time drilling concerns, is the amount of labor necessary to remove a specified volume of rock. To achieve the real-time calculation, the fundamental MSE methodology is described in terms of drilling parameters as follows:

$$MSE = \frac{WOB}{A_B} + \frac{120\pi \times N}{A_B \times ROP} \qquad (2-1)$$

In the formula above, A_B stands for bit surface area (inch^2), N for rotary speed (revolution per minute), T for bit torque (lbf × ft), and MSE for mechanical specific energy in (psi) (Teale, 1965).

To offer an indicator of the bit performance, Waughman proposed an approach that measures the MSE independently in each section that is drilled in conjunction with the present formation type. By contrasting immediate MSE values with the typical baseline, this illustrates a decision-making technique for determining when to pull the bit (Waughman et al., 2003).

Additionally, Dupriest said that the bit is effective if the particular energy values remain constant; but, when MSE goes consistently above the normal values, a dangerous indicator occurs and needs to be mitigated (Dupriest and Koederitz, 2005). Bit vibrations might undoubtedly result in a similar increase in MSE values, but monitoring MSE with penetration rate can somewhat alleviate this mistake (Motahari et al., 2008).

In the end, the primary factor affecting bit wear and performance is the rock's physio-mechanical characteristics, which influence the pace of drilling bit penetration (Prillet, 1990). They create resistance and barriers that the bit must get beyond to achieve maximum penetration. These include the traits of breaking, hardness, strength, texture, elasticity, plasticity, and abrasiveness. The chemical and mineral makeup of the rocks has an impact on how well the drill bit works (Prillet, 1990). The rate of penetration, bit life, and bit wear rate could be used to gauge and quantify a bit's performance (Tatiya, 2005; Hustrulid, 1999).

2.4 Factors Influencing Disc Cutter Wear

The number of cutters used in hard rock tunnel boring machines is influenced by a variety of factors (TBMs). Normal TBM operation results largely in abrasive wear of the cutter rings, which has been proven to be proportional to cutter rolling distance by many researchers (Rostami, 1997 0; (Bruland, 1998); (Frenzel et al., 2008). Costs and performance in hard rock and soil materials are greatly impacted by disc cutter wear in mechanized tunneling. Numerous geological and technical elements have an impact on wear. Prediction models and case studies have taken a number of factors into account. The wear of TBM cutters has been described and measured in numerous previous attempts. A prediction model put forth by (G. Wijk, 1992) specifies the cutter life in terms of cutter rolling distances. According to (Gehring, 1995), the mass loss rate of the cutter ring, which exhibits an exponential relationship with CAI, represents the degree of tool wear. Through a series of laboratory cutting tests, (Rostami, 1997) created the CSM model for the calculation of cutting forces. The model was later used for the prediction of cutter wear (Hassanpour et al., 2015); (Li et al., 2017).

By considering the connection between the overcut length and the gauge cutters' length, (Gharahbagh et al., 2013) created a novel method to evaluate gauge cutter wear. Based on field data gathered from a water conveyance tunnel project, (Liu et al. 2017) examined the wear of a 20-inch disc cutter and suggested a method to forecast the cutter life in hard rock.

2.4.1 Rolling Distance vs Wear

The wear of disc cutters is inversely correlated with rolling distance, according to (Rostami, 1997); (Bruland, 2000). According to (Bruland, 2000) analysis of the equations in his prediction models, the rolling distance of the cutter has an impact on the production of a specific cutter (m3/cutter), in addition to the abrasiveness of the rock, cutter head diameter, disc cutter diameter, spacing, and penetration. The wear of disc cutters can be considerably decreased by decreasing cutter head rotation or increasing penetration, as is obvious. Several hard rock TBM-driven projects over the past few years have verified this dependence.

2.4.2 Abrasivity vs Wear

There are a few recognized and often used test methods for determining the abrasiveness of rocks, including the Cherchar test (Valantin, 1974), the LCPC test (Normalization Francaise P18-579, 1990), and the Abrasion Value Steel (AVS) test method (Dahlet al., 2012). Additionally, over the past ten years, some researchers have developed studies to categorize the abrasiveness of rocks (Plinninger and Restner, 2008); (Thuro and Kasling 2009); (Dahl et al., 2012). Plinninger and Restner's, (2008) summarized some of the most prevalent testing techniques and grouping of the findings. A classification of abrasiveness for soil and rock was introduced by Thuro and Kasling, (2009) in comparative research employing three approaches for abrasivity assessments. The drillability test ratings from the Norwegian University of Science and Technology (NTNU)/SINTEF were given by (Dahl et al., 2012). Rock abrasiveness cannot be viewed merely as an intrinsic feature and the full tribological system should be examined in addition to the geological properties of the rock. None of the present laboratory test procedures were designed with the intention of assessing cutter wear, therefore they do not accurately mimic the wear behavior experienced during tunnel boring. Figure 2-4 shows the Cher char Abrasivity Index that is used for the classification of different rock types.

It was, therefore, thought fascinating to design a novel rock abrasivity test method to assess cutter wear in hard rock tunneling as closely to reality as feasible drillability test due to the significance of cutter wear. Several scholars examined the relationship between abrasive wear and the

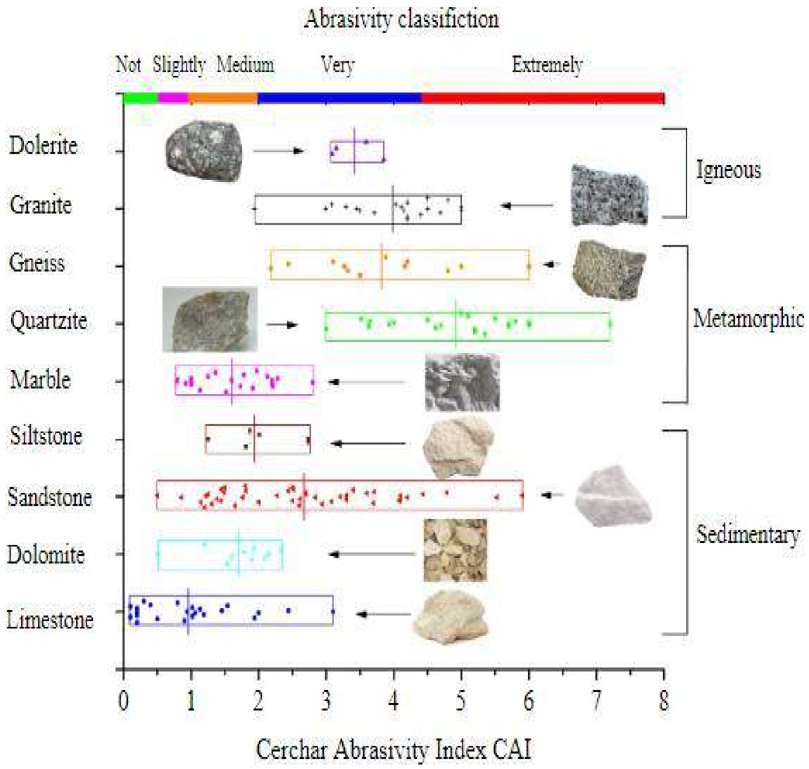


Figure 2-4. CAI values for different rock types. (Jin D. et al. 2021).

characteristics of rock and steel, and other factors related to the tribological system (Petrica et al., 2013); (Ratia et al., 2014); (Espallargas et al., 2015); (Ellecosta et al., 2015). (Petrica et al., 2013), investigated wear behavior and its relationship to the mechanical and physical characteristics of rocks. In their examination of the impact of abrasive qualities on steels and hard metals, (Ratia et al., 2014), concluded that it is crucial to consider the contact circumstances and the entire wear environment when making wear evaluations. (Espallargas et al, 2015), studied how corrosion affected abrasive wear on TBM cutter steel when it encountered excavation fluid.

By evaluating a range of laboratory tests, Vickers hardness tests were carried out by (Ellecosta et al., 2015) with loads up to HV 30 and this helped to determine the effectiveness of the approach for assessment of rock abrasivity and wear, several rocks and related disc cutters.

2.4.3 Rock Strength Characterization vs Wear

The variability of rock strength has been extensively researched in recent years (Phoon and

Kulhawy, 1999); (Ruffolo and Shakoor, 2009); (Cai, 2011). Unconfined compressive strength (UCS) and tensile strength (TS) are two commonly used parameters for determining rock strength. They also have a significant impact on the wear of cutter tools due to their influence on the applied force between the cutter and the rock. Understanding rocks and formations requires an understanding of rock strength, one of the mechanical rock qualities. The establishment of secure structures (in the mining and civil sectors) and the assessment of drilling success (in the geotechnical and petroleum industries) both depend on knowing the rock's strength. Rock strengths have been determined using a variety of strength methodologies, indexes, and techniques. These techniques can be classified as Destructive Strength Methods (DSM) or Non-Destructive Strength Methods (NDSM).

Schmidt/Rebound Hammer and ultrasonic measurement are two of the NDSMs. Constrained and Unconfined Compressive Strength (CCS and UCS, respectively), Indirect Tensile Strength (ITS), and Point Load Strength Index (PLSI) are two of the DSM (PLSI).

Rock strength plays an important role in influencing the wear and damage of disc cutters over the course of a drilling operation. There is a linear relationship between wear and rock strength, the harder the rock, the more the increase in the wear and damage of the disc cutter and the decrease in the tool life of the cutters.

2.4.4 Drilling Operation Parameters

Failure of the disc cutter is also highly influenced by technical issues, which mostly apply to drilling operating parameters. Recent research has concentrated on the operational characteristics to forecast drilling success (Paltrinieri et al., 2016); (Acaroglu and Ekinci, 2013); (Wilfing, 2016); (Ghasemi et al., 2014); (Li et al., 2017). The onboard acquisition system records the characteristics relevant to drilling operations, such as rotation speeds (RPM, r/min), advance rates (AR, mm/min), thrust forces (Th, kN), and torques (Tq, kNm). By using the rotation speed and advance rate, it is possible to determine the penetration rate (PR) of cutter tools, which is commonly used to assess the wear of cutter tools.

2.5 Disc Cutter Wear Life and Consumption

The ability to predict tool life for a drilling operation is required for cutting tool design, as well as determining cutting conditions and tool change strategies. In tunnelling projects built with tunnel boring machines (TBM), estimating cutter consumption and the precise moment to replace worn-out cutters is always a hard issue. It is best to prevent catastrophic disc cutter failure because it can harm the cutters and significantly halt drilling operations. Instead, the crater wear and/or clearance face wear that develops over time on the cutter rake face can be used to define the usable life of disc cutters (flank wear). Flank wear is frequently used to indicate when a tool's useful life has ended.

An empirical model was created to anticipate cutter life by comparing input data to a TBM's field performance database and to calculate the cutters' likely rate of wear, (Nelson et al., 1994). Based on the on-site boring data from China's Qinling tunnel, (Zhao et al., 2007) discovered a relationship between penetration index and cutting coefficient in terms of boring performances. A proposition that the rolling distance life of a disc cutter decreases with increasing unconfined compressive strength (UCS) of intact rock and the corresponding higher CAI values was brought forward by (Maidl et al., 2008). They did this by examining the relationship between the mean rolling distance life of the discs, UCS, and the CAI for different types of intact rocks. A curve length wear-out coefficient to calculate the cutter wear extent (Zhang and Ji, 2009). New prognosis models and equations were developed for the relationship between CAI and tool wear based on the analysis of a wide variety of tunneling projects (127 km length in 7 tunneling projects), (Frenzel, 2011).

Chapter 3: Research Methodology

3.1 Introduction

Many factors influence drill bit wear, including drilling and rock properties, as well as the properties of the materials used to make the bit. The type and amount of wear are determined by several complicated factors that must be considered when predicting wear rates in field and laboratory conditions, such as the geometry of the bit, drilling parameters, and mechanical properties of the materials used to form the drill bit. There have been numerous descriptions of bit wear quantification technologies. To estimate the bit wear condition, each method relies on available measured data and prudent interpretation. Furthermore, each approach is premised on assumptions that limit its applicability.

Large-diameter drilling employs a wide range of cutters and bits. The disc cutter is a type of cutter that is commonly used on large-diameter cutter heads in rock excavation/drilling. The disc cutter is the primary breaking rock tool on the cutter head of a full-face hard rock boring machine. It comes into direct contact with the rock and suffers significant wear and tear. The disc cutter loses its ability to break rock when it reaches its wear limit, so its construction efficiency can be improved if the degree of wear and tear can be predicted. Disc cutters are now commonly used on cutter heads in tunnel boring, raise drilling and large-diameter blind drilling. Disc cutters are mounted on the cutter head for drilling purposes.

The disc-type cutter in hard rock works on the principle that by applying great thrust to the cutter, and thus pressure on the rock to be cut, a zone of rock directly beneath (i.e., in the cutting direction) and adjacent to the disc cutter is crushed, typically forming very fine particles. Continuous use of the disc cutters over an extended penetrating time during drilling will lead the disc cutters to

Figure 3-1. Damaged multi-edge disc cutters (Novamera Inc., 2022).

experience damage and wear, this wear will in turn influence or affect drilling performance. It is therefore very important to evaluate the damage and wear of the drilling disc cutters.

Because drill bit wear is considered an inherent cost, effective control and minimization of bit wear can result in significant savings. Real-time monitoring of the status of the bit wear is critical for increasing the rate of penetration and determining when to pull out the bit due to wear. Drilling with worn bits may result in bit loss, necessitating bit fishing, which adds to the overall drilling costs while also delaying the drilling operations. Figure 3-1 shows a damaged multi-edge disc cutter with worn bits.

A model can be made for the specific issue of disc cutter wear. It is advisable to distinguish between the following general wear patterns at disc cutters (Frenzel, 2010) for convenience's sake.

