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THE DEVELOPMENT OF A LINEAR CUTTING MACHINE USED TO CHARACTERISE FEM MODELLING PARAMETERS FOR CUTTING UG2 REEF

UNIVERSITY OF PRETORIA

BY

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Abstract

The development of a linear cutting machine used to characterise FEM modelling parameters during the cutting of UG2 reef

by

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Mining is still an important industry in South Africa. Traditional mining methods involving drilling and blasting have steadily been replaced by mechanised mining systems in soft rock environments but not in hard rock environments. Mechanised mining systems can lead to continuous mining, which lead to improved rates of face advance and better utilization of the invested capital.

A fundamental understanding of the tool-rock interaction, for rock found in gold and platinum mines in South Africa, and potential solutions to problems in mechanised mining methods in narrow reef hard rock mines, are required.

South Africa has two main platinum reef deposits namely the Merensky reef and the UG2 reef. A renewed effort is required to study the problem of mechanical mining, and develop numerical models, that take the rock properties into account. This will allow optimisation of the mechanised cutting in hard rock environments.

In this dissertation a linear cutting machine (LCM) was designed and manufactured to conduct laboratory scale cutting tests on both sandstone and UG2 reef samples. Firstly sandstone was cut to ensure that the LCM functions as expected. By conducting tests on sandstone, it ensured that all the functions of the LCM could be optimized. The comparison between the samples showed that there are similarities between the results from the different rock types, but some inconsistencies were found. The key difference is that the sandstone considered here has little to no variance in strength on a millimetre scale whereas the UG2 reef sample has large variance in strength on a millimetre scale. This introduces uncertainty in the results due to added variance. Another problem is the inconsistency in rock properties of the UG2 reef. The rock properties of the UG2 reef changes a lot from reef to reef as well as different areas in the mine.

The results showed that the optimal cutting parameters are similar for sandstone and UG2, but there are some differences. The depth of cut has a larger influence on the results of UG2 reef samples than for the sandstone samples. Therefore if the sandstone data was used to make design decisions for new mining equipment the decision might have been incorrect due to the assumption that sandstone

and UG2 cut similarly.

An important difference between cutting sandstone and UG2 reef is the size of the chips formed. At 2 mm cutting depth, for both samples, the force signals were impulsive and the material produced was fine fragmentations. At a cutting depth of 4 mm, for both samples, the force signals had a saw tooth shape. This implies larger fragment sizes were formed. The sandstone produced large fragments whereas the UG2 still produced fine fragmentations. This fine fragmentations is undesirable in underground mining conditions as this causes that material can not be easily cleaned and removed from the stopes.

A fast Fourier transform (FFT) analysis on the cutting signal showed that the sandstone had a periodic cutting force signal whereas the UG2 does not have a periodic cutting force signal. Also for the sandstone a good relationship was present between the size of the chips formed and the dominant frequencies of the FFT.

The numerical simulations showed that there are various model parameters that influence the results and while other have little effect. Thus, there are many choices that need to be made about model parameters, such as element size, element type, boundary conditions, contact parameters and model parameters. Some are based on material properties and other are obtained through trial and error.

It is possible to model rock cutting of UG2 reef samples using the Ansys LS-DYNA multi-physics simulation software and the continuous surface cap model (CSCM). But this is only possible by editing the model parameters through trial and error for one set of cutting parameters. When the cutting parameters are changed, the model does not give acceptable results. Future work is required to improve the ability of models to generalise when the cutting parameters change.

Acknowledgements

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Contents

Nomenclature

Abbreviations

AWJ	Abrasive water jet
BFGS	Broyden–Fletcher–Goldfarb–Shanno
CAD	Computer-aided design
CSCM	Continuous surface cap model
DEM	Discrete-element method
FEM	Finite-element method
FFT	Fast Fourier transform
GDP	Gross domestic product
LCM	Linear cutting machine
MSE	Mean squared error
NCHRP	National cooperative highway research program
SLSQP	Sequential least squares programming
TBM	Tunnel boring machine
TOR	Triaxial shear
TXC	Triaxial compression
TXE	Triaxial extension
ULP	Ultra-low profile

English letters and symbols

a	CSCM calculated parameter
a'	CSCM calculated parameter
b	CSCM user parameter
d	CSCM user parameter
D_1	CSCM isotropic compression curve parameter
D_2	CSCM isotropic compression curve parameter
D_o	Outer diameter
D_i	Inner diameter
D	Damage parameter
D_{max}	Maximum damage parameter
E	Young's Modulus
F_f	Shear surface
F_{drag}	Applied drag force to load cell design
FD	Mean drag force
FD'	Peak drag force
FD'_{Evans}	Peak drag force using equations from Evans
FD'_{Goktan}	Peak drag force using equations from Goktan
F_{norm}	Applied normal force to load cell design

FN	Mean normal force
FN'	Peak normal force
F_{side}	Applied side force to load cell design
G_{fc}	Fracture energy in uniaxial compression
G_{ft}	Fracture energy in uniaxial tension
G_{fs}	Fracture energy in pure shear
L	Moment arm 1
$recov$	Stiffness recovery parameter
N_c	Rate effect power in uniaxial compression stress
N_t	Rate effect power in uniaxial tensile stress
$ovwec$	Maximum overstress allowed in uniaxial compression stress
$ovwet$	Maximum overstress allowed in uniaxial tensile stress
p_{mod}	CSCM user parameter
$pwrc$	Shear-to-compression transition parameter
$pwrt$	Shear-to-tension transition parameter
Q_1	Rubin scaling function 1
Q_2	Rubin scaling function 2
$repow$	CSCM user parameter
s/d	Cutting spacing to cutting depth ratio
SG_1	Strain gauge 1
SG_2	Strain gauge 2
SG_3	Strain gauge 3
SG_4	Strain gauge 4
S_{rate}	Effective shear stress to tensile stress fluididity parameter
S	Moment arm 2
W	Maximum plastic volume strain
X_0	Initial location of cap
x_{pred}	Predicted load value
x	Actual load value

Greek Symbols

α	CSCM shear surface parameter for TXC
α_1	CSCM shear surface parameter for TOR
α_2	CSCM shear surface parameter for TXE
$\hat{\beta}$	Deviatoric plane angle
β	CSCM shear surface parameter for TXC
β_1	CSCM shear surface parameter for TOR
β_2	CSCM shear surface parameter for TXE
η_{c0}	Rate effect parameter in uniaxial compression stress
η_{ct}	Rate effect parameter in uniaxial tensile
ε_V^p	Plastic volume strain
ε	Strain

λ	CSCM shear surface parameter for TXC
λ_1	CSCM shear surface parameter for TOR
λ_2	CSCM shear surface parameter for TXE
ν	Poisson's ratio
ρ	Density
σ	Stress
τ_c	Energy-type term
τ_{c0}	Damage energy threshold
θ	CSCM shear surface parameter for TXC
θ_1	CSCM shear surface parameter for TOR
θ_2	CSCM shear surface parameter for TXE

Chapter 1

Introduction and Literature review

1.1 Background

Despite mining becoming a smaller fraction of the gross domestic product (GDP) over the past few years, it remains an important industry in South Africa. In 2022 it still contributed 7% to the GDP of South Africa, according the Minerals council of South Africa.

Traditional mining methods involving drilling and blasting have steadily been replaced by mechanised mining systems, to the extent that mechanised mining has become the predominant mode of mining for new mine developments in softer rock (Moxham, 2004). This is however not the case for gold and platinum mines and the other hard rock mining operations in the Bushveld complex.

In South Africa the gold and platinum mines have extremely narrow reefs, less than 1 m. The current equipment used for mechanised mining in soft rock is too large for the narrow reef hard rock environments. The current method of drilling and blasting that is used in narrow reef hard rock mines has a cyclic nature. This constrains the rate of face advance and leads to poor utilization of the invested capital (Moxham, 2004). Thus new equipment is required for narrow reef hard rock mechanised mining that can operate in the restrictive environment and utilizes new cutting methods that work for hard rock environments. Alternatively a different utilization of existing equipment is required (Pickering, 2007).