3.2 Research Materials and Equipment

Palmieri Wear Gage

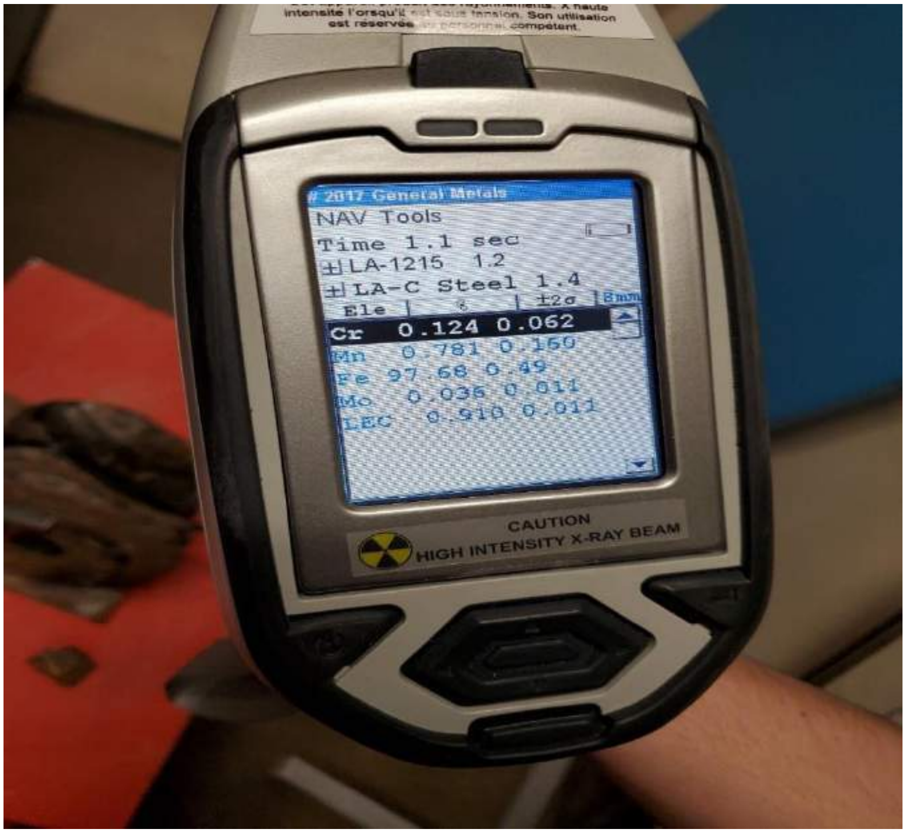
Due to their ability to precisely assess samples subjected to wear, surface mapping devices have emerged as an essential tool in tribology research. The wear gage can be used to predict and map progressive cutter consumption, Figure 3-2 depicts an image of a wear gage used on the field. To use the wear gage to predict cutter wear effectively, an unchanged reference area is marked on the body of the disc cutter throughout the course of the drilling operation. After every trip in and out of the wellbore, the cutter wear is measured so as to help the drilling operator determine when the tool life of the disc cutter is no longer able to provide optimum drilling efficiency during drilling. The wear gage was utilized in the field for the chapter 4 study of this research.

Hand-held XRF Spectrometer

For the identification of chemical constituents in paints, metal alloys, and other materials of aesthetic importance, XRF (X-ray Fluorescence) spectroscopy is a non-destructive analytical technique that is frequently employed in archaeometry.

Figure 3-2. Image of Wear Gage used on the field. (Tytler et. al., 2022)

Therefore, there is strong justification for the creation of mobile equipment based on XRF spectroscopy for measurements on the field.



```
# 2017 General Metals
NAV Tools
Time 1.1 sec
±LA-1215  1.2
±LA-C Steel 1.4
 Ele |  %  | ±2σ |8mm
Cr   0.124 0.062
Mn   0.781 0.160
Fe  97.68  0.49
Mo   0.036 0.011
LEC  0.910 0.011
```

Figure 3-3. Image of a hand-held XRF spectrometer.

The XRF analysis has a very high level of repeatability and precision. Figure 3-3 depicts a working XRF spectrometer. When adequate standard specimens are available, very accurate results are feasible, but they are also possible in instances where no specific standards can be identified. The measurement duration can range from a few seconds to thirty minutes, depending on the number of elements to be determined and the needed accuracy. Only a few seconds pass after the measurement before the analysis begins.

The two main categories of spectrometer systems are energy dispersive systems (EDXRF) and wavelength dispersive systems (WDXRF), which will be covered in more detail later. The spectrometer technology being utilized largely determines the components that can be studied and their detection levels. From sodium to uranium, the EDXRF elemental range is available (Na to U). It is even wider for WDXRF, ranging from beryllium to uranium (Be to U). The range of concentrations is (sub) ppm levels to 100%. In general, heavier elements have lower detection limits than those with high atomic numbers.

In XRF, a source emits X-rays that irradiate the sample. The source is often an X-ray tube, although it can also be a synchrotron or a radioactive substance. The sample's constituent components will emit fluorescent X-ray radiation at discrete energy (corresponding to hues in optical light) that is unique to them. A distinct color corresponds to a different energy. It is possible to identify the elements present by measuring the energy (or detecting the colors) of the radiation emitted by the sample. The qualitative analysis step comes after this. The amounts of each element in the sample can be calculated by measuring the intensities of the emitted energy (colors). Analyzing data quantitatively is the next stage. The XRF spectrometer, the mechanical servo press, the bench clamp, and the pin spanner wrench were utilized in the field for the Chapter 5 study of this research.

Mechanical Servo Press

Figure 3-4. Image of a Mechanical Servo-Press.

The mechanical servo press has a simple driving chain without a flywheel, clutch, or brake, which are necessary for a conventional mechanical press. As a result, maintenance is made easier for the servo press because all press motions, such as starting, changing velocity, and stopping, are handled solely by the servo motor. Figure 3-4 shows an image of a mechanical servo press, which outperforms the long-used hydraulic servo press in terms of productivity, product precision, and machine dependability without the noise of a hydraulic pump or convoluted piping. Flexible sliding movement is the servo press's key characteristic. The mechanical servo-drive press combines mechanical press speed, accuracy, and dependability with the flexibility of a hydraulic press (unlimited slide (ram) speed and position control, availability of press force at any slide position). Metal forming processes can be made more productive and efficient with servo drive presses.

Pin Spanner Wrench

Pin spanners, commonly referred to as "pin keys," operate somewhat differently than the other spanners described in this article. They grasp a fastener by inserting two metal pins into designated holes in the fastener head rather than holding it around the outside. The fasteners that pin spanners are used on are called ‘lock nuts’ and are mostly used to attach abrasive grinding pads to grinder power tools. When the spanner is turned, the moving pins cause the fastener to move too. Figure 3-5 depicts an image of a pin spanner wrench.

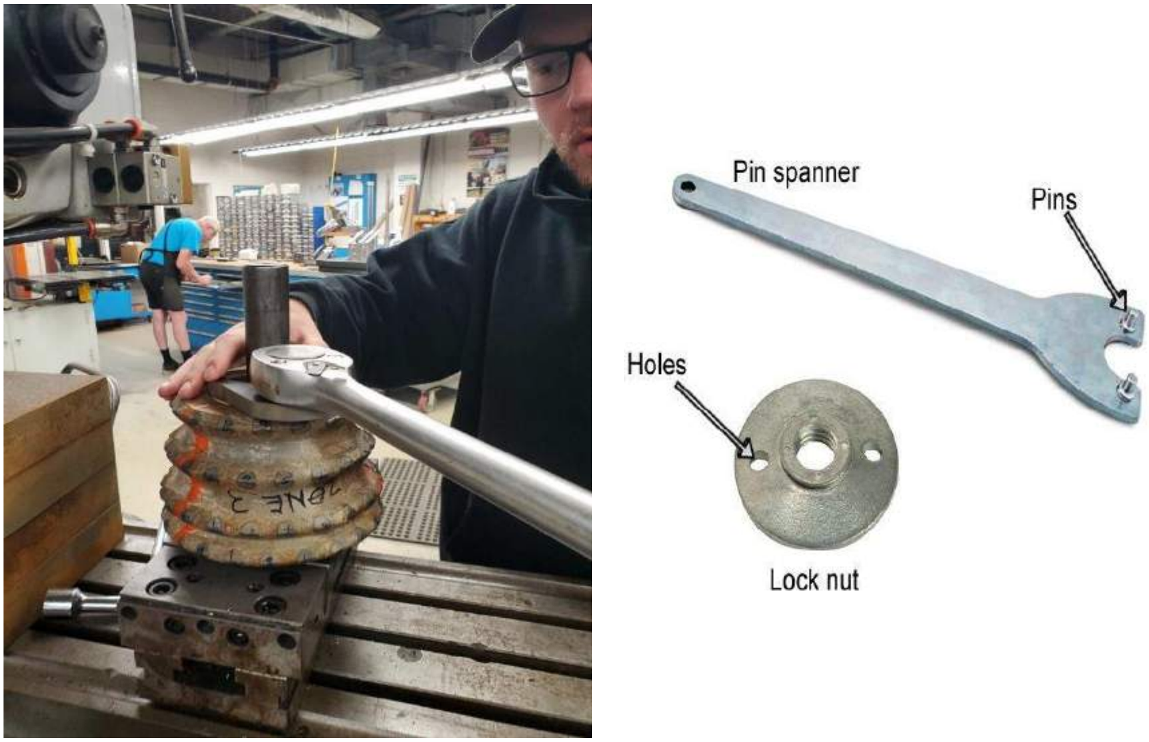


Figure 3-5. Image of a Pin Spanner Wrench

There are a few different pin spanner designs, all of which produce the same outcomes. Some have adjustable jaws, some have no jaws, and some have a pair of jaws with a pin on each jaw. Adjustable pin spanners have an adjustable screw or can be opened to fit a second pin after inserting the first one. A hole is present in many pin spanners, allowing for the connection of several tools or the attachment of a lanyard. The specifications for the pin spanner wrench fabricated with the help of technical services of MUN are Palmieri DC wrench / Circle Diameter - 91mm / Pin Length - 4mm / Pin diameter - 6mm; LDD DC wrench / Circle Diameter - 68mm / Pin Length - 7mm / Pin diameter - 8mm.

Bench Clamp

A bench clamp is a short-term tool used to clamp down objects on a workbench. A C-clamp, which is named after the letter C and has an adjustable throat or reach, tightly binds things together. Typically,

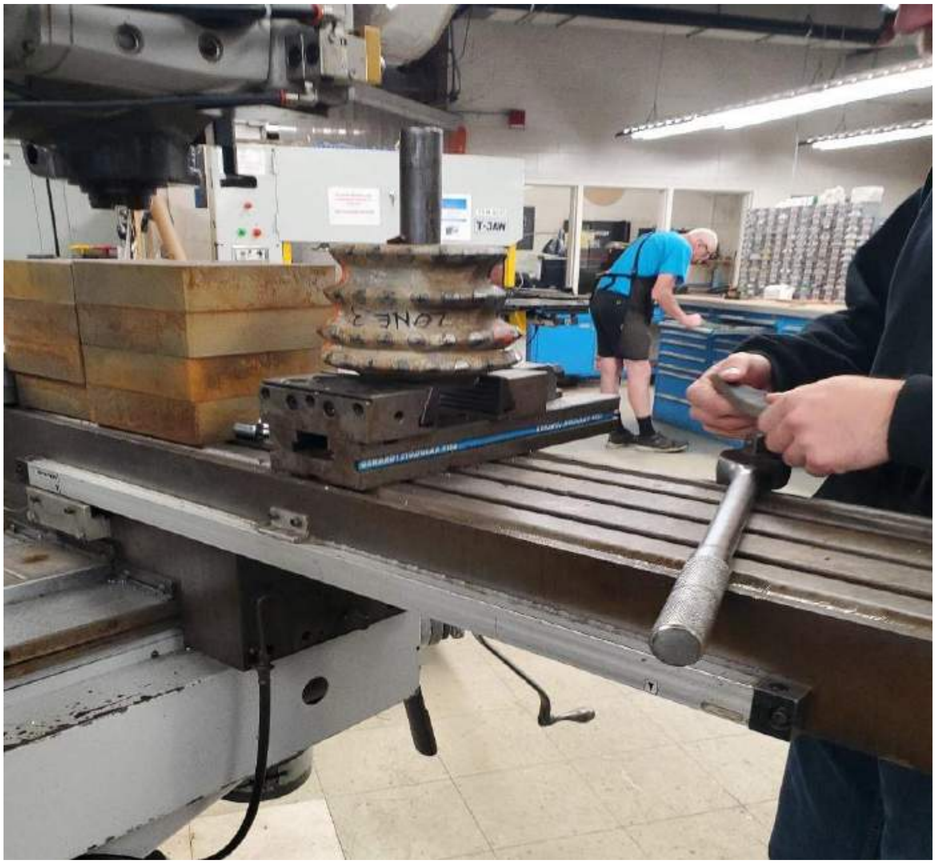


Figure 3-6. Image of a Bench Clamp in use.

steel or cast iron is used to make it. Once the workpiece is completely stabilized, the clamp is applied by turning a screw through the bottom of the C frame. Between 3/4 inch and 12 inches are the sizes of clamps (1.9 cm to 30.48 cm). Figure 3-6 depicts an image of a bench clamp.

3.3 Methodology Adopted for Wear Evaluation of Disc Cutters

A standard procedure for disc cutter wear and damage measurement for the Drilling Technology and Laboratory group was adopted for this research (Zijian et al., 2021). To assess the disc cutter's state before and after a certain period of drilling, the disc cutter wear and damage estimation counts the damaged inserts on the disc cutter. In this measurement, the damaged inserts are categorized as blunt, broken, chipped, or missing. Then each cutter's damaged inserts for each disc are tallied. A damage weight score system is then employed to evaluate the degree of wear and damage. On the field, the wear gage is also used to determine the extent of wear. This was the methodology employed in Chapter 4 of the research.

3.4 Methodology Adopted for Forensic Analysis of Damaged Disc Cutters

Although field measurements of wear and damage of disc cutters are the physical form of determining the extent of wear and failure that disc cutters may experience during a drilling operation, there is an intrinsic aspect of disc cutter wear that is unseen to the human eye. To ensure a thorough wear evaluation, it is paramount to carry out a forensic analysis of disc cutters after a drilling operation to determine how other parameters may have influenced the observed wear and failure of these cutters. Failure of disc cutters may occur due to manufacturing issues such as improper sealing of the internal components of the disc cutters, inadequate or lack of lubrication that can therefore lead to inefficient drilling performance and in the long run disc cutter damage, failure could also be due to drilling operation parameters such as vibration, torque, thrust, etc. The methodologies employed in the process of conducting the forensic analysis were.

- X-ray Fluorescence (XRF) scan of the stabilizer wear plate, disc cutter matrix, and drilling tools used on the field.

- Data analysis of field data mined during the drilling operation to observe any skew in the drilling parameters during drilling and to determine the likely depths, and formation type at which the skew is observed.
- Disc cutter disassembly to check internal components such as the shaft, seal, and bearing of the disc cutter to ascertain if there were any manufacturing issues.
- Conduct Fault Tree Analysis, FTA, which is a top-down approach that reverses engineers' wear and failure observed in the internal components of the disc cutters to determine if there was overheating, torque spike, vibration, etc.

3.5 Methodology for Thrust and Torque Relationship

For TBM design, thrust and torque on the cutter head are the two most crucial parameters. Figure 3-7 illustrates the roughly linear relationship between torque and thrust (ZT), as well as penetration (m).

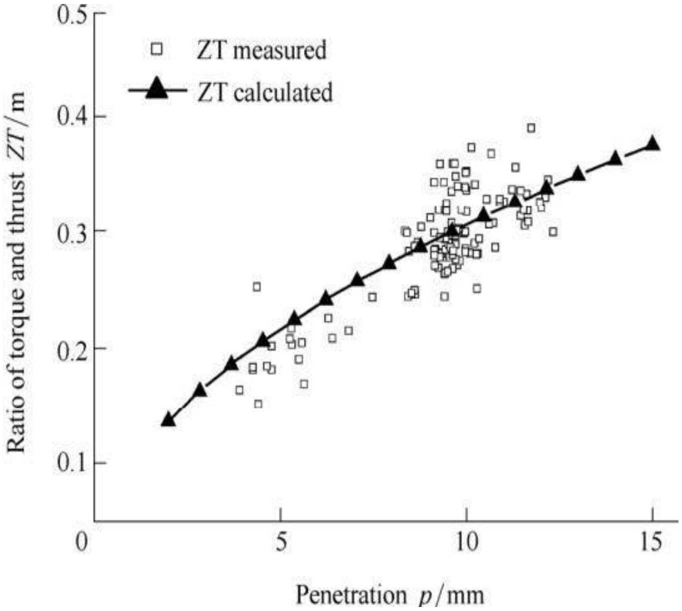


Figure 3-7. Relationship between penetration, p and torque and thrust, ZT ratio on TB880E. (Liu Jianqin et.al, 2015).

Z= Thrust, N

T = Torque, Nm

P = Penetration, /mm

Since the relationship between them changes depending on how the cutters are arranged on the cutter head, the torque grows faster than the thrust as penetration increases.

Chapter 4: Evaluation of Wear and Damage on Large-Diameter Disc Cutters.

This chapter discusses a yet-to-be-published technical paper titled "Evaluation of Wear and Damage on Large-Diameter Disc Cutters". The authors of this paper are Oluwafemi Tytler, Zijian Li, and Dr. Stephen Butt. This paper is completed and is due for submission for the proceedings of the ASME 2023 42nd International Conference on Ocean, Offshore, and Arctic Engineering OMAE 2023 June 11-16, 2023, in Melbourne, Australia. The author's contributions are described below:

- Oluwafemi Tytler: Research topic proposal, experimental plan and performance, data analysis, and manuscript preparation.
- Zijian Li: Manuscript review and methodology preparation.
- Judith George: Manuscript review.
- Dr. Stephen Butt: Lead supervisor. Manuscript review and paper approval.

4.1 Abstract

The disc cutter is commonly used on cutter heads for drilling engineering, including tunnel boring, raise drilling, large diameter drilling, etc. Continuous use of the disc cutters over an extended penetrating time during drilling will lead to the disc cutter's wear and damage, leading to reduced drilling performance, lost time, and ultimately higher economic cost. It is significant to evaluate the development of the wear and damage of disc cutters in the drilling process and how they influence the drilling operation, thereby improving drilling performance prediction and cutter life assessments. In this study, the disc cutter wear and damage development were studied based on several ongoing field trials and research, and a quantitative method of measuring the wear and damage of disc cutters was developed and has been used over the course of the research project.

4.2 Introduction

Large-diameter drilling (LDD) employs a wide range of cutters ranging from those with steel matrix and inserts to those with steel matrix and tungsten carbide inserts. The disc cutter is a type of cutter that is normally used on large-diameter cutter heads in rock excavation/drilling. Disc cutters are now commonly used in tunnel boring, raise drilling and large-diameter blind drilling. The disc cutters are mounted on the cutter head for drilling purposes, and they are the primary breaking rock tool on the cutter head of a full-face hard rock boring machine. It comes in direct contact with the rock and suffers significant wear and tear, and sometimes severe failure. The disc cutter loses its ability to break rock when it reaches its wear limit, (Jianqin, 2020).

Continuous use of the disc cutters over an extended drilling period will lead the disc cutters to experience damage and wear, with the wear in turn affecting drilling performance.

While wear increases the cost of cutters used for the operation, constant change of these worn cutters during drilling operations leads to downtime, which eventually increases the planned operation time. Thus, wear is a key consideration in the planning and execution of any large-diameter drilling project. Cutter wear is caused by a complex tribological system that interacts with the geological properties of the rock mass, (Macias, 2016).

The performance and efficiency of any disc cutter are heavily influenced by rock properties such as strength, hardness, and abrasion resistance. It is therefore very important to evaluate the damage and wear of the drilling disc cutters. Because drill cutter wear is considered an inherent cost, effective control and minimization of bit wear can result in significant savings, (K. Abbas, 2018).

Real-time monitoring of the status of the bit wear is critical for increasing the rate of penetration and determining when to pull out the bit due to wear. Drilling with worn bits may result in bit loss, necessitating bit fishing, which adds to the overall drilling costs while also delaying the drilling operation. Figure 4-1 shows an image of a scaled set of multi-edge disc cutters.

Many factors influence drill cutter wear, including drilling parameters and rock properties, as well as the properties of the material to make the cutters. The type and amount of wear are determined by several complicated factors that must be taken into consideration when predicting wear rates in field and laboratory conditions, such as the geometry of the cutter, drilling parameters, and mechanical properties of the materials that form the cutter, (Ersoy et al 1997). There have been numerous descriptions of cutter wear quantification technologies. To estimate the disc cutter wear condition, each method relies on available measured data and prudent interpretation. Furthermore, each approach is premised on assumptions that limit its applicability.

Figure 4-1. Diagram of a Scaled Set of Multi-Edge Disc Cutters.

This paper evaluates the wear and damage of large-diameter disc cutters. The method proposed is a qualitative approach to estimating wear using a damage-weighted score system and it has proven to be a consistent and easy-to-use methodology that has been adopted in an ongoing full-field trial, (Zijian L. et al Q3-2021).

4.2.1 Application of Large-Diameter Disc Cutters

The disc-type cutter in hard rock works on the principle that by applying great thrust to the cutter, and thus pressure on the rock to be cut, a zone of rock directly beneath (i.e., in the cutting direction) and adjacent to the disc cutter is crushed, typically forming very fine particles.

Figure 4-2. A diagrammatic representation of a large-diameter disc cutter. (Novamera Inc., 2022).

The crushed zone creates a pressure bulb of fine rock powder that exerts hydraulic pressure downward (again, in the cutting direction) and outward against the adjacent rock. The adjacent rock then cracks and chips spall from the excavated rock face, (Friant et. al. 1996).

In large-diameter drilling, the use of disc cutter penetrations and excavation production rates allows for lower thrust requirements for cutter head penetrations and lowering the weight of the structure required to support the cutters, Disc cutter, and excavation equipment (Excavation Engineering Associates, Inc., 2022). Figure 4-2 below shows a diagrammatic representation of a large-diameter disc cutter.

4.2.2 Wear and Damage in Large-Diameter Disc Cutters

Cutter wear is defined as a reduction in radial length. The fragmentation of rocks by disc cutters per revolution can result in the intermittently recurrent wear of a specific point on the cutter tip. Thus, the wear capacity of disc cutters can be determined by measuring the wear of a point on the cutter tip when they crush rocks, i.e., radial wear coefficient; whereas, macroscopically, disc cutter wear is the result of interaction between the disc cutter and its working objects and emerges during the TBM excavation process in the field, (Zhang et. al. 2011). Wear results from friction and it is mostly seen in steel disc cutters where the hardness value of steel is 140 for mild steel and 900 for hardened steel, using the Vickers hardness scale. But for large diameter drilling disc cutters with tungsten carbide inserts, much wear is not expected as the hardness of tungsten carbide is 2500 using the Vickers hardness scale.

An empirical model was created for estimating steel disc cutter wear in sedimentary and low to medium-grade metamorphic rocks, (Hassanpour, 2018). Based on the data from the field excavation parameters, (Li, and Su, 2010) predicted overall steel cutter wear using the Elman neural network model. (Chen et al. 2011) investigated the cause and form of the wear and described a series of disc cutter wear-reduction measures.

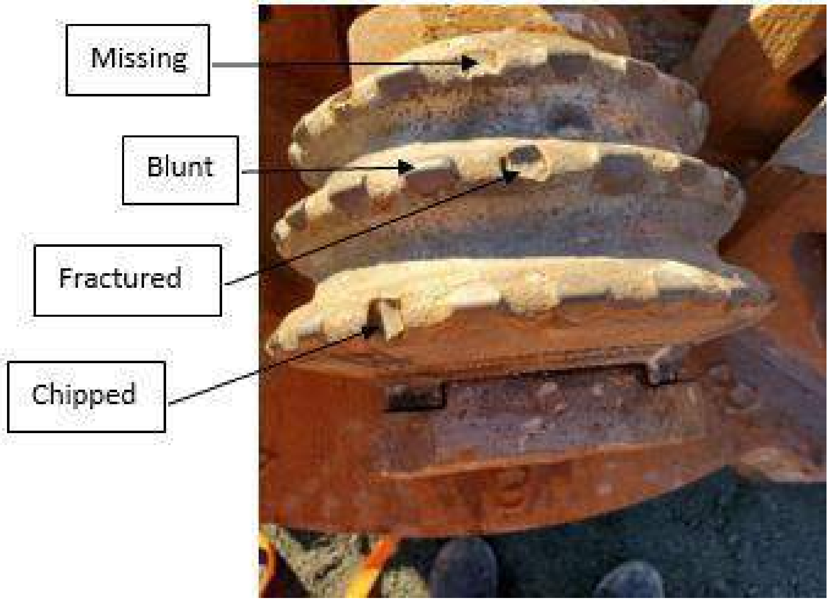


Figure 4-3. Diagram of Worn-Out Disc Cutter

Previously, work was done on the rock-cutting mechanism of the disc cutter, including laboratory testing. Models developed at the Colorado School of Mines by (Rostami et. al. 1993); (Rostami 1997) and the Norwegian University of Science and Technology (Bruland, 1998) were proposed to predict the force on the cutter based on a large amount of statistical data. Using laboratory testing, (Parviz, 1975) demonstrated that wear would impair the cutting performance of steel disc cutters. Figure 4-3 shows a worn-out disc cutter after the drilling operation.

4.2.2.1 Description of Damage to Disc Cutter Inserts

Tungsten carbide (TC) inserts are a category of button inserts and are known to have very high hardness values in the range of 1950-2150HV when compared to steel body disc cutters which have hardness values in the 430-530HV range. In a similar manner, TC inserts have low fracture toughness (6.7-7. 4MPa.m$^{0.5}$) in comparison to steel body disc cutters (34-62MPa.m$^{0.5}$). This gives an indication of how the damage to disc cutters is viewed, due to their high hardness value, they are very tough and can drill through very hard formations such as quartz, granite, etc., but because of their relatively low fracture toughness when compared to steel, they tend to experience cracking or fracture at a faster rate during a drilling operation. This observation was recorded for most of the inserts during this research. The TC inserts progressed from being fractured to being chipped and sometimes they go missing from the steel body matrix.

4.2.3 Major Factors Contributing to the Wear of Large-Diameter Disc Cutters.

There are several factors and drilling parameters that can influence and contribute to the rate of wear of large-diameter disc cutters. Drilling parameters such as the torque and drag in the drilling operation, the WOB, hydraulics, and the cutting size distribution. Formation properties also play an important role in determining how the wear comes by.

- Torque and Drag:

Drilling tool wear increases as torque and thrust forces increase. The increase in torque may cause the disc cutter to break or chip. Side forces and friction are the two main causes of torque and drag. Side forces include forces that exist between the wellbore wall and any element of the drill string, as well as normal forces created by the drill string with the wellbore walls. The movement/rotation of the drill string causes friction. Other factors that contribute to torque and drag include hole cleaning and wellbore stability.

Torque and drag are dependent on trajectory inclination, which is depicted by the friction coefficient, μ in equation 1 below.

$$TOB = \frac{D_B}{3}\,\mu WOB \qquad (4-1)$$

μ = friction coefficient

TOB =Torque on Bit, KN-m

WOB = Effective Weight on Bit, KN

D_B = bit Diameter, m

From equation 4-1, an increase in friction coefficient across the drilled depth will result in an increase in torque which can increase the wear and damage of the disc cutters. The friction coefficient, μ may change for different formations which relate to the rock strength and hardness and thus influences the rate of wear experienced by the cutters. The bit diameter is 1m as this is the diameter of the cutter head being considered.

- Hydraulics:

A higher (optimal) flow rate will aid in the efficient circulation of drill fluid and the lifting of cuttings to the surface. A good circulation system will result in efficient hole cleaning, little to no re-grinding, and less damage and wear on the disc cutters. There are three optimal hydraulics methods, which define the three zones for a well:

- ✓ Zone 1 – Shallow (short drill string and annulus), maximum flow rate, Qmax. This is because there are more cuttings at shallow depths, necessitating a higher flow rate for efficient hole cleaning.

$$1714\,HHP \times \frac{E}{Pmax} = Qmax \qquad (4-2)$$

HHP = hydraulic horsepower, hp

E = efficiency,

Pmax = maximum pressure, Psia

Qmax = maximum flowrate, usgpm

- ✓ Zone 3 - the deepest interval, with the lowest flow rate.

$$30D \text{ usgpm} \approx \text{Qmin} \qquad (4-3)$$

Qmin = minimum flowrate, usgpm

- ✓ Zone 2 – Intermediate depth

$$\text{Qmin} \leq \text{Qpump} \leq \text{Qmax} \qquad (4-4)$$

Qmin = minimum flowrate, usgpm,

Qpump = pump flowrate, usgpm,

Qmax = maximum flowrate, usgpm

- Weight on Bit:

This is the amount of downward force exerted on the drill bit by drill collars, which are thick-walled tubular pieces in the drilling assembly. Gravity's downward force on these steel tubes provides force for the drill bit to effectively break the rock. While the drill bit is just off the bottom of the wellbore, the weight of the drilling assembly is controlled and measured. The drill string is then gradually and carefully lowered until it reaches the bottom. As the driller lowers the top of the drill string, more of the assembly's weight is applied to the disc cutters, resulting in less weight hanging at the surface. Increase in WOB will result in increased rotation until it reaches founder point where an increase in WOB will begin to decrease rotation.

- Cutting sizes:

From ongoing field trials, it was observed that larger and sharper cuttings sizes were lifted to the surface when reverse circulation was employed as the mode of circulation, it can be deduced that the larger the cuttings sizes, the less for a potential to regrind downhole. Continuous regrinding can increase the wear rate of the disc cutters and thus the overall drilling performance of the drilling operation. Meanwhile, smaller, and finer cuttings were observed at the surface when direct flush was employed as the mode of circulation indicating that there was a potential for regrinding to occur.

4.2.4 Formation Properties in Relation to Wear.

- Abrasivity:

Rock abrasivity can be measured using several methods but for this paper, the Che char Abrasivity Index (CAI) test was used, which involves scratching the sawn ends of intact cores using a hardened and pointed stylus following ASTM standard D7625. The CAI is then estimated by microscopic evaluation of the wear of the pointed tip of the stylus. The more abrasive the formation, the more wear and, damage to the disc cutters.

- Hardness:

The rebound hammer test following ASTM standard D5873 was used in this paper to establish the hardness property of the formation which can in turn be used to determine how much wear the disc cutter will likely undergo. The test provides a Rebound Number which is proportional to the hardness of the formation. The harder the formation, the more likely it is for the disc cutters to undergo more wear.

- Strength:

Several strength tests were conducted such as the unconfined compressive strength test (UCS), the indirect tensile strength test (IT), also known as the Brazilian strength test, and the point load strength index (PLSI).

✓ Unconfined Compressive Strength:

Using ASTM standard D7012, which involves compressing the test specimens axially in a compressive loading frame until compressive failure is observed. Note that since UCS is based on intact core specimens, it is more influenced by existing fractures and similar planes of weakness present in the rock than the PLSI tests. Thus, UCS is more representative of fractured rock mass strength while PLSI equivalent UCS is more representative of the intact rock strength.

✓ Indirect Tensile Strength (ITS):

ITS tests provided an estimate of the tensile strength of the rock formation and were conducted on disks of a core that has been seen to an approximate 1 to 2 cm thickness. The ITS tests involve loading the disk specimens diametrically until tensile failure following ASTM standard D3967.