Mechanised cutting potentially offers significant advantages to drilling and blasting in the hard rock environment. The reason for this is that cutting operations can lead to continuous mining, which lead to improved rates of face advance and better utilization of the invested capital. Once perfected, mechanical methods of mining offer the potential to be significantly faster than drill-and-blast methods (Vogt, 2016).

Replacing the method of drilling and blasting with mechanised mining equipment in narrow reef hard rock mines also offers other advantages. Mechanised cutting does not have the instability of the rock due to explosions, there is no need to ventilate toxic gases before people can access the mine again after blasting, and it has the potential to reduce waste dilution (Moxham, 2004).

South African hard rock narrow reef environments pose very difficult challenges for mechanised cutting. In South Africa various approaches have been explored. The former Chamber of Mines Research Organisation pursued an approach based on breaking the rock using impact rippers. Anglo American pursued a methodology that comprised a mixture of slotting and breaking. Lonmin Platinum and a few other companies co-developed a narrow reef miner that utilizes the method of undercutting (Moxham, 2004). Neither of these approaches have however made the breakthrough required to reach full commercial scale application.

As a result mining companies such as Anglo American Platinum are still investing capital in developing an ultra low profile fleet of equipment that uses the method of drilling and blasting (see for example Fourie et al., 2014), due to the lack of breakthroughs required to reach full commercial scale application of mechanised mining equipment.

1.2 Problem Statement

A fundamental understanding of the tool-rock interaction, for rock found in gold and platinum mines in South Africa, and potential solutions to mechanised mining problems in narrow reef hard rock mines in South Africa are required. This includes an understanding of the effect of different rock properties, such as strength, brittleness and abrasiveness on the tool-rock interaction.

South Africa has two main platinum reef deposits namely the Merensky reef and the UG2 reef. Other types of hard rock are also found in South Africa, but the focus was placed on the platinum mines. A renewed effort is required to study the problem of mechanical mining, and develop numerical models, that take the rock properties into account. This will assist in the optimisation of the mechanised cutting in hard rock environments.

1.3 Objective

This study investigates various adaptations of conventional rock cutting methods. A rock cutting method will be selected for further understanding of the tool-rock interaction. A linear cutting machine will be designed and manufactured to conduct laboratory scale tests. Numerical simulations will also be conducted to determine if the tool-rock interaction can be numerically simulated with acceptable accuracy.

The experimental test will measure the mean and peak cutting forces, namely drag force, normal force and side force, and the specific energy required to perform the cut. The results will be compared to the results obtained from the numerical simulations. The tests will be conducted on rock samples of sandstone and the UG2 reef. The results will show the optimal parameters for the selected cutting method and the specific rock used. The results will also show the difference between the optimal parameters for the different rock samples.

This will contribute to a more a fundamental understanding of the tool rock interaction, of rock found in gold and platinum mines in South Africa. This will pave the way for future development of new equipment that will be used in narrow reef hard rock mines in South Africa.

1.4 Literature review

The literature review gives background about various aspects of underground mining and the methods used. The literature review describes different machines used in underground mines, how the cutting method for the different machines work and how different tools are used for different mining methods.

The main tools that are studied are drag and pick type of tools as well as roller tools. Hybrid methods are also investigated. The rock-breakage mechanism of the tools and the different design parameters for the pick type tools are described to demonstrate the current state of art in the field.

Previous laboratory scale cutting tests are investigated to show the advantages and disadvantages of different designs to assist with the design of the linear cutting machine that will be used in this study.

Numerical simulations based on rock cutting are investigated to determine the pros and cons of different methods such as finite-element method and discrete-element method. The investigation highlighted different software that can be used and various material models that are suitable to simulate rock cutting.

1.4.1 Aspects of underground mining related to this study

Extracting the ore in an underground mine requires physical access to the orebody, extracting the ore from the host rock and transporting the ore from the orebody to the mine surface. There are three types of excavations. These are the stopes (a stope is the site of ore production in an orebody), the stope access and service excavation and the permanent access and service excavation (Bilgin, Copur and Balci, 2013). Regardless of the mining method used for the orebody, the functions and required safety performance of the stope access and service excavation and the permanent access and service excavation remain mostly the same.

Stopes are normally the largest excavation in an underground mine. Thus, it is of utmost importance to control the stability of the rock within the stope and adjacent to the stope. This will ensure efficient geomechanical and economical performance of the stope and thus of the mine itself. The shape, size and location of the stope is the most important for the design of the mine. This determines the location and design of the other two types of excavation (Bilgin, Copur and Balci, 2013). The permanent access and service openings must remain stable over a time period exceeding the life of the orebody excavation. Examples of these are hoisting shafts that need to be capable of supporting continuous high speed operation of cages and skips. Haulage and drives must remain safe for high speed operations of loaders, trucks, ore trains and personnel transport vehicles.

A mining method is a sequence of production operations that are repetitively conducted in and around the stope. The common operations of mining methods are access to orebody, extraction of ore and transport of ore. The different mining methods use different techniques for these operations. There are many orebody properties that influence the mining method used in underground mines. These properties include geometric configuration of orebody, disposition and orientation, size, geomechanical setting, orebody value and spatial distribution of value and engineering environment.

Underground mining methods can be divided into three different types, namely pillar supported, artificially supported and unsupported. Each of the three types of underground mining methods employs different mining techniques. The pillar supported underground mining can be room-and-pillar or sub-level and longhole open stoping methods. The artificially supported underground mining can be bench-and-fill stoping, cut-and-fill stoping, shrink stoping, vertical crater retreat stoping and longwall mining. Unsupported underground mining can be longwall mining, sub-level caving and block caving (Bilgin, Copur and Balci, 2013).

1.4.2 Excavation methods

There are currently two main methods of excavation in underground mines, namely drill and blast methods and mechanical excavation. Both of the excavation methods have advantages and disadvantages. Mechanical excavation is safer, causes less ground disturbance, produces an uniform fragmentation size, can conduct selective mining and allows for continuous excavation. Mechanical excavation has a higher initial cost, less flexibility and typically struggles to cut very hard rock (Bilgin, Copur and Balci, 2013).

There are also research and development being done on alternative and hybrid methods of excavation (Sifferlinger, Hartlieb and Moser, 2017). Alternative methods include high pressure water cutting, using microwaves, electropulse or laser. Hybrid methods of excavation are combinations of alternative methods and mechanical methods. The hybrid methods attempt to exploit the benefits of both methods with minimal disadvantage.

1.4.3 Underground excavation machines

An underground excavation machine can either be a full-face or a partial-face excavation machine depending on how the machine attacks the rock face. A full-face underground excavation machine attacks the entire rock face simultaneously. A good example of a full-face underground excavation machine is a tunnel boring machine (TBM), shown in figure 1.1.

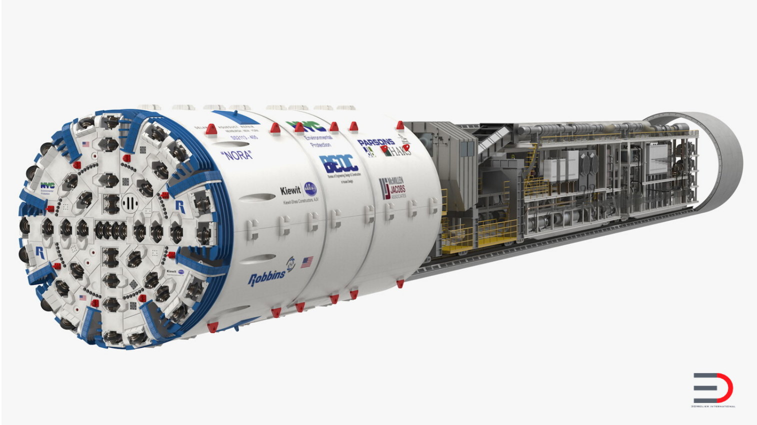


Figure 1.1: Nora Tunnel Boring Machine (Artstation, 2020)

A full-face underground excavation machine usually cuts a circular opening due to the cutting mechanics of the machine (Bilgin, Copur and Balci, 2013). For partial-face underground excavation machines, the face is attacked in sections. Partial-face underground excavation machines can excavate differently shaped openings. Roadheaders and continuous miners are good examples of partial-face underground excavation machines, figure 1.2 shows examples of partial-face underground excavation machines.