✓ Point Load Strength Index (PLSI):

These tests and analyses were conducted following ASTM standard D5731 to determine the strength of the formation.

4.3 Materials and Methods

This paper discusses how wear and damage of large-diameter disc cutters with tungsten carbide inserts of a full field trial in a mining field drilling operation were evaluated. The cutter head comprises 9-disc cutters as shown in Figure 4-4, of which 6 of the 9-disc cutters have 3 discs while the remaining 3-disc cutters have 4 discs. The aim of the tungsten carbide inserts is to enable the disc cutters to withstand more wear during the drilling operation and this differentiates this large-diameter disc cutter from the likes of the TBM which is solely a steel matrix and steel teeth disc cutter. A qualitative approach to quantify wear and damage was developed and this approach has thus far helped in estimating wear observed on the field.

The theory of the disc cutter's wear and damage mechanism serves as a foundation not only for assessing overall wear and damage but also predicting the impact of wear and damage on drilling efficiency and performance. As a result, scholars both at home and abroad have put a lot of effort into characterizing disc cutter wear. Several analytical or judgmental methods have been used by numerous competent researchers, these methods can be summarized as analyzing cutter load empirical formulae, engineering data fitting analyses, experimental parameters derived from rock grinding, and qualitative cutter wear analysis. Wear is a significant cause of disc cutter failure. There is no current theory that provides a standard for predicting disc cutter wear.

Also, an investigation into the mode of circulation (direct flush or reverse circulation) was carried out and the influence of the cutting’s transportation was evaluated. Cutting size distribution, also known as grain size analysis, was carried out to confirm this theory.

4.3.1 Approach Developed to Estimate Wear and Damage

The purpose of the disc cutter wear and damage estimation is to count the damaged inserts on the disc cutter and compare the disc cutter's condition before and after a specific time of drilling. The damaged inserts are classified as blunt, fractured, chipped, or missing in this measurement. The number of damaged inserts for each disc of each cutter is then counted.

4.3.1.1 Measurement Standard of Procedure

- Take numerous shots of the entire drill bit, merely to keep track of the general state of the bit.

Figure 4-4. Diagram of a fully labeled cutter head.

Figure 4-4 shows a fully labeled cutter head showing the location and position of each disc cutter. There are 9-disc cutters in total. The number of each cutter head can be found on the body of the large-diameter disc cutters. There are two kinds of disc cutters. One with 3 discs and one with 4 discs.

- Start with number one, then number two, number three, and so on until you reach number nine. Draw lines 1, 2, 3, and 4 on the side of the outermost disc for each disc cutter, with one line on the cutter's base. The angles between the first, second, third, and fourth marks should be around 90 degrees. As indicated in Figure 4-5, the lines should then be extended so that they cross the top of the cutter. The function of the pen marker is to split the cutter into four zones, making it easier to tally the number of damaged inserts. The marks serve as a guide for estimating wear. Figure 4-6 shows how the disc cutter is divided into four zones to serve as a reference for the wear estimation.

Figure 4-5. Diagram showing disc cutter divided into zones.

- Extend the lines from each zone, from the side of the disc and across the top of the cutter as shown in Figure 4-5.
- For each zone, count the number of damaged inserts on each disc, such as (1-2) and (2-3). Photograph the current zone's cutter in addition to counting and documenting the number. The following is a recommended SOP: Figure 4-6 shows how to photograph the cutter number and the number (1-4) on the side of the cutter. Take a photo of each disc on the cutter after that (3 or 4, depending on the number of discs for the certain cutter). By ranking the photographs in order of file name or time, it is straightforward to sort them and discover the damaged insert of the source cutter and disc in this pattern.

Figure 4-6. Diagram showing extended lines across the top of the cutter.

- Measure the bit wear on disc cutter No. 1 first, and then move on to disc cutter No. 2. After counting all the inserts in one zone, turn the cutter and move to the next zone, until all four zones are completed.

Figure 4-7. Diagram of multi-edge disc cutter.

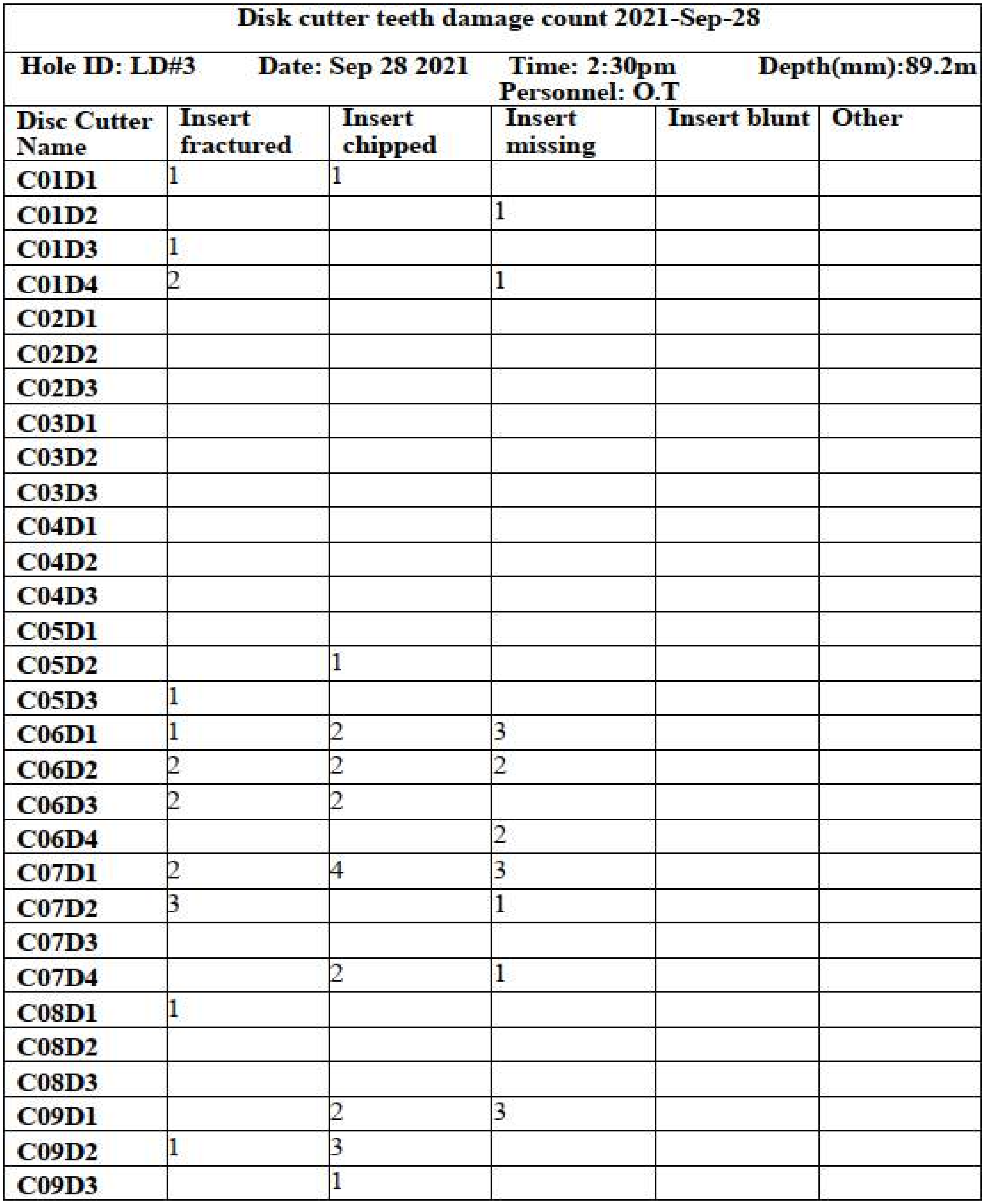
• Repeat these measurement steps for all the 9-disc cutters.

• Record and document data in the disc cutter teeth damage counting template as shown below in Table 4-1.

• Count the number of damaged inserts on each dis8c. It's either blunt, chipped, missing, or fractured, depending on the condition. The amount of damage done to each disc is calculated. The 'other' section lists significant incidents or major bodily damage.

• The severity of the disc cutter insert damage is then quantified using a scoring system. A score of 1, 2, 3, or 4 is assigned to each blunt, fractured, chipped, or missing insert.

Table 4-1. Table of Disc Cutter Damage Count.



Disk cutter teeth damage count 2021-Sep-28

Hole ID: LD#3 Date: Sep 28 2021 Time: 2:30pm Depth(mm):89.2m
Personnel: O.T

Disc Cutter Name	Insert fractured	Insert chipped	Insert missing	Insert blunt	Other
C01D1	1	1			
C01D2			1		
C01D3	1				
C01D4	2		1		
C02D1					
C02D2					
C02D3					
C03D1					
C03D2					
C03D3					
C04D1					
C04D2					
C04D3					
C05D1					
C05D2		1			
C05D3	1				
C06D1	1	2	3		
C06D2	2	2	2		
C06D3	2	2			
C06D4			2		
C07D1	2	4	3		
C07D2	3		1		
C07D3					
C07D4		2	1		
C08D1	1				
C08D2					
C08D3					
C09D1		2	3		
C09D2	1	3			
C09D3		1			

Below is Table 4-2 showing the weighted score system:

Table 4-2. Damage Weight score system.

Damage type	**Blunt**	**Fractured**	**Chipped**	**Missing**
Weighted score	0	1	2	3

Figure 4-8. Diagram of a fractured insert.

• The damage score for each cutter is then calculated by adding the damage scores of the discs. The score of the cutters with four discs (cutter nos. 1, 6, and 7) is calibrated against the score of the cutters with three discs by multiplying their score by 3/4. The total number of damaged inserts and the damage score are then summarized and compared in another sheet. Figure 4-8, and, Figure 4-9, depicts diagrams of fractured and chipped inserts respectively.

Figure 4-9. Diagram of a chipped insert.

4.4 Results and Discussion

This damage weight score system enables us to quantitatively describe the disc cutter's damage condition. The four stages of the tungsten carbide (TC) insert damage are blunt, fractured, chipped, and missing, with each stage increasing in severity. A blunt insert is given a zero score because blunt inserts have no fractures and can be used to continue the drilling operation. Higher severity damages are derived from lower severity damages. Thus, by comparing each cutter's damage score, we can determine which cutter has the most damage.

Furthermore, the scoring system aids in the tracking of damage progression over time. By comparing the damage scores obtained at different times, we can determine the speed of the damage and the time interval with the most damage occurrence.

To compute the damage evaluation score, the damage weight score system in Table 1 is utilized thus:

If two (2) TC inserts are fractured;

Where a fractured insert is given a damage score of 1

$$2 inserts \times 1 = 2\ damage\ score \tag{4-5}$$

If two (2) TC inserts are chipped;

Where a chipped insert is given a damage score of 2

$$2 inserts \times 2 = 4\ damage\ score \tag{4-6}$$

If two (2) TC inserts are missing;

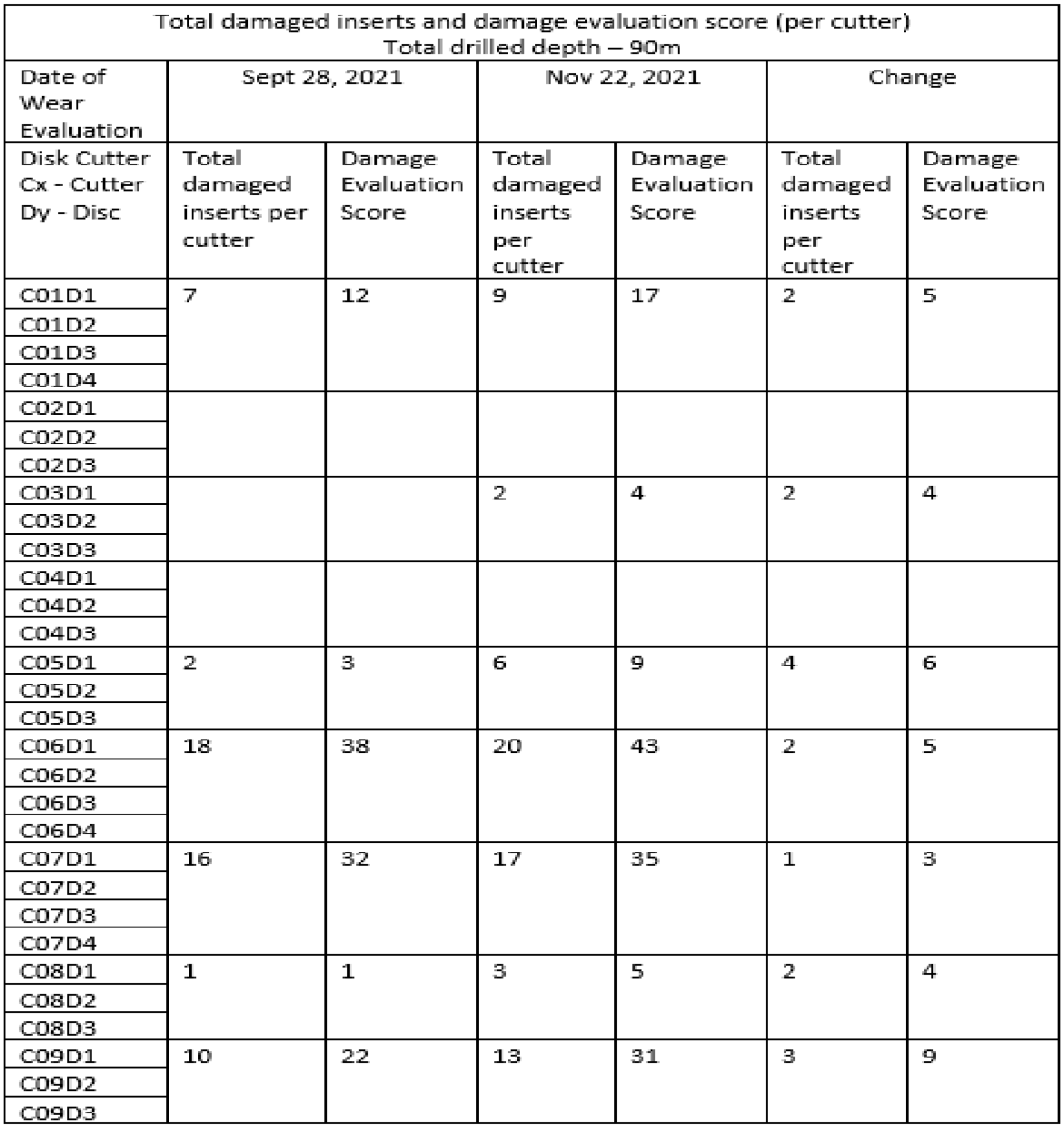
Where a missing insert is given a damage score of 3

$$2 inserts \times 3 = 6\ damage\ score \tag{4-7}$$

The total damage score across the cutter head is then calculated and computed across the cutter head for every disc and cutter.

Below is Table 4-3, showing a result of the damage evaluation score per cutter upon knowing the total number of damaged inserts from the field on Sept 28, 2021, and using the weighted score system to calculate the change in the evaluation of the wear observed after the cutter head was tripped out on Nov 22, 2021.

Table 4-3. Template of damage evaluation score using a weight score system.