(a) MH621 Roadheader for hard rock (Sandvik, 2015)

(b) MC350 Continuous miner (Sandvik, 2015)

Figure 1.2: Partial-face underground excavation machines

Full-face underground excavation machines are long and heavy machines that have large turning radii whereas partial-face underground excavation machines are smaller and has a much shorter turning radius'. Typically a roadheader only needs an entry way of width 6 to 8 meters to cut a 90° turnoff (Sifferlinger, Hartlieb and Moser, 2017). Also partial-face machines are better in selective excavation. But due to the cutting mechanics and weight of the full-face machines they are better at excavating hard rock.

Roadheaders and continuous miners are commonly used in roadway and tunnel excavation (Kotwica, 2019). The roadheaders and continuous miners mainly use rotary-tangential picks, also known as conical picks.

1.4.4 Cutting tools

The cutting tools of an excavation machine is the most important part of the machine because it transfers the energy of the machine to the rock to break the rock. Thus, it is important to have the proper material for the tool and also the correct design for the tool for the given machine and rock conditions. The efficiency and economical success of the machine, and therefore the mine, depends on these choices of material and design of the cutting tool.

There are three main types of cutting tools, drag/pick type tools, roller tools and impacting tools (Kotwica, 2019). The performance of a cutting method is measured by the specific energy. The specific energy is the amount of energy required to cut one cubic meter of rock. There are different types of drag/pick tools. The most common types are conical picks, radial picks, scrapers and chisels. Figure 1.3 show examples of a conical and a radial pick.

(a) Conical pick (Tools, 2022) **(b)** Radial pick (Sandvik, 2022)

Figure 1.3: Drag/pick type tools

For roller tools there are different methods of excavation namely undercutting and crushing. Figure 1.4a shows an example of crushing and figure 1.4b shows an example of undercutting. These roller tools are either symmetrical or asymmetrical, as shown in figure 1.4.

(a) Symmetrical roller tool **(b)** Asymmetrical roller tool

Figure 1.4: Symmetrical and asymmetrical roller tools (Stopka, 2021)

The rollers (disks) can either be smooth or armed with carbide inserts (Kotwica, 2018), as shown in figure 1.5.

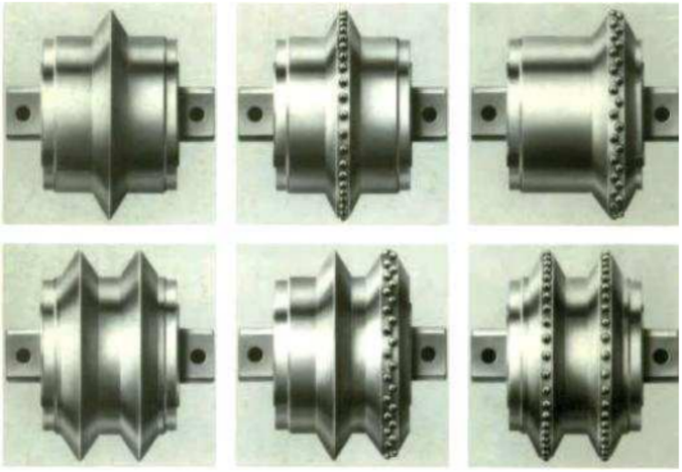
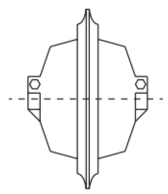
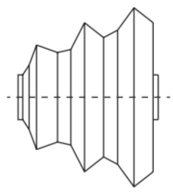


Figure 1.5: Smooth rollers and armed rollers (Kotwica, 2019)

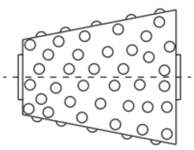
The rollers can be manufactured as true rolling or non-true rolling. Examples of these rollers are multi-disk cutters and strawberry cutters, shown in figure 1.6.



(a) Single roller disk



(b) Multi-disk



(c) Strawberry cutter

Figure 1.6: True rolling and non-true rolling cutting disk (Bilgin, Copur and Balci, 2013)

Impacting tools break the rock by high frequency cyclic impacts on the face of the rock. Bilgin has a good general comparison between the drag/pick tools and the roller tools (Bilgin, Copur and Balci, 2013).

1.4.5 Rock-breakage mechanism

The rock-breakage mechanism is different for different tools. Some are based on tensile fracturing and other on shearing (Ozdemir, 1977). Tensile strength and compressive strength are dominant rock properties in rock cutting with chisel tools and conical picks (Bilgin, Demircin, et al., 2006). When the tool is cutting the rock, a crushing zone is formed due to the highly concentrated compressive stress (CCS) in front of and beneath the cutting tool (Evans, 1962). This concentrated compressive stress creates tensile fractures in the rock. Figure 1.7 shows how the crushing zone is formed under a disk cutter.

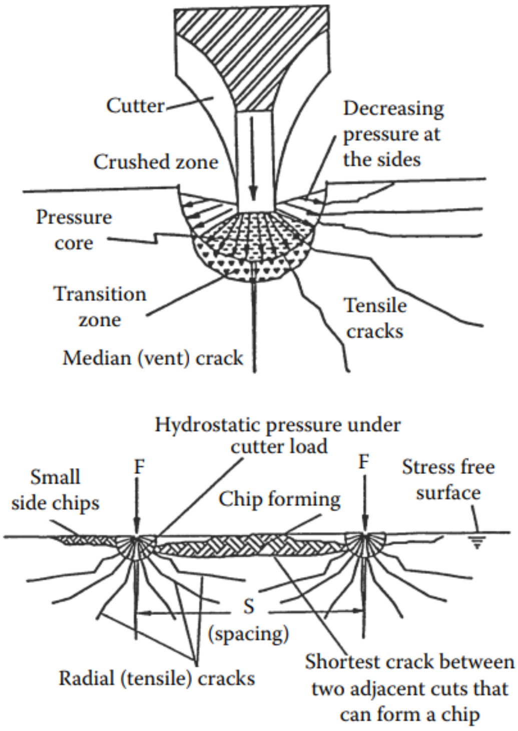


Figure 1.7: Idealized tensile breakage under CCS disk cutter (Bilgin, Copur and Balci, 2013).

When chips are formed while cutting rock, two cracks are formed. The first crack propagates into the rock until the tensile strain at the crack tip falls below the required tensile strain for fracture propagation. The second crack extends to the surface of the rock to form chips in the rock. Figure 1.8 shows how the cracks develop using a wedge-type cutting tool.

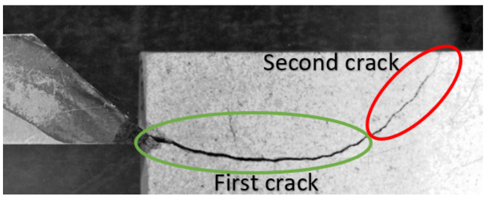


Figure 1.8: Tensile breakage by a wedge-type cutting tool. Adapted from (Bilgin, Copur and Balci, 2013).

Conical picks are the most widely used cutting tools. Thus, it is important to know the cutting behaviour of the tool in different rock types and geotechnical environments. If the cutting behaviour is known more efficient cutting systems can be designed. Thus will result in better operational parameters and better estimating cutting performance of the excavation machines.

Owing to the cutting behaviour of cutting tools being a crucial part in the efficiency of the excavation machine and thus the overall efficiency of the mine itself, many researchers have formulated mathematical models to better explain the cutting behaviour and to determine the optimal configuration of the cutting tools. Evans (1962) formulated equations for the mean peak cutting force of both chisel picks and conical picks . The equations take the following parameters of the rock and the tool into account. The depth of cut, tool width, rake angle, tensile strength, compressive strength and tip angle, these parameters are shown in figure 1.9.

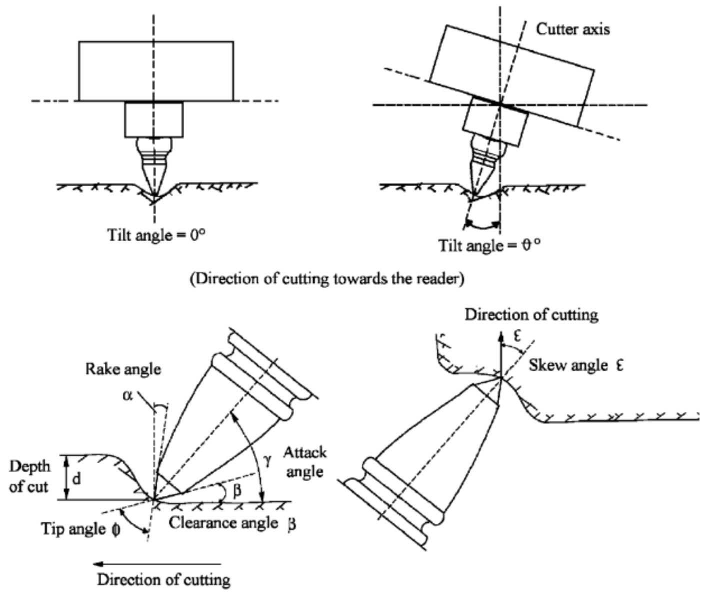


Figure 1.9: Parameters of conical picks (Kotwica, 2019)

There are also fracture mechanics approaches to model the cutting behaviour. These approaches give information about the crack progressive failure, crack propagation, corresponding load requirement and stability of the crack propagation (Kotwica, 2019). Goktan (1997) suggested a modification to Evans' equation for conical picks to account for the friction coefficient. Nishimatsu (1972) also developed an equation where he added the rock shear strength as a parameter. He found that the rock shear strength is a dominant parameter in cutting high strength rock (Nishimatsu, 1997). By optimizing the design of the cutter parameters, the problems due to vibrations are minimized and the specific energy is lowered. Thus the overall efficiency of the machine is improved which leads to a more efficient mine. Lateral stress in the rock causes an increase in cutting force. The equations of the mean peak cutting force stated above do not take lateral stresses into account.

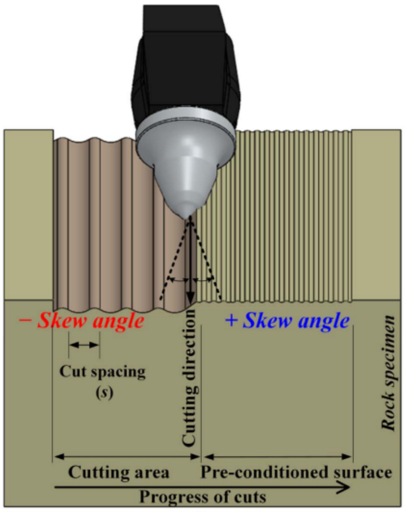
1.4.6 Drag/pick tools

There are various types of drag/pick tools used in rock excavation. As stated earlier the most common are conical picks, radial picks, scrapers and chisels. Scrapers and chisels are wedge type drag tools. Conical picks generate higher forces than scrapers and chisels. In abrasive rock, conical picks also last longer than scrapers and chisels (Bilgin, Demircin, et al., 2006). When mining hard rock, large bending forces act on the cutting tool. Owing to the large bending forces radial picks get damaged (Kotwica, 2019). Thus, conical picks are preferred over radial picks. The design of the holders of the conical pick allows for the conical pick to rotate, with a proper selected skew angle, the rotation of the conical pick causes even wear. The even wear increases the life of the conical pick.

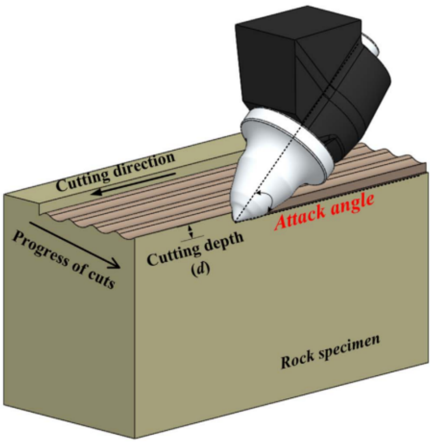
Drag/pick tools mill the face of the rock when cutting. The process of milling the rock generates a considerable amount of dust and can cause sparks that can lead to an explosion in the mine if methane is present. When the tool is extensively worn the amount of dust generated increases. The amount of dust that is generated can cause a dust hazard and also lower the efficiency of the excavation machine.

Conical picks

There are various parameters that can be changed when designing an excavation machine using conical picks. When looking at individual picks the depth of cut, attack angle, skew angle and cut spacing can be changed to optimize the performance of the cutting process, depending on the properties of the rock that is being cut (Park et al., 2018). Figure 1.10 shows the parameters of the conical pick.



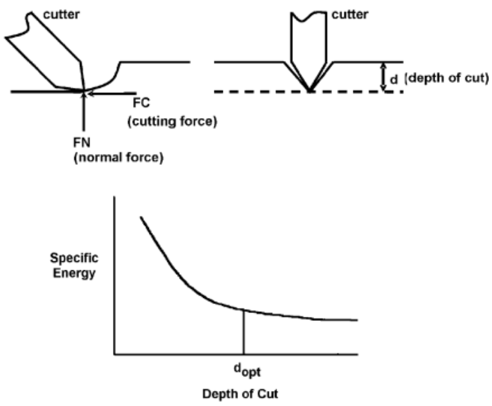
(a) Front view



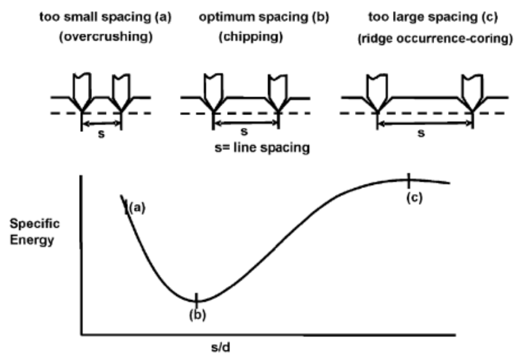
(b) Side view

Figure 1.10: Conical pick parameters (Park et al., 2018)

Different researchers found that there is an optimal ratio of cutter spacing to cutting depth, this ratio effects the specific energy (Bilgin, Demircin, et al., 2006; Copur et al., 2017; Park et al., 2018). Figure 1.11 shows the effect that cutting depth and cutter spacing has on the specific energy.



(a) Unrelieved cutting mode, no interaction between groves.

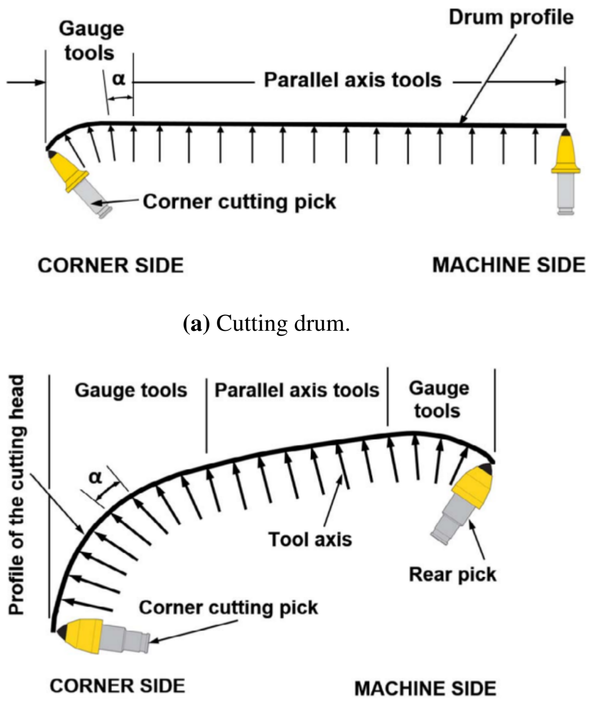


(b) Relieved cutting mode, interaction between groves.

Figure 1.11: Effect of cutter spacing and cutting depth on the specific energy (Bilgin, Demircin, et al., 2006).