Total damaged inserts and damage evaluation score (per cutter) Total drilled depth – 90m						
Date of Wear Evaluation	Sept 28, 2021		Nov 22, 2021		Change	
Disk Cutter Cx - Cutter Dy - Disc	Total damaged inserts per cutter	Damage Evaluation Score	Total damaged inserts per cutter	Damage Evaluation Score	Total damaged inserts per cutter	Damage Evaluation Score
C01D1	7	12	9	17	2	5
C01D2						
C01D3						
C01D4						
C02D1						
C02D2						
C02D3						
C03D1			2	4	2	4
C03D2						
C03D3						
C04D1						
C04D2						
C04D3						
C05D1	2	3	6	9	4	6
C05D2						
C05D3						
C06D1	18	38	20	43	2	5
C06D2						
C06D3						
C06D4						
C07D1	16	32	17	35	1	3
C07D2						
C07D3						
C07D4						
C08D1	1	1	3	5	2	4
C08D2						
C08D3						
C09D1	10	22	13	31	3	9
C09D2						
C09D3						

4.5 Conclusion

The scope of work for this paper is focused on wear and damage measurements of large- diameter drilling disc cutters. The qualitative method for estimating wear and damage was developed for an ongoing field trial in a mining drilling operation and the measurements can be taken without much difficulty and in a timely approach. The field data compiled for wear and damage of large-diameter drilling disc cutters showed that the method is consistent and can be adequate to estimate disc cutter wear as researchers race to develop more novel methods to quantify the wear of disc cutters.

Unlike in the oil and gas industry where there is a standard naming such as the IADC to quantify wear and damage such is not the case for the mining industry, where different disc cutter/bit manufacturers and designers propose numerous wear estimation techniques.

Future work and research are in the works to develop a quantitative approach using prediction models to determine the wear rate of disc cutters.

4.6 Acknowledgements

The authors would like to acknowledge several funding provided by Novamera Inc., the Natural Sciences and Engineering Research Council (NSERC) of Canada, MITACS Canada, and the School of Graduate Studies at the Memorial University of Newfoundland, Canada.

Chapter 5: Forensic Analysis of Damaged Disc Cutters

This chapter discusses a combination of several research studies that were documented to review a forensic analysis that was conducted on damaged disc cutters used in the mining field of the ongoing Sustainable Mining by Drilling project that is being carried out by the Drilling Technology Laboratory group in collaboration with a partner research company.

The authors are:

- Oluwafemi Tytler: primary investigator, field data analysis and measurements, and manuscript preparation.
- Abdelselam Abugharara: manuscript contributor, lab testing and data analysis.
- Prof. Stephen Butt: supervised and provided final review of technical report.

5.1 Abstract

In order to improve drilling performance prediction and cutter life assessments in ongoing SMD (Sustainable Mining by Drilling) project, this paper aims to build on existing knowledge of disc cutter wear estimation and evaluation (Palmieri and LDD cutter heads from full field trial 1, FFT#1).

Forensic analysis was carried out on the multi-edge disc cutters used during the mining operation from full field trial so as to establish what likely influenced the wear of these disc cutters over the course of the mining operation. Particularly in hard rock settings, cutter consumption and characteristics like cutter ring wear play a considerable influence in drilling performance and cost forecasts. Rock characteristics like strength, hardness, and abrasion resistance have a significant impact on the effectiveness and performance of any disc cutter. The main tool for breaking rock on a full-face hard rock boring machine is a disc cutter. It is directly in contact with the rock and

sustains significant damage. Predicting how much wear a disc cutter will experience is necessary because once it reaches its wear limit, it loses its capacity to shatter rock.

This work is limited to the forensic analysis of SMD large-diameter drilling multi-edge cutters and drilling tools. The experimental analysis was done in collaboration with the Memorial University technical services.

5.2 Introduction

To investigate the cause of the failure of some of the multi-edge disc cutters during the full field trial, a consensus was reached with the parent research firm to carry out a forensic analysis of the damaged disc cutters that were utilized in the field, which include, the disassembly of the disc cutters to determine the condition of the internal components (shaft, bearing, and seal) of the disc cutters.

X-ray Fluorescence, XRF scanning of a foreign metal stuck in the cutter head and the stabilizer wear plate, using fault tree analysis, FTA which is a top-down approach that reverse-engineers the root cause of a potential failure through the root cause analysis process to evaluate the failure of the disc cutter bearing.

5.3 Materials and Methods

To conduct a thorough forensic analysis, several materials and methods were employed in this paper. Two adjustable pin spanner wrenches had to be fabricated by the technical services of Memorial University of Newfoundland to disassemble the disc cutters.

5.3.1 Pin Spanner Wrenches:

The pin spanner wrenches were the main tool used to disassemble the multi-edge disc cutters to gain access to their internal components. They had specific dimensions; these dimensions are attached in the appendix.

- Palmieri DC wrench / Circle Diameter - 91mm / Pin Length - 4mm / Pin diameter - 6mm.
- LDD DC wrench / Circle Diameter - 68mm / Pin Length - 7mm / Pin diameter - 8mm.

5.3.2 Mechanical Press:

A mechanical press shears, punches, forms, or assembles metal or other materials using tools or dies attached to slides or rams.

5.3.3 XRF Spectrometer

The abbreviation XRF stands for X-ray fluorescence spectroscopy. The elemental composition of materials can be ascertained using the non-destructive analytical technique known as XRF. To avoid tautology, the research materials utilized in this research can be found in Chapter 3 of this research work.

5.4 Experimental Methodology and Results

5.4.1 Disc Cutter Disassembly Forensic Analysis

The disc cutters were placed on a clamp to ensure it is steady when using the adjustable pin spanner wrenches to open the disc cutter. The disc cutter has a small bearing side and a big bearing side and both sides have seals. The primary sealing is at the small bearing side, and this is where the adjustable pin spanner is used.

After the disc cutter is opened, the seal of the small bearing side is taken out. The disc cutter is then taken to a press machine where the other internal components are pressed out of the disc cutter matrix into a cylindrical cup that receives the internal components when they are pushed out.

The press machine is set at a pressure of about 30 bars to press the components out. It is important to note that any pressure higher than 30 bars could lead to potential damage to the disc cutter.

5.4.2 Forensic Results from Disc Cutter Disassembly

- ✓ 9 Palmieri cutters and LDD were disassembled: There are two bearing cups inside the disc cutter, the small bearing cup, and the big bearing cup. The bearings are tapered roller bearings, and each bearing side has a seal with an O-ring. Figure 5-1 shows the image of a disassembled disc cutter.

Disc Cutter 1 (focal):

- ✓ The small bearing side:
  - ✓ Seal – free of nicks, burrs, scratches, and lapped surfaces isn't damaged, and the O-ring is in good condition.
  - ✓ Small bearing cup - observed scratches and heat marks. The damaged area where foreign material wore through.
  - ✓ The tapered roller bearing is damaged, the O-ring is in okay condition.
  - ✓ Bearing retainer – damaged.

Figure 5-1. Disassembled disc cutter parts.

- ✓ The big bearing side:
  - ✓ Seal – free of nicks, burrs, scratches, and lapped surfaces isn’t damaged, and the O-ring is in good condition.
  - ✓ Big bearing cup - observed scratches and heat marks. Pitting observed upon feeling/touching.
  - ✓ Tapered roller bearing is okay, O-ring is in okay condition.
  - ✓ Bearing retainer – in good condition.
  - ✓ Shaft: was observed to be in good condition.
- ✓ Palmieri cutters 2 to 9 & 9 LDD cutters (All appeared to be in good condition).

- ✓ The small bearing side:
    - ✓ Seal – free of nicks, burrs, scratches, lapped surfaces aren't damaged, and the O-rings are in good condition except in cutters 2 and 4 where O-rings are damaged.
    - ✓ Small bearing cup – in good condition.
    - ✓ Tapered roller bearings are in good condition, O-ring is in okay condition.
    - ✓ Bearing retainer – good condition.
- ✓ The big bearing side:
    - ✓ Seal – free of nicks, burrs, scratches, lapped surfaces aren't damaged, and the O-ring is in good condition. Figure 5-2 depicts the image of the disc cutter roller bearing.

Figure 5-2. Image showing roller bearing.

- ✓ Big bearing cup – all in good condition.
- ✓ Tapered roller bearings are okay, O-ring is in okay condition.
- ✓ Bearing retainer – in good condition.
- ✓ Shaft: was observed to be in good condition for most cutters except for cutter 4 with a fractured shaft pin and cutter 5 with a broken shaft pin, half stuck in bearing retainer.
- ✓ Dirty grease was found in cutter 7 and a broken shaft pin in cutter 5. Figure 5-3 shows the comparison between dirty grease and clean grease.

Figure 5-3. Image showing dirty grease vs clean grease.

5.4.3 Stabilizer Wear Plate Spectrometry

During the mining operation from full filed trial one and drilling was brought to an abrupt end due to a foreign metal getting stuck in the cutter head, a forensic analysis was done to determine the source of this metal and the likely cause of drilling non-penetrating time, NPT. Figure 5-4 depicts a diagram of a damaged cutter head.

Figure 5-4. Diagram of the damaged cutter head.

Several analyses were conducted using the XRF spectrometer to determine the material composition of the foreign metal and compared with the material composition of several likely drilling tools (disc cutter matrix, stabilizer wear plate, etc.) found downhole upon tripping out. A scan was carried out on the stabilizer wear plate using an XRF spectrometer and the material property of the metal was determined. The red arrows in Figure 5-4 point to the wear and damage experienced by the cutter head from the obstruction of the foreign metal.

The scan result shows a similarity in material properties between the foreign metal that jammed into the cutter head from full field trial #1 and the recently scanned stabilizer wear plate.

5.4.4 Results from XRF Spectrometry

The results from the scan show that the foreign metal that got stuck in the cutter head, thereby leading to a non-penetrating time during the mining operation has an identical material composition to the stabilizer wear plate. From further investigation, a working theory was deducted, and it was determined that there was a likely spike in torque during drilling which led to the failure of one of the stabilizers downhole. The stabilizer wear plate gave way and got stuck between disc cutters thereby preventing them from rotating and in the long run brought to a halt the drilling operation. Figure 5-5 shows a plot of the foreign metal matching the stabilizer wear plate.

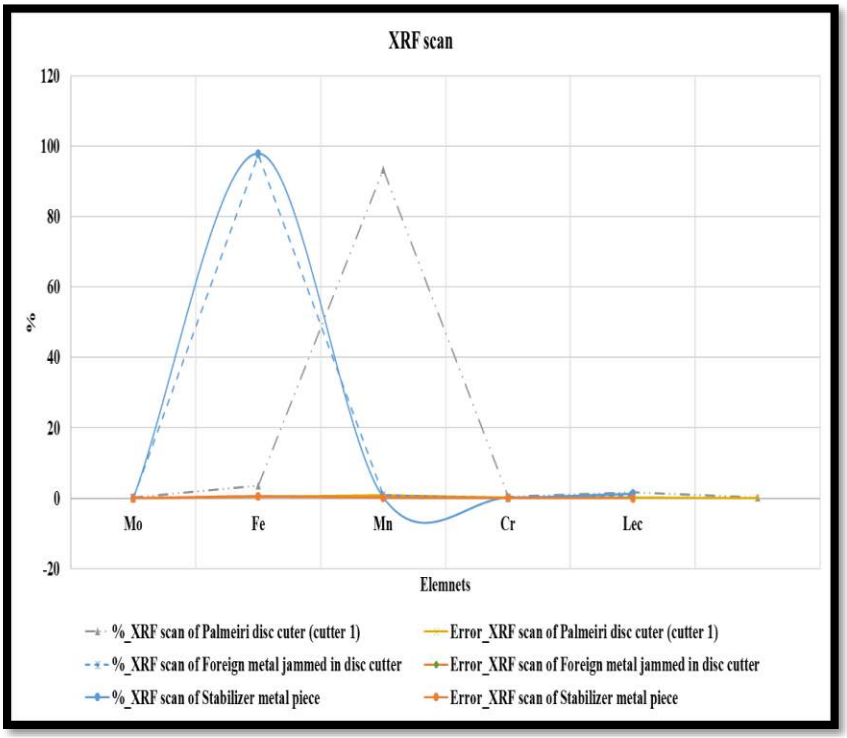


Figure 5-5. Plots of XRF scans of Palmieri disc cutter, foreign metal, and stabilizer wear plate.

Table 5-1 shows a comparison of detailed material compositions between the stabilizer wear plate, the Palmieri disc cutter, and the foreign metal that caused the damage. The material composition of the stabilizer wear plate matches that of the foreign metal that was trapped in the cutter head during drilling.

Table 5-1. Material composition comparing stabilizer wear plate, foreign metal, and Palmieri disc cutter.

Elements _ XRF scan of foreign metal jammed in disc cutter	%_XRF scan of Stabilizer metal piece	%_XRF scan of foreign metal jammed in disc cutter	%_XRF scan of Palmieri disc cuter (cutter 1)
Sb	<LOD	<LOD	<LOD
Sn	<LOD	<LOD	<LOD
Cd	<LOD	<LOD	<LOD
Pd	<LOD	<LOD	<LOD
Ag	<LOD	<LOD	<LOD
Ru	<LOD	<LOD	<LOD
Mo	0.042	0.036	0.319
Nb	<LOD	<LOD	<LOD
Zr	<LOD	<LOD	<LOD
Bi	<LOD	<LOD	<LOD
Pb	<LOD	<LOD	<LOD
Se	<LOD	<LOD	<LOD
Au	<LOD	<LOD	<LOD
W	<LOD	<LOD	<LOD
Zn	<LOD	<LOD	<LOD
Cu	<LOD	<LOD	<LOD
Ni	<LOD	<LOD	3.612
Co	<LOD	<LOD	<LOD
Fe	97.934	97.679	93.402
Mn	0.339	0.781	0.438
Cr	0.176	0.124	1.745
V	<LOD	<LOD	<LOD
Ti	<LOD	<LOD	<LOD
Al	<LOD	<LOD	<LOD
Lec	1.297	0.91	0.295

5.4.5 Fault Tree Analysis (Bearing)

The wear of the disc cutter was evaluated using fault tree analysis of the internal components (seal, bearing, shaft). By investigating the failure of any of these components, in this case, the roller bearing, the resulting observations can translate to the overall cause of the failure of the disc cutter.