Park and co-workers determined the optimal ratio of cutter spacing to cutting depth. They used this optimal ratio to determine optimal parameters for the skew angle and attack angle. The optimal parameters were determined by comparing the specific energy. The study found that the optimal spacing of the cutter changed for different rock specimens with different uniaxial compressive strength, cutting depth and attack angle. A positive skew angle is preferred because the contact area is reduced. The study did not consider tool wear, symmetry of tool wear or number of tool rotations. A larger attack angle performed better in hard rock (Park et al., 2018).

There are other cutting sequence parameters that also have an affect on the performance of the excavation machine. Figure 1.12 shows two different cutter profiles of the cutting drum, that can be found on mechanical mining machines. An examples of these cutting profiles of the cutting drums are shown in figure 1.2.



(a) Cutting drum.

(b) Cutting head

Figure 1.12: Cutter profile (Hekimoglu, 2018).

As seen in figure 1.2 each machine has two cutting drums. The corner side shown in figure 1.12 is at the sides of the machine and the machine side, in figure 1.12, is in the middle of the machine.

Hekimoglu (2018) determined the tilt angle, α in figure 1.12, for the gauge tools and also whether it is optimal to start the cutting sequence on the machine side or the corner side. Thus, is it better to cut from the machine side to the corner side or from the corner side to the machine side.

Hekimoglu found that there is an optimal tilt angle, 67°, which is half breakout angle of the rock. This is shown in figure 1.13.

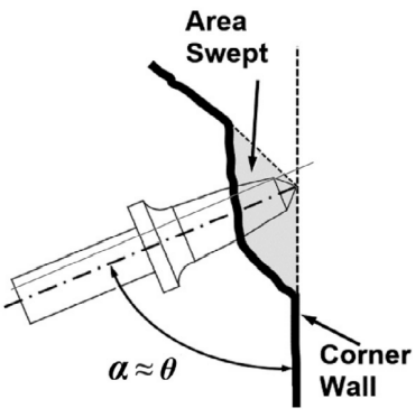


Figure 1.13: Optimal tilt angle (Hekimoglu, 2018)

For most roadheaders the cutting sequence is from the corner side to the machine side, this is done for loading requirements to ensure easier clearing of the cut rock. But the study suggests that it is optimal to cut from the machine side to the corner side. This shows that there is a lack of knowledge with regards to the cutting sequence. The parallel axis tools are not influenced by whether the cutting sequence starts from the machine side or from the corner side.

Hybrid methods using conical picks

There are several hybrid methods with conical picks that have been proposed. There are two types of hybrid methods that use water. The first uses water as lubrication to increase the number of tool rotations. This reduces the tool wear and make the tool wear more symmetrical. This increases the life of the tool and also generate less dust when cutting.

The second type of hybrid method that uses water is rock breaking using a conical pick that is assisted by an abrasive water jet. The abrasive water jet is used to weaken the strength of very hard rock. This decreases the force required by the conical pick and thus decreases the amount of tool wear.

The rotation of a conical pick while cutting rock is very important. Without the rotation the pick wears unevenly and much faster compared to a pick that rotates. The geometry of the conical pick, the mounting of the pick inside the holder and the holder itself is very important to ensure rotation of the conical pick. If the above-mentioned design considerations are not properly met, improper tool operation can occur that can lead to blocking of the rotation of the tool in the holder which will lead to very fast tool wear.

As mentioned before, the main reason for uneven tool wear is the lack of tool rotation. This is due to the stagnation of cooperation conditions between the inner surface of the holder sleeve and the tool shank surface. The stagnation is due to particles of dust and/or small grains of output, penetrating both the inner surface of the holder sleeve and the tool shank surface. A team from AGH University of Science and Technology in Cracow attempted to force lubrication in-between the inner surface of the holder sleeve and the tool shank surface (Kotwica, 2018). They used both emulsion and clean water as lubricant. In both cases the surfaces were free of impurities such as dust.

Kotwica tested the performance of a new holder that uses forced lubrication against conical picks without forced lubrication, water jet assisted cutting where the water jet is in front of and behind the conical pick (Kotwica, 2018). The tests were conducted using concrete with an uniaxial compressive strength of about 105 MPa. The lubricated tool holder performed the best due to the increased number of tool rotations and even wear was observed. Figure 1.14 shows the four conical picks after cutting approximately 2500 m. The cutting depth remained the same for all the tests at 9 mm.

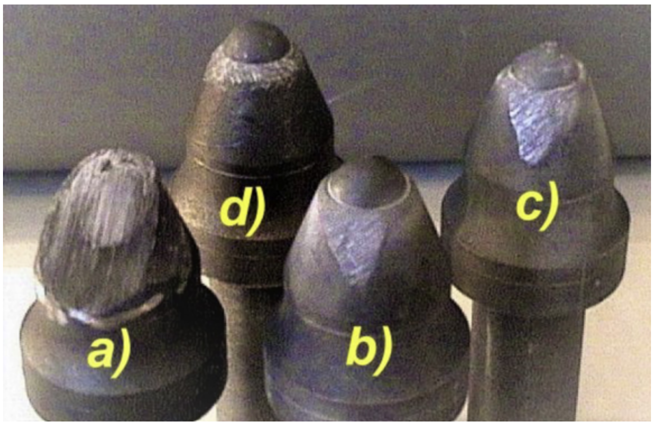


Figure 1.14: (a) no lubrication (b) water jet assisted at the front of conical pick (c) water jet assisted behind the conical pick (d) with lubrication (Kotwica, 2018)

The tool wear was measured using an optical microscope. This allowed the imaging of the tool profile. The imaging of the tool profile allowed the measuring of volumetric tool edge wear and also the wear character (is the wear even or uneven). The results showed that a conical pick without lubrication failed miserably, not only did the carbide insert wear unevenly, part of the tool head also experienced catastrophic wear. Both cases of water jet assisted cutting had considerably less wear than just the conical pick but uneven wear were observed which can lead to faster tool wear. The tool holder with lubrication showed the best results with even wear that will lead to longer tool life.

Liu and co-workers determined that conical picks assisted by an abrasive water jet (AWJ) decreased the cutting resistance and specific energy (Liu et al., 2020). The water jet creates a kerf and the conical pick makes a fracture pit. The kerf and fracture pit are shown in figure 1.15. The kerf and fracture pit reduces the resistance of the secondary cut, a cut with a conical pick that is not assisted by the AWJ but in the same line as the first cut just at a larger depth. Using the AWJ the stability of the cutting resistance is improved, reducing the impact fracture and wear of the conical pick leading to a longer tool life.

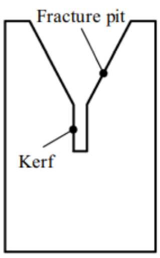
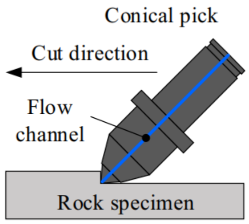
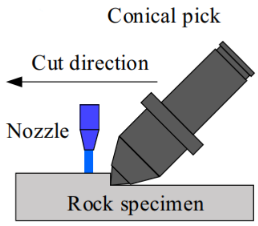


Figure 1.15: Fracture pit and kerf (Liu et al., 2020)

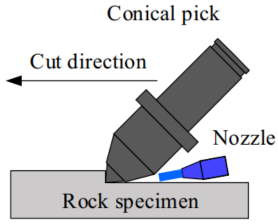
The position of the AWJ is important and influences the performance of the rock cutting. Liu and co-workers proposed four different configurations of conical pick and AWJ. Figure 1.16 shows the four proposed configurations.



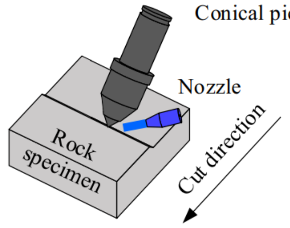
(a) Jet through the conical pick



(b) Jet placed in front of the conical pick



(c) Jet placed behind the conical pick



(d) Jet placed at the side of the conical pick

Figure 1.16: Proposed configuration of AWJ assisted conical picks (Liu et al., 2020)

The study found that the jet through the conical pick preformed the best in reducing the resistance force. The jet placed at the side of the conical pick performed the worst and the jet in font of the conical pick performed the second best. For further optimization of parameters the study only used the jet through the conical pick and changed parameters to determine the optimal parameters for the AWJ assisted conical pick.