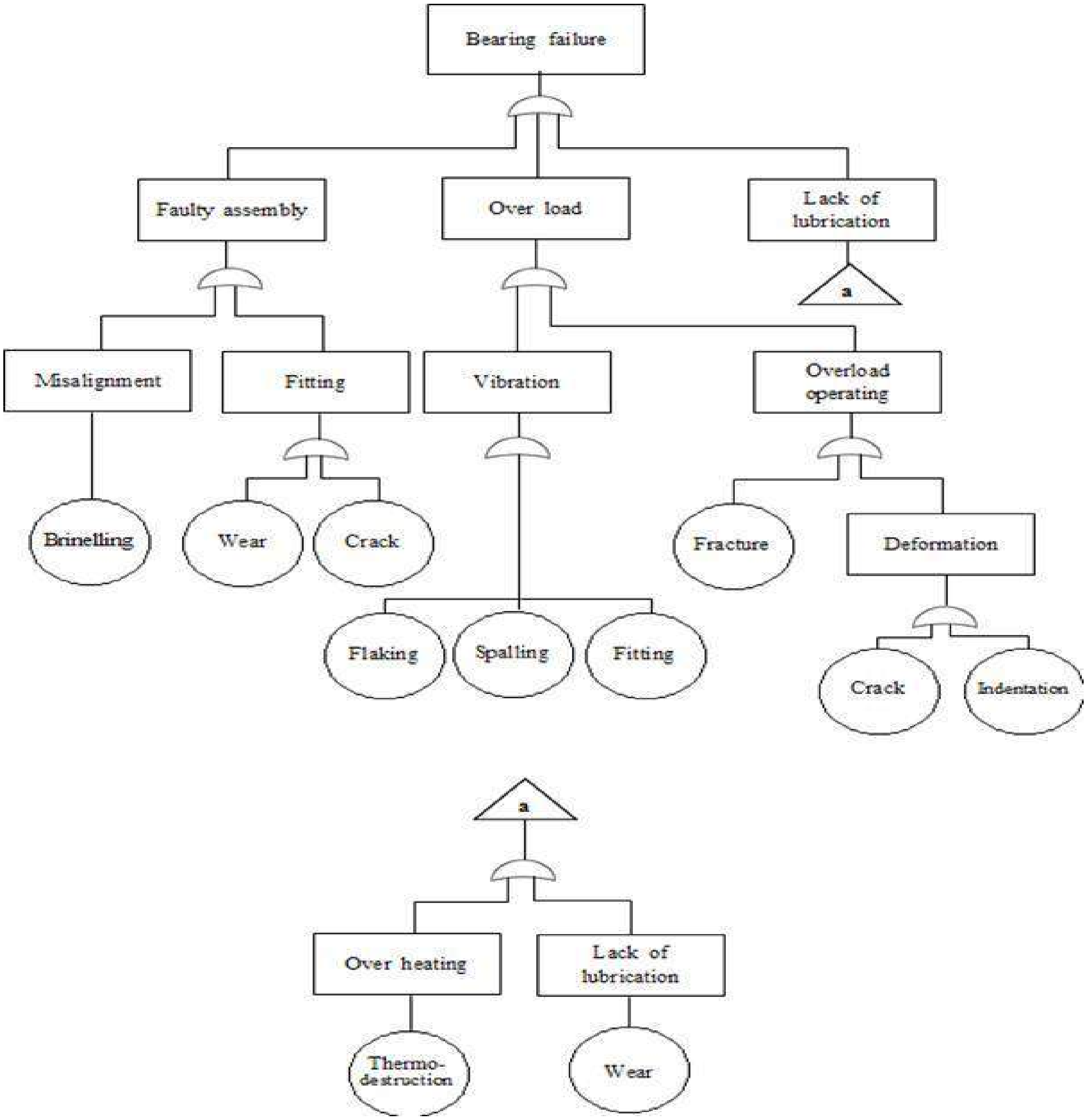


Figure 5-6. Fault tree diagram of bearing failure.

The fault tree analysis method was applied to quantitatively investigate the causes of the failure of the disc cutter bearing. It is a top-down approach that reverse-engineers the root cause of a potential failure through the root cause analysis process. Bearings must be properly installed, lubricated, and maintained to maximize longevity, assuming the application is correct to begin with. Poor operating conditions, especially in moist or contaminated areas, as well as improper handling practices, invite premature bearing failure. When a bearing fails, it is critical to determine the precise cause so that appropriate adjustments can be made. The failure mode frequently reveals the true cause of failure.

From the fault tree in Figure 5-6, bearing failure in disc cutters can be caused by three major causes. The First cause of bearing failure is faulty assembly of the disc cutters, when disc cutters fail to be properly assembled by the manufacturer there is a likelihood for bearing failure to occur. Faulty assemblies are in themselves caused by misalignment of the roller bearings or O-rings, or by fitting on any of the bearing components’ sides. The second cause of bearing failure can be attributed to overloading the bearing during drilling. Overloading is often experienced when there is vibration or an increase in torque during a drilling operation, overloading can also occur when the operation parameters such as the weight on the bit are excessive or overloaded. These in turn lead to fracture or deformation of drilling components such as disc cutters. The third major cause of bearing failure can be attributed to the lack of lubrication. Inadequate lubrication of the seal and roller bearings can lead to overheating which in turn leads to bearing failure and ultimately the wear and damage of disc cutters. It is important to properly lubricate the internal components of the disc cutter to avoid consequential damage during a drilling operation.

5.5 Conclusions

These analyses were a very critical part of this research, as they helped to understand how disc cutter wear and failure can be influenced by numerous parameters. It is always difficult to draw conclusions where disc cutter wear is concerned as a number of incidents might happen downhole during the drilling operation that can influence disc cutter failure. Therefore, conducting forensic analysis will help understand the disc cutter wear limit, and guide the drilling operator's decisions on when to trip out to avoid emergency shutdowns like the one experienced during the course of this mining operation thereby avoiding drilling NPT.

5.6 Acknowledgements

This research is funded by Novamera Inc., the Natural Sciences and Engineering Research Council (NSERC) of Canada, MITACS Canada, and the School of Graduate Studies at the Memorial University of Newfoundland, Canada.

I also acknowledge the tremendous help of the technical services of Memorial University of Newfoundland, Canada.

Chapter 6: Drilling Parameters Analysis to Evaluate Wear

This chapter discusses how several drilling parameters were analyzed in order to evaluate the wear and damage of the multi-edge disc used in the mining field of the ongoing Sustainable Mining by Drilling project that is being carried out by the Drilling Technology Laboratory group in collaboration with a partner research company.

The authors are:

- Oluwafemi Tytler: primary investigator, field data analysis and measurements, and manuscript preparation.
- Judith George: manuscript contributor, field data analysis.
- Prof. Stephen Butt: supervised and provided a final review of a technical report.

6.1 Abstract

There is a linear relationship between wear, torque, and thrust against depth, so either thrust or torque may be measured to give an indication of the wear of the drill.

Drilling parameters such as torque and thrust were analyzed from data generated during the mining operation's full field trial 1. The results determined were able to provide a view of how these parameters affect the wear and damage of disc cutters.

6.2 Introduction

Analyzing the drilling parameters (vibration, torque, and thrust) is a critical approach to evaluating the wear of the multi-edge disc cutters as there is a linear relationship between wear, torque, and thrust against depth, so that either thrust or torque may be measured to give an indication of wear of the drill.

The linear relation between torque and wear of the drill implies a linear variation of specific cutting energy with wear. (Liu Jianqin et al., 2015). This follows that a linear relation exists to the same depth of approximation between torque, thrust, or wear.

6.3 Experimental Methodology and Results

6.3.1 Input Drilling Parameter (Thrust/Effective WOB)

Ten-second intervals were used to log the drilling parameters. The obtained drilling data were examined after the FFT1 to account for the real times the cutter head was on the bottom making hole.

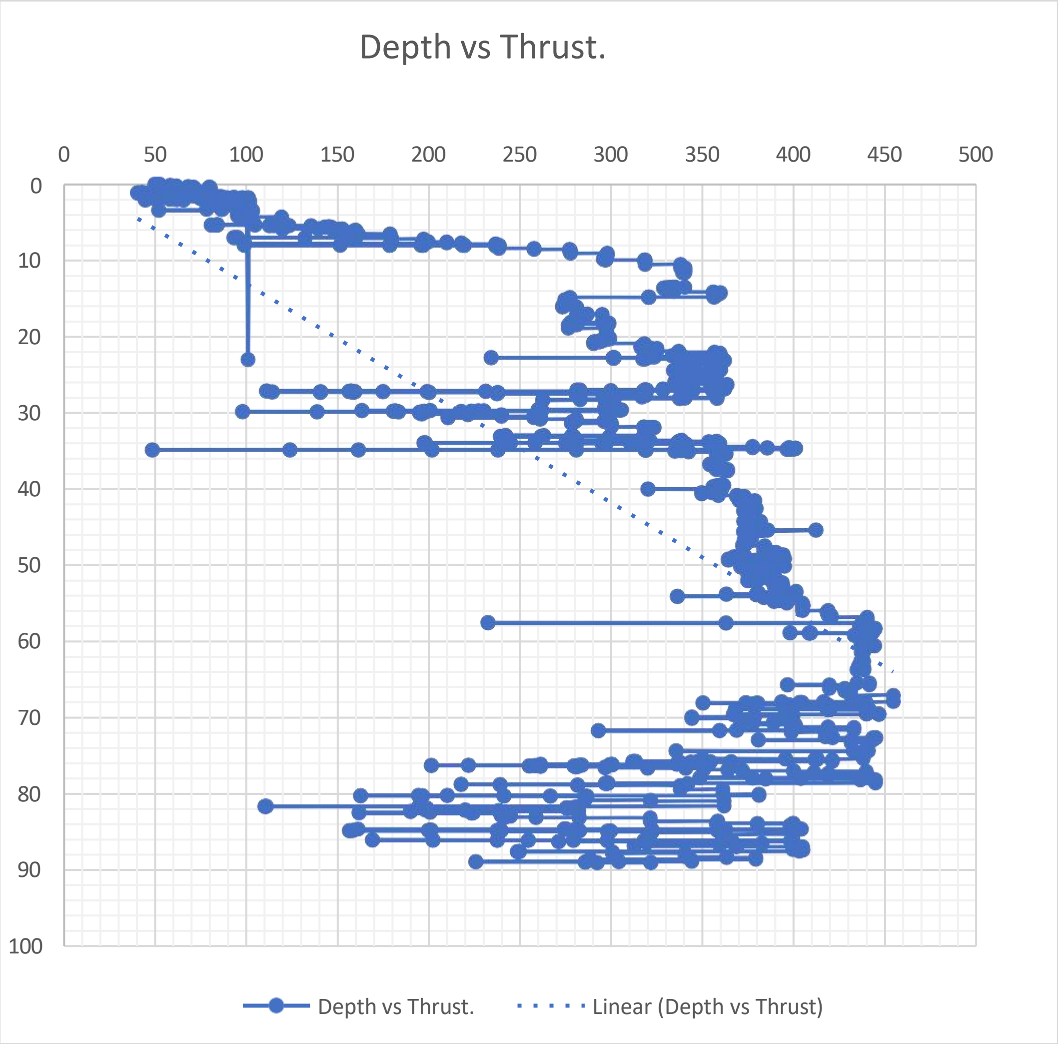


Figure 6-1. Plot of Depth against Thrust.

Up until a maximum of 22rpm, the rotational speed gradually rose. The initial applied thrust also increased gradually as drilling continued. Figure 6-1 shows a plot of depth against the applied thrust. The string weight and skin friction had an effect on the bit's effective weight on the bit when it was applied to the rock surface at the bottom of the hole. The hole tortuosity and roughness are caused by skin friction. The skin friction is calculated as a percentage of the normal forces perpendicular to the hole's axis. The calculated coefficient of static friction (μ) is 1.13 based on the results of the free stroke test performed during the FFT1.

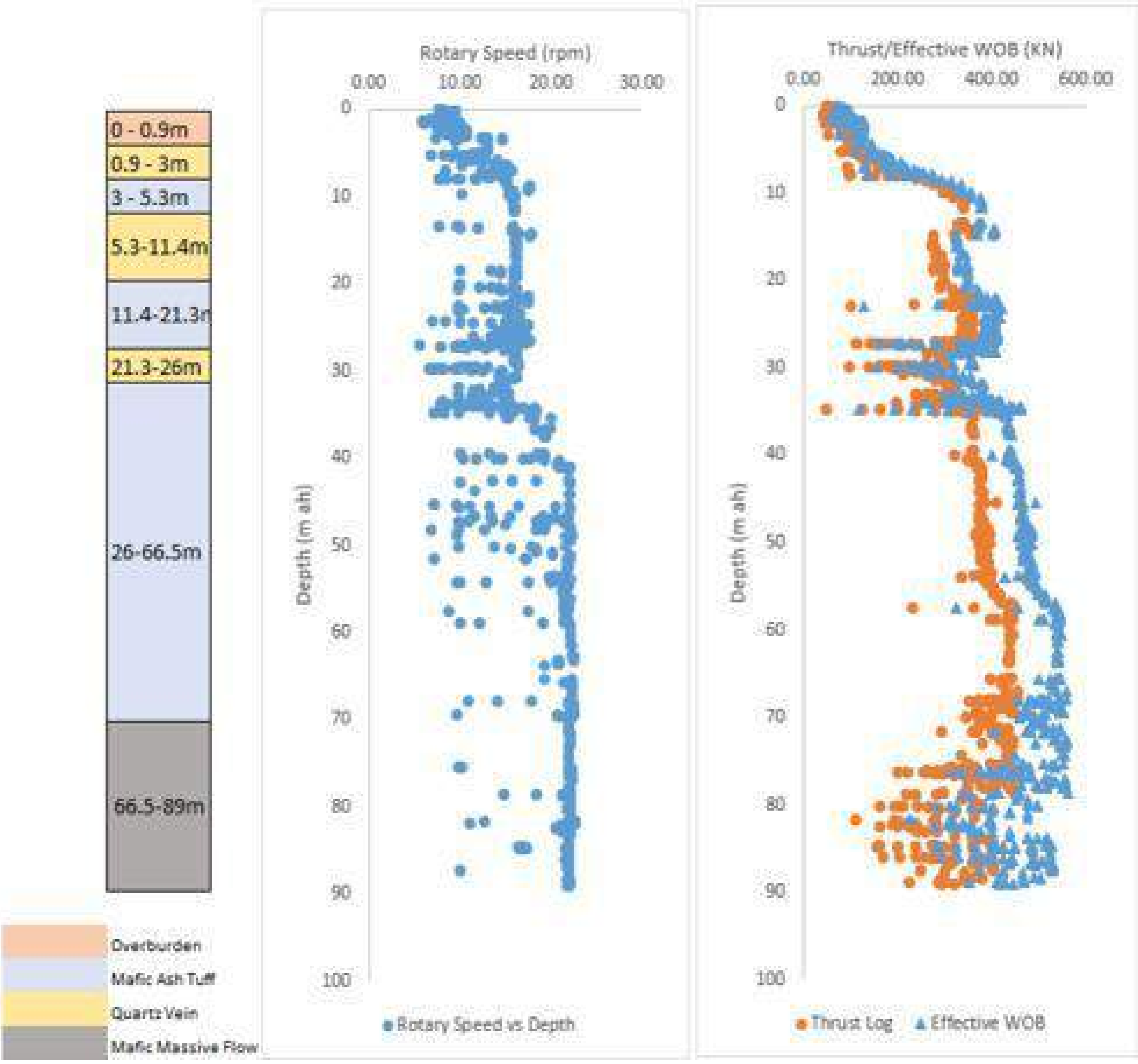


Figure 6-2. Plots of input drilling parameters (Q4 2022, DTL report).

The effective WOB was computed using equation 6-1 below;

$$W_e = T + W_b - F_s \qquad (6-1)$$

We = Effective WOB (KN)

T = Applied Thrust (KN)

Wb = buoyed string weight with inclination (KN)

Fs = Skin friction (KN)

Equation 6-1 was based on the idea that since drilling was done with surface thrust, all of the drill string’s buoyed weight acting down the hole's axis would have been completely transported to the rock surface before any further surface thrust was applied. The drilling was done in water, and the steel and water densities were used to calculate the buoyancy factor. Furthermore, LD#1 has an approximately 30 degrees inclination and a 60 degrees dip angle.