The abrasive particle size was changed to ensure that the particle had enough kinetic energy and produce a good rock breaking depth. The water pressure was also changed during the testing. The water jet pressure determines the depth of the kerf. The depth of the fracture pit and the water pressure has a linear relationship (Liu et al., 2020). The study conducted three tests for each set of parameters. The average of the tests was used as data for the given parameters. By doing this the study ensured that any deviation in the data did not effect the decisions of the optimal design parameters.

The study used the specific energy to determine the best water pressure, thus kerf depth, and the cutting depth of the conical pick. They also conducted a second cut to add to the consideration of optimized parameters. The study was only conducted by laboratory tests and was not tested on a large scale in a mine. The study found that the specific energy decreased as the water pressure was increased but at a certain water pressure the relationship between specific energy decrease and water pressure increase flatlines. The cutting resistance increased with an increase in cutting depth. The second cut was also assisted by the kerf that was created by the first cut, lowering the specific energy of the second cut.

New designs for drag/pick tools

Various researchers have optimized and redesigned the shape of a conical pick to cut very hard rock. Owing to the high hardness required by the pick, to cut very hard rock, chips occur that lead to breaking of the conical pick. Owing to the breaking of the conical pick when cutting very hard rock, a new cutting tool and holder is required.

The crown pick shown in figure 1.17 is an alternative drag/pick cutting tool. The crown pick uses the same tool holder as a conical pick. The circumference of the working part of the crown pick is armed with eight cone-shaped carbide inserts. The individual carbide inserts apply point pressure on the rock face that causes loosening of rock fragments (Kotwica, 2018). The non-uniform load acting on the individual carbide inserts will cause an increase in tool rotation speed at a smaller deflection angle compared to the normal conical pick.

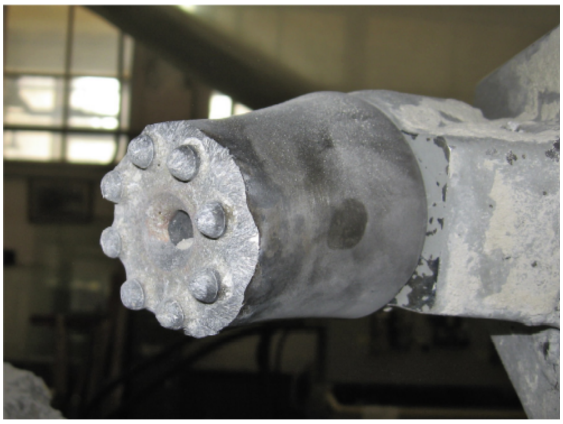


Figure 1.17: Crown pick with 8 carbide inserts with a diameter 8 mm, after a test of sample mining for a distance of 1200 m (Kotwica, 2018).

The crown pick was tested using a special laboratory test stand for single tool testing. The test measured and compared tool wear, load on the tool and the number of tool rotations. Eight different crown picks were compared. The different crown picks had different numbers of carbide inserts around the circumference of the working part of the tool. The size of the cone-shaped carbide inserts were different, as shown in figure 1.18.

Figure 1.18: Crown picks with different design parameters (Kotwica, 2018)

The results of the test were satisfactory. The crown pick showed minimal tool wear and significant number of tool rotations. The best crown pick has eight carbide inserts with a diameter of eight millimetre. The crown pick can be used on normal roadheaders and continuous miners that have the standard conical pick tool holders. The research does not optimize any other design parameters such as attack angle or skew angle.

1.4.7 Roller cutting tools

Cutting very hard rock causes extensive wear on the cutting tool which leads to different wear related problems. Cutting with static pressure is the second most common method of mechanical excavation. The cutting is done by crushing the rock with a disk, usually a symmetrical disk. The disk edge is driven into the rock face with a large pressure force that is perpendicular to the rock face. The main problem with this type of mining method is the requirement of a large pressure force (Kotwica, 2018). This leads to extremely large and heavy machinery that are able to provide the required pressure force (Sifferlinger, Hartlieb and Moser, 2017).

Cutting with static pressure can also be done using an asymmetrical disk. Asymmetrical disks are more commonly used in undercutting mining method. Asymmetrical disk tools have been used for longwall shears to increase the output of large size grade. Using an asymmetrical disk in the method of undercutting allows for lower energy consumption and pressure forces. This in return makes the machinery smaller and lighter.

Undercutting

Undercutting is a mining method where the rock is cut towards a free breaking face. Similar to conical picks, the disk attacks the rock face tangentially, but the main difference is that the sliding friction caused by the conical pick is eliminated and rolling friction is added due to the rolling movement of the disk. Figure 1.19 shows the mining method of undercutting. The disk is free to rotate. Usually six to eight cutting disks are mounted on a plate that is driven while cutting.

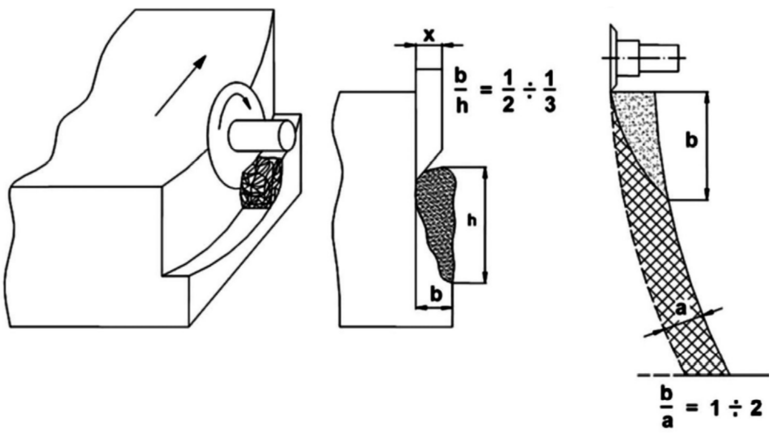
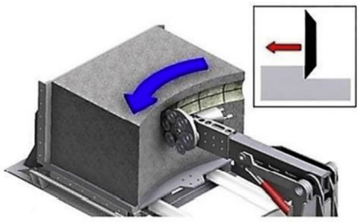
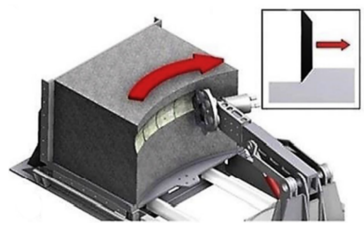


Figure 1.19: Undercutting mining method (Kotwica, 2018)

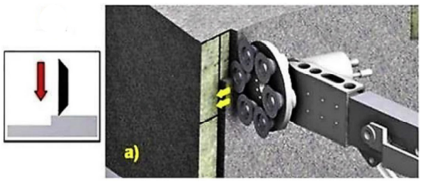
There are various methods of undercutting. Undercutting can be done vertically or horizontally and the orientations of the asymmetrical disk can also vary. Figure 1.20 shows the variations of undercutting methods.



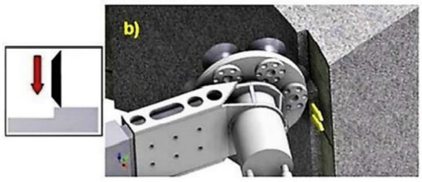
(a) Horizontal cutting with flat surface of disk attacking the rock body



(b) Horizontal cutting with inclined surface of disk attacking the rock body



(c) Vertical cutting with flat surface of disk attacking the rock body

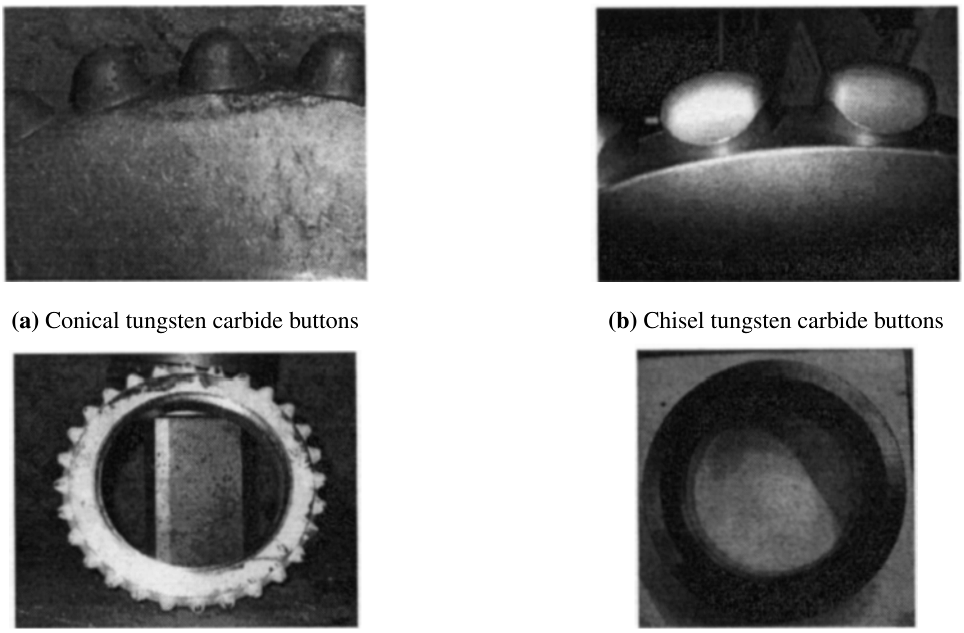


(d) Vertical cutting with inclined surface of disk attacking the rock body

Figure 1.20: Various methods of undercutting (Kotwica, 2018)

Tests were conducted for the various methods of undercutting to determine the best method. The rotation velocity of the plate was changed. The cutting spacing and cutting depth were changed to determine the best parameters for undercutting. They measure the output grain size, pressure force, cutting force and side force for the different tests. They found that vertical cutting produced larger output grain size than horizontal cutting. It was observed that when cutting vertically the rock chipped and when cutting horizontally the rock was milled (Kotwica, 2018). It was also found that better results were obtained when the flat surface of the disk attacks the rock body (Mendyka, 2017).

Lonmin Platinum, Voest Alpine and Sandvik Tamrock co-developed a narrow reef miner using undercutting. They found the process generated loads on the cutter disk and cutter bearings that are distinctly different to loads generated by conventional cutting (Moxham, 2004). The loads generated caused disk and bearing failure at first. Various disk designs were used in the testing of the narrow reef miner. Figure 1.21 show some of the disks used in the tests.



(a) Conical tungsten carbide buttons

(b) Chisel tungsten carbide buttons

(c) Ring with tungsten carbide buttons

(d) Steel disk

Figure 1.21: Various disks for undercutting (Moxham, 2004)

The tests found that disks with conical tungsten carbide buttons performed the best in terms of wear, cutting rate and condition of cut material. The normal steel disk performed the best when just comparing cutting rate and condition of cut material but the steel disk wore out extremely fast. An increase in effectiveness of the cutting process was achieved when the number of cutters on the head were increased.

1.4.8 Narrow reef hard rock mining

The mining process in narrow reef hard rock, in South Africa mostly platinum and gold mines, has not changed over the last century (Pickering, 2007). Narrow reef hard rock mining requires the use of ultra-low profile (ULP) mining equipment. The ULP mining equipment must operate in stoping widths between 90-120 cm (Fourie et al., 2014). In South Africa most of the gold and platinum reefs are tabular in nature with a reef width of less than 1 m (Moxham, 2004). Narrow reef hard rock mining, as for any mining operation, is dangerous and requires certain services and infrastructure. Current narrow reef hard rock mining operations aim to reduce the number of personnel need at the face of the rock that is being cut, this will improve safety. The personnel are separated from the hazardus areas by using remotely operated machines.

Various mechanized mining equipment are used in narrow reef hard rock mining. The equipment are required for both on-reef pre-development as well as for the selected mining method. In South Africa the mining methods still require blasting to break the rock. Anglo American Platinum uses a scattered breast mining stoping method. The method consists of a ULP dozer and ULP sweeper, ULP roof bolting, ULP face drilling, charge up and blast then the cycle is repeated. Anglo American Platinum commissioned the development of a ULP fleet in 2011. The ULP fleet is capable of operating in stoping widths between 0.9 and 1.2 m at dip angles up to 22°. The fleet can operate at depths between 350 and 1800 m. Figure 1.22 shows the ULP fleet.

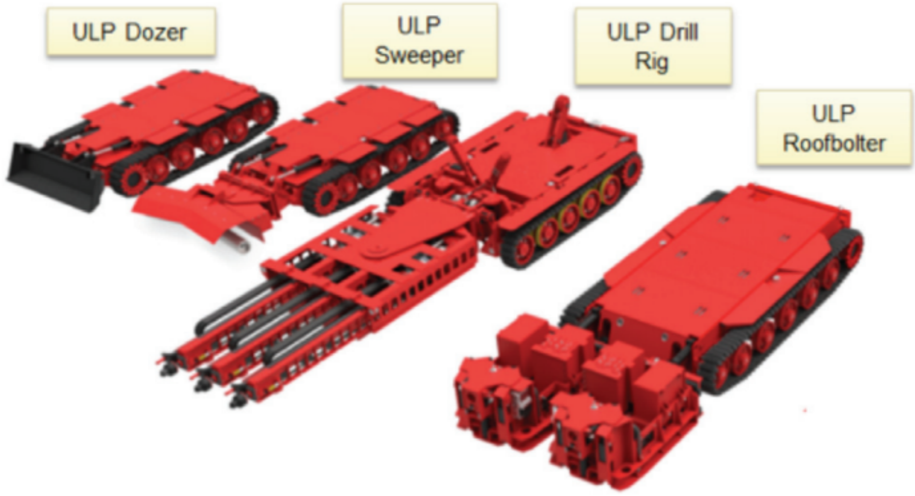


Figure 1.22: ULP fleet (Fourie et al., 2014)

As mentioned before, each of the equipment in figure 1.22 has a dedicated purpose. The ULP dozer and ULP sweeper are both cleaning tools. The ULP dozer clears the mined material from the stopes. The ULP sweeper is used for sweeping tasks in the stopes where the ULP dozer would not reach. The ULP drill rig drills the holes for the explosives and the ULP roofbolter is used to install hangingwall supports. The design and operation layout of the ULP fleet was conducted in such a manner to improve safety, sustainability and productivity but in a cost effective way.

South Africa requires non-explosive methods of rock breaking to replace the traditional drilling and blasting method. The soft rock mining industry illustrated that cutting the rock in a continuous manner is more cost-effective and safer. By using non-explosive mining methods in narrow hard rock reefs the safety of the personnel will increase by removing the damages to the stope that occurred due to the blasting and personnel will be removed from danger. The personnel will not be required to conduct arduous forms of work and more interest will be sparked for the development of mines and mining equipment creating jobs and innovation. The cutting will also lead to better control of the stope width and thus decrease dilution.

In 2001 Lonmin Platinum, Voest Alpine and Sandvik Tamrock co-developed and tested a narrow reef miner that used undercutting as the method of mining. Figure 1.23 shows the ARM 1100 prototype, the narrow reef miner.

Figure 1.23: ARM 110 prototype (Moxham, 2004)

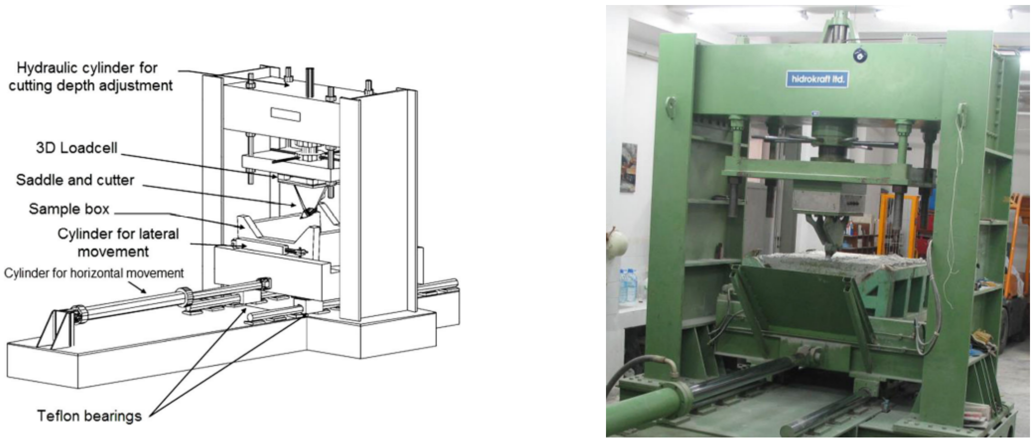
The main purpose of the testing was to illustrate that it is possible to cut hard rock within the size constraints of a reef and that a non-explosive mining method can be feasible in terms of cutter life.