6.3.2 Output Drilling Parameter (Torque)

The cutter head’s location at various points in time and the recorded torque are the drilling parameters that are recorded. The rate of penetration (mm/min) was calculated from the shifting cutter head location with respect to time. Net advance rate (depth of cut in mm/rev) was obtained by dividing the rate of penetration (mm/min) by the rotary speed in order to normalize for variations in rotary speed.

Equation 6-2 depicts the relationship between recorded torque and depth with a coefficient of determination of 0.751.

$$T = 1.3935D - 44.42 \qquad (6-2)$$

T = recorded torque (KNm)

D = hole depth (m)

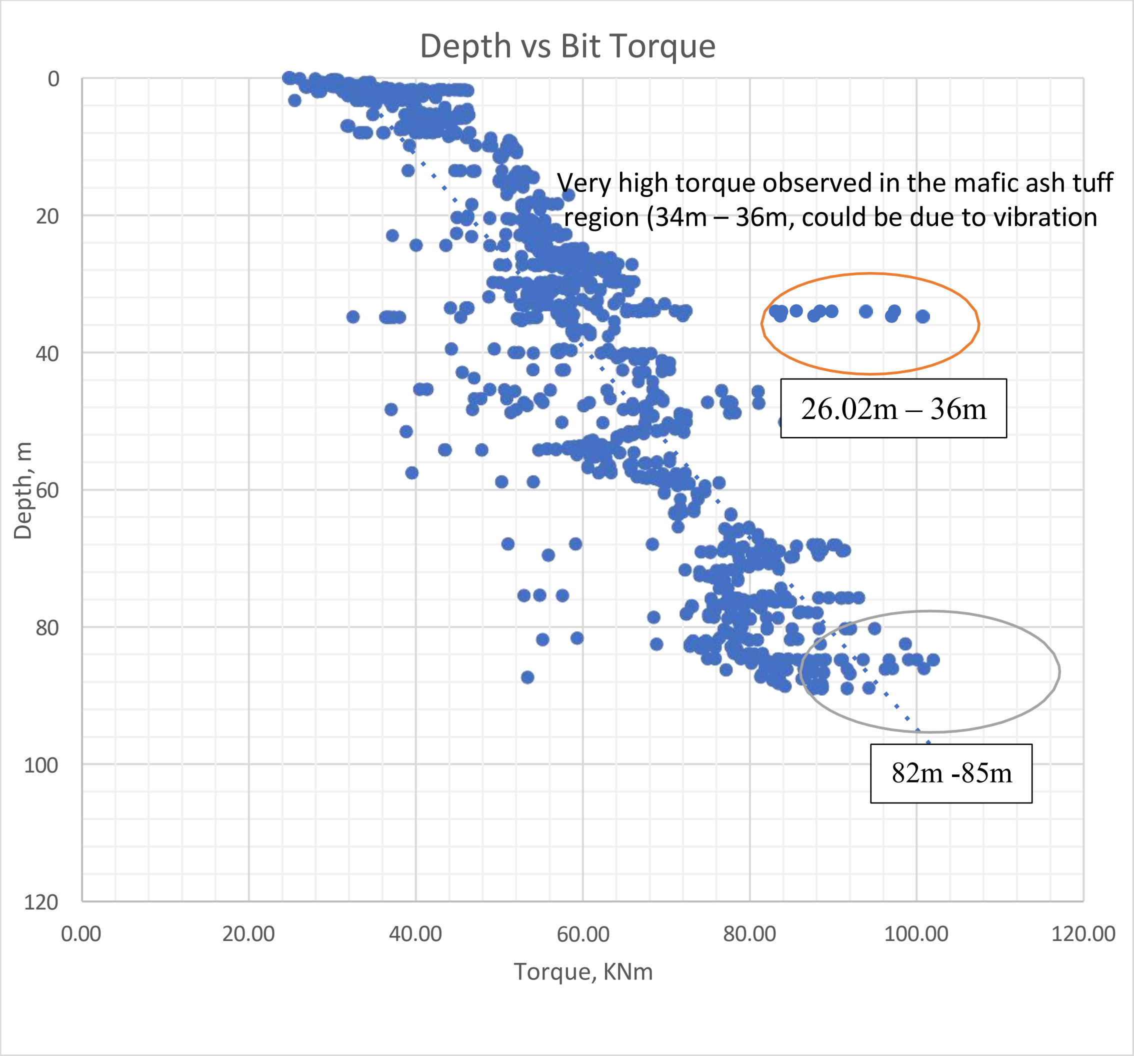


Figure 6-3. Plot of Depth against Torque.

Reaction torque (Tr) is subtracted from the total recorded torque to get the torque on the bit (Tb) (T). Off-bottom testing, also known as free stroke tests, was conducted during the FFT1 to create the reaction torque model. Two models were created to compute the response of torque as shown in equations 6-3 and 6-4 (De Moura, 2021). Figure 6-3 shows a plot of depth against torque.

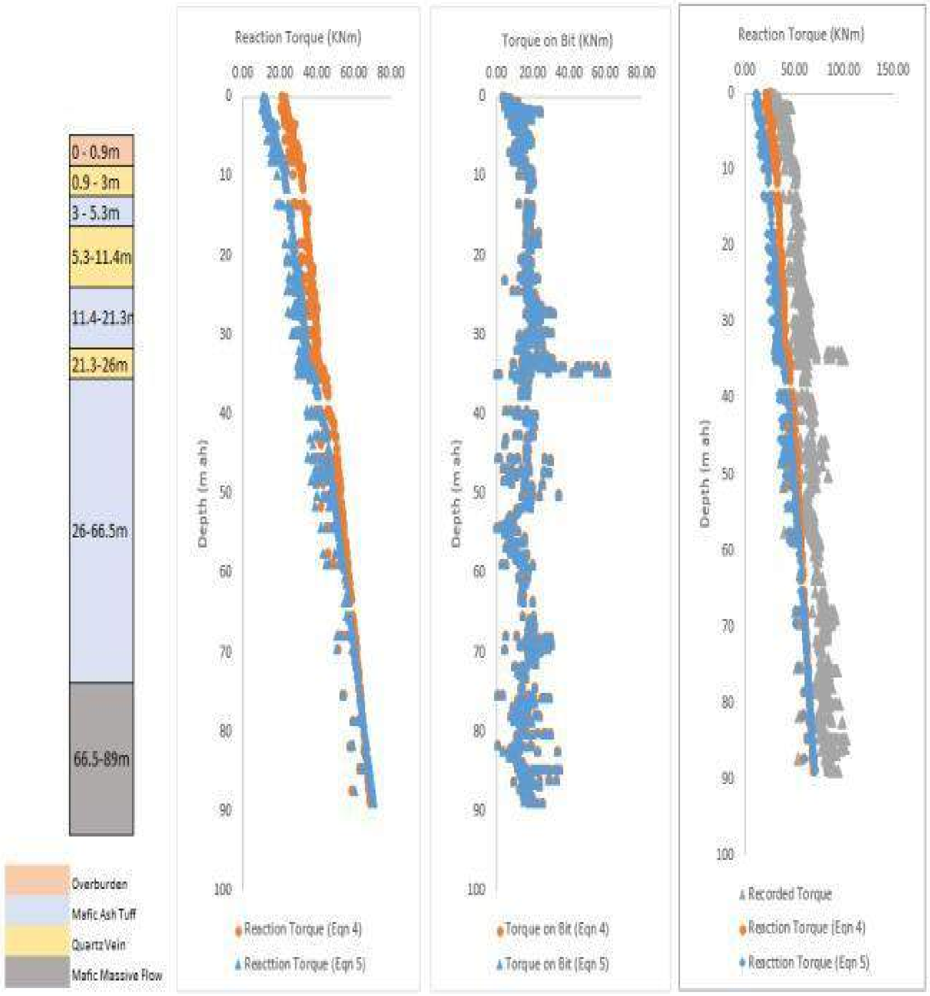


Figure 6-4. Torque log data (Q4 2022, DTL report).

According to Equation 6-3, the reaction torque depends on the rotational speed in rpm (N) and the drilled depth in meters (L). The equivalent length (meters) of the stabilizers utilized in the drill string is denoted by the symbol L* in Equation 6-4.

$$41L + 0.7664N + 15.35 \qquad (6-3)$$

$$T\ (L^{*}, N) = 0.5479L + 0.7664N + 5.08 \qquad (6-4)$$

The range of reaction torque is calculated using equations 6-3 and 6-4. The response torque at short intervals in Equation 6-3 is slightly overstated. The two sets of response torque estimates, however, began to converge as the depth of the drill hole increased, and at around 72 m.

Figure 6-4 demonstrates that equation 6-4 began to overestimate the reaction torque. As a result, the effect of the stabilizer length on the reaction torque increased as the depth of the hole was dug. Regardless of the method employed to calculate the reaction torque, the torque on bit values was nearly the same. The torque applied to the bit varied from 1 to 40 KNm, with an average value between 17 and 19 KNm for both techniques.

In Figure 6-4, depth across lithology was plotted against bit torque, a very high torque was observed in the 34m to 36m depth region, and this could be attributed to a likelihood of vibration occurring downhole. It is difficult to say for certain that this observation could be due to vibration as other factors can influence a spike in torque. If this torque spike is due to vibration, the vibration effect on drilling tools, more importantly, disc cutters is critical to understand because it has a significant impact on performance and can lead to disc cutter failure.

6.3.3 Relative Wear to Changes in Friction Coefficient

An increase in friction coefficient, μ, can lead to an increase in wear and damage of disc cutters. The friction coefficient may change for different formations and may increase to indicate an increase in wear and damage of disc cutters. The friction coefficient, μ is expected to be constant for the same lithology for normal and efficient drilling. If not constant, or if there is a notable spike in torque then it can be assumed that the disc cutters have done more work, bringing about inefficient drilling.

From Figure 6-5, it can be observed that there is a variation in the friction coefficient in the mafic ash tuff region, across hole depths 26.02m to 36m, this could have led to the observed anomalous increase in torque in relation to the effective weight on bit applied by the disc cutters, and hence, damage to the bearing of the disc cutters.

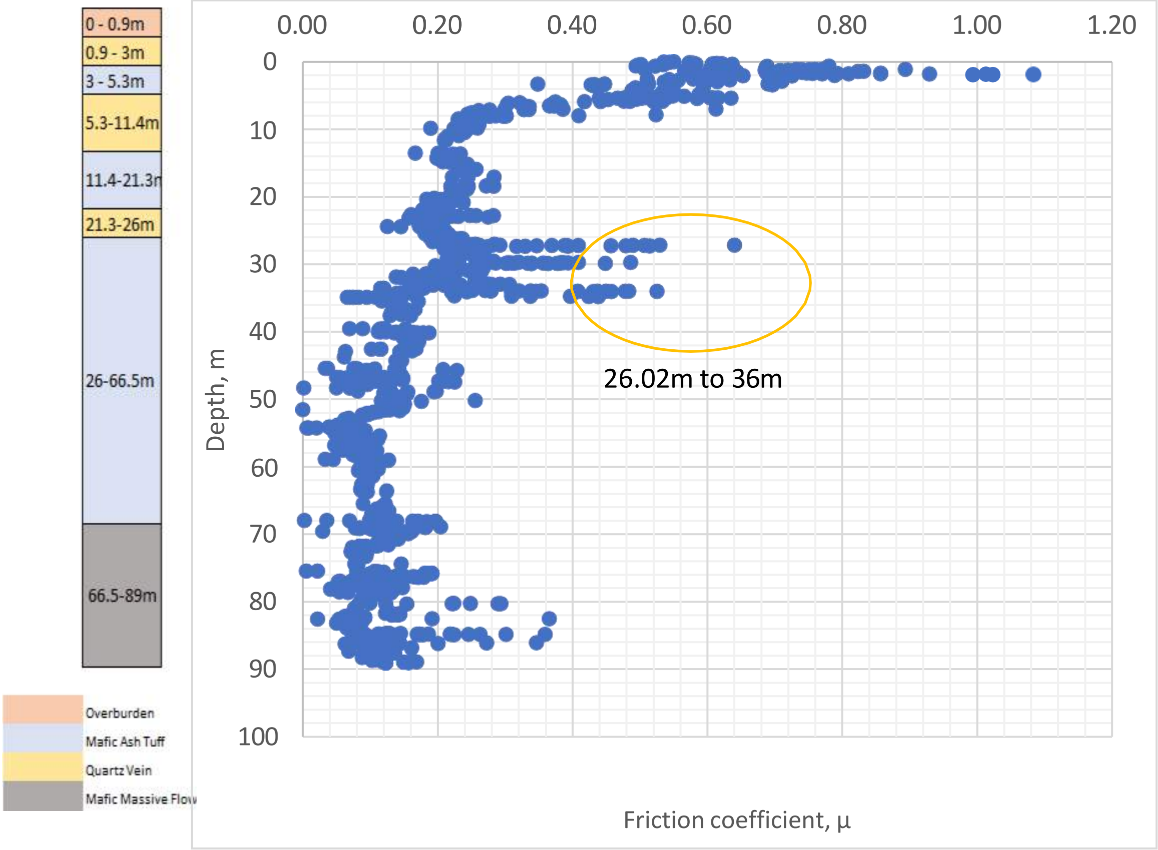


Figure 6-5. The plot of depth against friction coefficient.

6.4 Conclusion

The analyses of the drilling parameters were a very critical part of this research, as they helped to understand how disc cutter wear and damage can be influenced and evaluated. The drilling parameters such as effective WOB, torque, and friction coefficient accounted for, helped to understand the real-time performance of the drilling operation. Torque spikes can lead to vibration, which will ultimately lead to drilling tools and disc cutter failure. An increase in friction coefficient, µ, can lead to an increase in wear and damage of disc cutters. The friction coefficient, µ is expected to be constant for the same lithology for normal and efficient drilling.

6.5 Acknowledgements

This research is funded by Novamera Inc., the Natural Sciences and Engineering Research Council (NSERC) of Canada, MITACS Canada, and the School of Graduate Studies at the Memorial University of Newfoundland, Canada.

Chapter 7: Summary and Conclusion

This chapter concludes and provides a summary of this research work. The goal of this research was to evaluate the wear and damage of multi-edge disc cutters over the course of the ongoing Sustainable Mining by Drilling, SMD project and to determine how this wear affects drilling performance in the duration of the drilling operation that was conducted on a mining field in the north of Newfoundland, Baie Verte.

Over the course of this research, novel methods of measuring and estimating wear and damage of multi-edge disc cutters were created by the Drilling Technology Laboratory, DTL group. Forensic analysis of damaged disc cutters was conducted to support wear evaluation techniques. The methodology employed in this research study was highlighted as well as the materials and equipment used.

For the first study, field measurements were conducted in the mining field and these measurements and wear estimation techniques followed a standard of procedures that is peculiar to the SMD project. A damage weight score was used to evaluate the extent of wear of each multi-edge disc cutter on the cutter head, the tungsten carbide inserts were documented as blunt, cracked, fractured, or missing. Although this is a qualitative wear measurement technique, more work is to be done in the future to provide a quantitative wear measuring technique for this research.

The second study focused on conducting a forensic analysis of damaged disc cutters brought from the field to MUN to determine how several other factors might have influenced the wear and failure of these disc cutters. Drilling parameters such as torque and vibrations were observed to have had somewhat of an impact during drilling. Some disc cutters were also observed to have been plagued with likely some manufacturing issues during the disassembly process, an example was a disc cutter discovered to be improperly lubricated which could have led to overheating of the disc cutters during drilling. Fault tree analysis was also conducted to determine the conditions of the disc cutter's internal components, the roller bearing was the focal point investigated. A forensic analysis was also done to determine the variation of the friction coefficient, μ across the several lithologies of the 90-meter hole depth. This analysis helped to understand the anomalous deviation of the friction coefficient observed across the mafic ash tuff zone which likely led to a torque spike, and hence damage to the disc cutters over the duration of the drilling operation.

Lastly, these methods work in tandem to determine how wear influences the overall drilling performance and efficiency of a drilling operation. It is important to note that it can be very difficult to estimate the wear and failure of disc cutters because several variables could have been at play downhole during drilling. It is expected for an engineer to do a root cause analysis so as to determine probable causes that could have led to wear and damage to the drilling tool.

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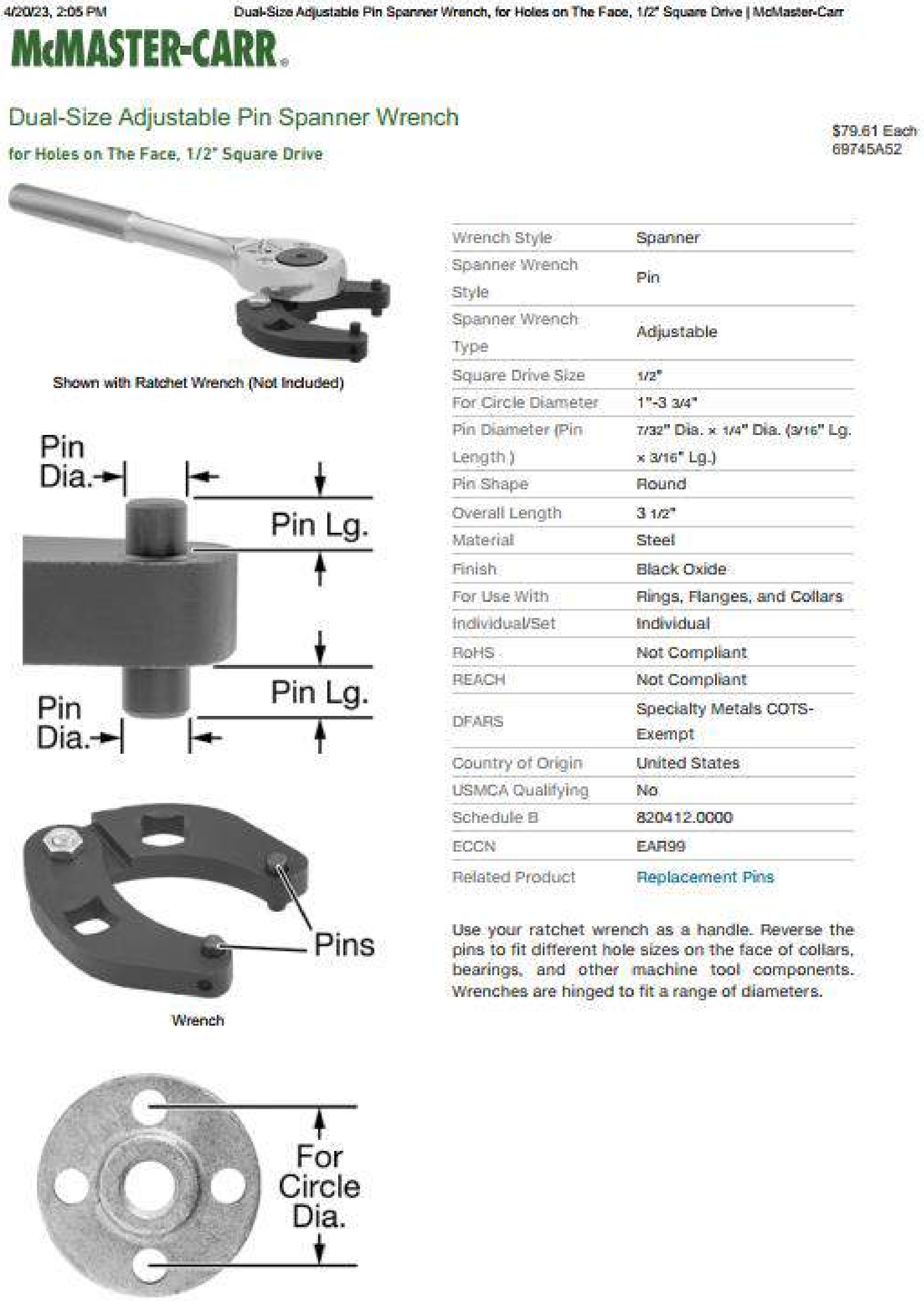
Appendix

Appendix 1: Pin Spanner Wrench Specifications



4/20/23, 2:05 PM Dual-Size Adjustable Pin Spanner Wrench, for Holes on The Face, 1/2" Square Drive | McMaster-Carr

McMASTER-CARR

Dual-Size Adjustable Pin Spanner Wrench

for Holes on The Face, 1/2" Square Drive

$79.61 Each
69745A52

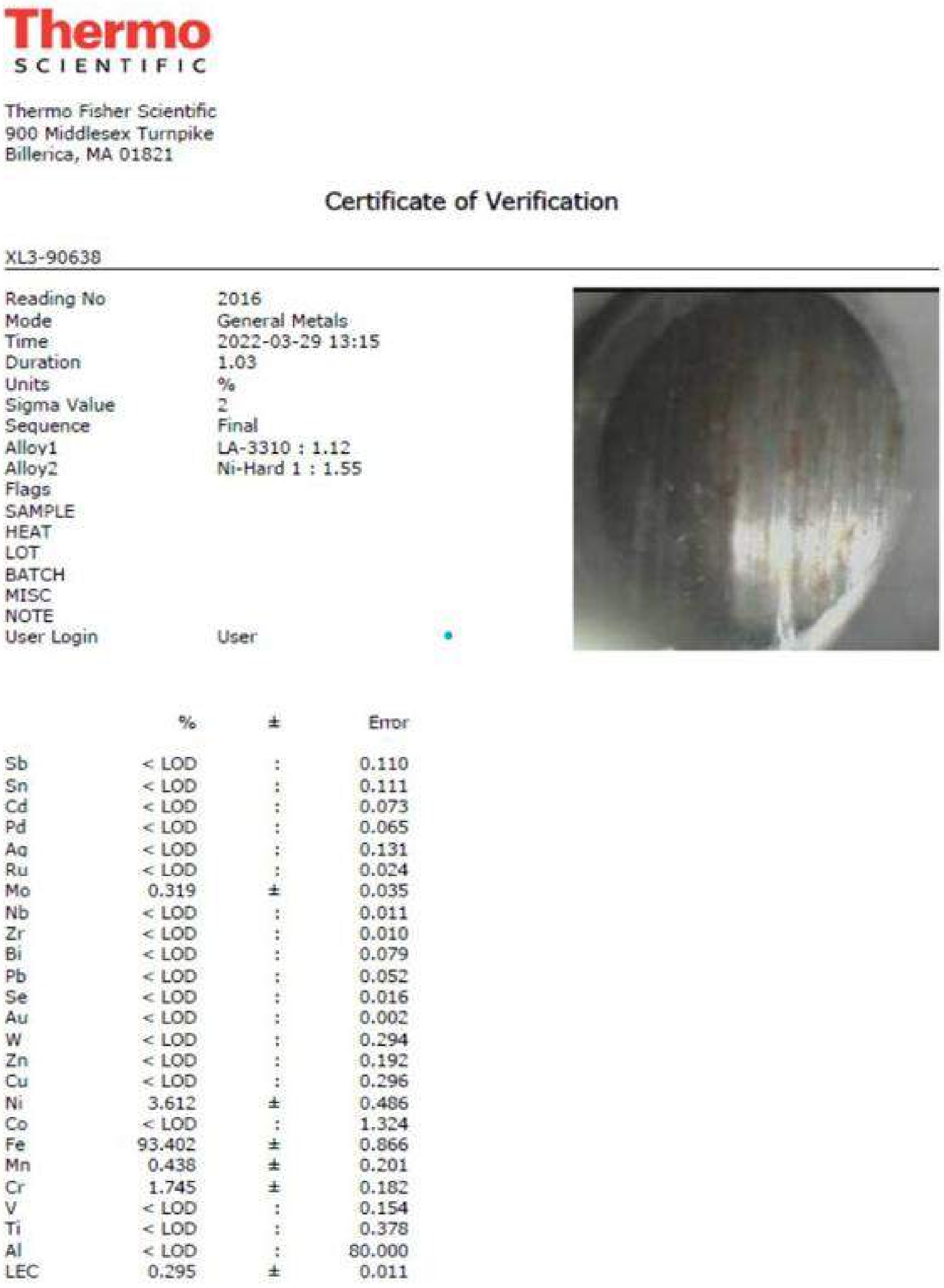
Shown with Ratchet Wrench (Not Included)

Wrench

Wrench Style	Spanner
Spanner Wrench Style	Pin
Spanner Wrench Type	Adjustable
Square Drive Size	1/2"
For Circle Diameter	1"-3 3/4"
Pin Diameter (Pin Length)	7/32" Dia. × 1/4" Dia. (3/16" Lg. × 3/16" Lg.)
Pin Shape	Round
Overall Length	3 1/2"
Material	Steel
Finish	Black Oxide
For Use With	Rings, Flanges, and Collars
Individual/Set	Individual
RoHS	Not Compliant
REACH	Not Compliant
DFARS	Specialty Metals COTS-Exempt
Country of Origin	United States
USMCA Qualifying	No
Schedule B	820412.0000
ECCN	EAR99
Related Product	Replacement Pins

Use your ratchet wrench as a handle. Reverse the pins to fit different hole sizes on the face of collars, bearings, and other machine tool components. Wrenches are hinged to fit a range of diameters.

Appendix 2: XRF reports for the 3 components tested.



Thermo
SCIENTIFIC

Thermo Fisher Scientific
900 Middlesex Turnpike
Billerica, MA 01821

Certificate of Verification

XL3-90638

Reading No 2016
Mode General Metals
Time 2022-03-29 13:15
Duration 1.03
Units %
Sigma Value 2
Sequence Final
Alloy1 LA-3310 : 1.12
Alloy2 Ni-Hard 1 : 1.55
Flags
SAMPLE
HEAT
LOT
BATCH
MISC
NOTE
User Login User

	%	±	Error
Sb	< LOD	:	0.110
Sn	< LOD	:	0.111
Cd	< LOD	:	0.073
Pd	< LOD	:	0.065
Ag	< LOD	:	0.131
Ru	< LOD	:	0.024
Mo	0.319	±	0.035
Nb	< LOD	:	0.011
Zr	< LOD	:	0.010
Bi	< LOD	:	0.079
Pb	< LOD	:	0.052
Se	< LOD	:	0.016
Au	< LOD	:	0.002
W	< LOD	:	0.294
Zn	< LOD	:	0.192
Cu	< LOD	:	0.296
Ni	3.612	±	0.486
Co	< LOD	:	1.324
Fe	93.402	±	0.866
Mn	0.438	±	0.201
Cr	1.745	±	0.182
V	< LOD	:	0.154
Ti	< LOD	:	0.378
Al	< LOD	:	80.000
LEC	0.295	±	0.011

Thermo
SCIENTIFIC

Thermo Fisher Scientific
900 Middlesex Turnpike
Billerica, MA 01821

Certificate of Verification

XL3-90638

Reading No	2017
Mode	General Metals
Time	2022-03-29 13:16
Duration	1.15
Units	%
Sigma Value	2
Sequence	Final
Alloy1	LA-1215 : 1.24
Alloy2	LA-C Steel : 1.39
Flags	
SAMPLE	
HEAT	
LOT	
BATCH	
MISC	
NOTE	
User Login	User

	%	±	Error
Sb	< LOD	:	0.056
Sn	< LOD	:	0.066
Cd	< LOD	:	0.044
Pd	< LOD	:	0.045
Ag	< LOD	:	0.075
Ru	< LOD	:	0.014
Mo	0.036	±	0.011
Nb	< LOD	:	0.014
Zr	< LOD	:	0.006
Bi	< LOD	:	0.048
Pb	< LOD	:	0.046
Se	< LOD	:	0.023
Au	< LOD	:	0.002
W	< LOD	:	0.337
Zn	< LOD	:	0.134
Cu	< LOD	:	0.167
Ni	< LOD	:	0.302
Co	< LOD	:	0.691
Fe	97.679	±	0.492
Mn	0.781	±	0.160
Cr	0.124	±	0.062
V	< LOD	:	0.212
Ti	< LOD	:	0.313
Al	< LOD	:	80.000
LEC	0.910	±	0.011

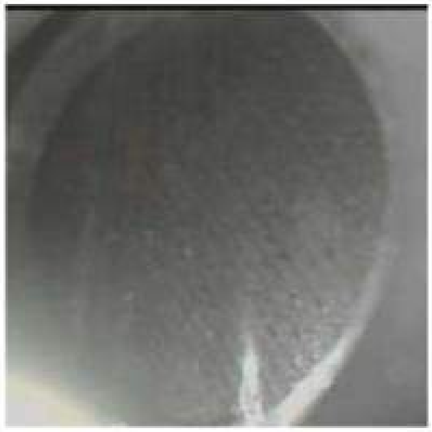
Thermo
SCIENTIFIC

Thermo Fisher Scientific
900 Middlesex Turnpike
Billerica, MA 01821

Certificate of Verification

XL3-90638

Reading No	2290
Mode	General Metals
Time	2022-11-14 09:00
Duration	0.78
Units	%
Sigma Value	2
Sequence	Final
Alloy1	LA-C Steel : 0.74
Alloy2	No Match : *1.77
Flags	
SAMPLE	
HEAT	
LOT	
BATCH	
MISC	
NOTE	
User Login	User



	%	±	Error
Sb	< LOD	:	0.073
Sn	< LOD	:	0.066
Cd	< LOD	:	0.055
Pd	< LOD	:	0.049
Ag	< LOD	:	0.094
Ru	< LOD	:	0.020
Mo	0.042	±	0.014
Nb	< LOD	:	0.016
Zr	< LOD	:	0.009
Bi	< LOD	:	0.051
Pb	< LOD	:	0.106
Se	< LOD	:	0.021
Au	< LOD	:	0.002
W	< LOD	:	0.293
Zn	< LOD	:	0.144
Cu	< LOD	:	0.199
Ni	< LOD	:	0.493
Co	< LOD	:	0.841
Fe	97.934	±	0.607
Mn	0.339	±	0.162
Cr	0.176	±	0.083
V	< LOD	:	0.211
Ti	< LOD	:	0.421
Al	< LOD	:	80.000
LEC	1.295	±	0.011

Supervised By: ____________________