1.4.9 Laboratory scale rock cutting testing equipment

Numerous studies have been conducted using different laboratory scale rock cutting equipment. The purpose remained the same for all the equipment. To cut rock on a small scale to better understand rock breaking mechanics and to optimize design parameters of the cutter.

The literature above described the parameters that can be optimized for the different excavation methods. Some laboratory scale rock cutting equipment is for conical picks, some for disk cutting, either undercutting or crushing, and others are able to conduct testing for both methods. The design of the laboratory scale rock cutting equipment depends on the type of excavation method, the size of the rock specimen, the parameters that are required to be optimized and the rock conditions that the test requires, such as lateral forces to simulate underground cutting conditions.

Copur and co-workers (2017) used the laboratory scale rock cutting equipment shown in figure 1.24 for their tests.



(a) Schematic view **(b)** Photograph

Figure 1.24: Laboratory scale rock cutting equipment used by Copur and co-workers (2017)

Copur and co-workers (2017) used full-scale linear cutting testing equipment. They decided to conduct full-scale tests to diminish the uncertainty that can be caused due to scaling. The full-scale tests also reflects the behaviour of the rock cutting better than small-scale tests. The rock specimen that was used for the testing was cast in concrete within the sample box. The size of the rock specimen that was cast into the concrete was 70 $\times$ 100 $\times$ 50 cm. They used other samples of the same rock to determine the rock properties.

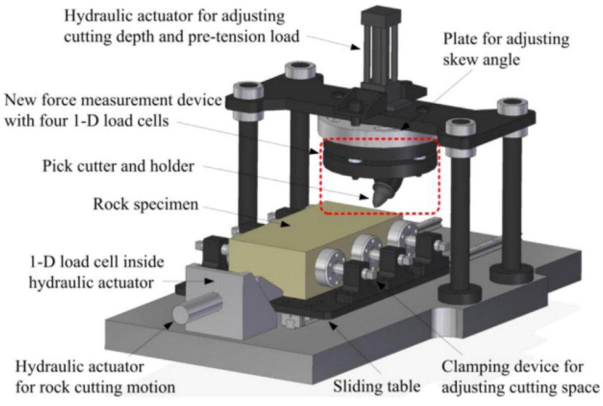
The testing equipment uses a servo controlled hydraulic cylinder to move the sample box at a constant velocity, either 25.4 or 12.7 cm/s. Other parameters such as cutting depth and cutting spacing can be adjusted by hydraulic cylinders. A 3-D loadcell was used to measure the orthogonal forces acting on the tool. The testing sequence worked as follows:

- Make cut.
- Collect cut material.
- Measure cut length.
- Weigh cut material.
- Sieve cut material.
- Move rock box by certain spacing to simulate multiple cutters on cutter head.
- Repeat cycle.

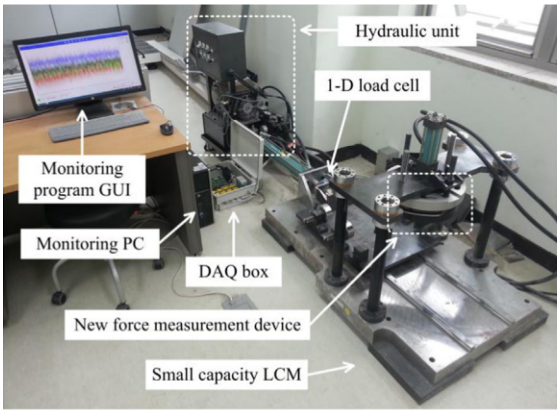
The cut material was sieved to analyse the size of the muck samples and to determine the coarseness index. The cuts were replicated three times. The cut surface was also photographed. A minimum sampling rate of 1000 Hz for the load cell was used. The 3-D load cell was directly connected to the tool holder and the load cell was calibrated with a hydraulic jack prior to the testing. The three forces that need to be measured are the cutting force, normal force and side force.

The cutting force is parallel to the horizontal plane and in the direction of the cutting. The cutting force is used to determine the specific energy and also relates to the torque needed by the excavation machine. The normal force acts perpendicular to the horizontal plane and the direction of the cutting. The normal force is used to determine the required mass and thrust of the excavation machine to maintain a certain cutting depth. The side force is perpendicular to the normal force and the direction of the cutting. All three forces are used to balance tool lacing, this will minimize machine vibrations (Copur et al., 2017).

Park and co-workers designed and manufactured a small-scale linear cutter as shown in figure 1.25 (Park et al., 2018).



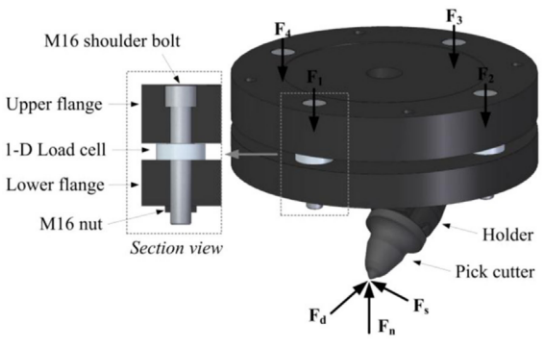
(a) Schematic view (Park et al., 2018)



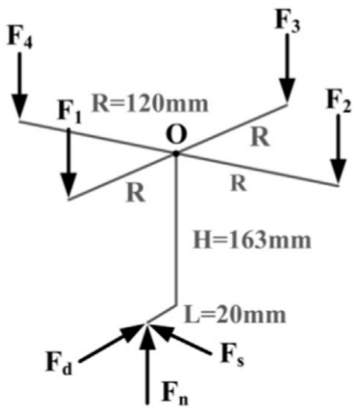
(b) Photograph (Kang et al., 2016)

Figure 1.25: Laboratory scale rock cutting equipment used by Park and co-workers and designed by Kang and co-workers.

Park et al.(2018) did not use rock specimens but rather cement mortar samples that are 300 × 200 × 200 mm. They conducted uniaxial compression tests to determined the strength of the cement mortar sample. Park also used a hydraulic cylinder to move the sliding table. The depth of cut and skew angle could be changed by a hydraulic cylinder. Kang et al.(2016) proposed the force measurement device, load cell configuration, used by Park and co-workers (Kang et al., 2016). The force measurement device consists out of four 1-D load cells that are arranged as shown in figure 1.26. The force measurement device reduces cost of the small-scale linear cutter and performed with acceptable accuracy.



(a) Force measurement device (Kang et al., 2016)

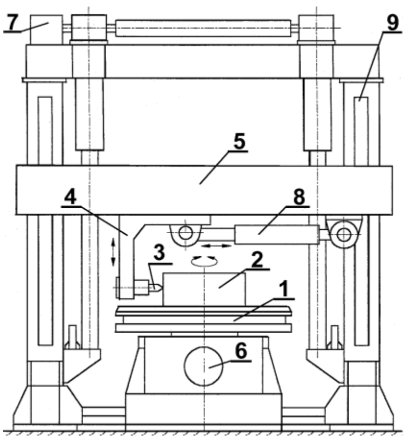


(b) Force vectors (Kang et al., 2016)

Figure 1.26: Kang and co-workers force measurement device (Kang et al., 2016)

They performed finite element analysis on the small-scale linear cutter to ensure that it is stable and stiff enough for the expected forces that will act on the small-scale linear cutter. The finite element analysis was also conducted to do an initial calibration for the small-scale linear cutter. For the actual tests preconditioning was performed on the cement mortar sample by pre-cutting the sample to simulate a rock face that was already cut by a roadheader. They measured the forces and weighed the cut material and measured the length of cut after each cut. The measured forces were then used to calculate the cutting force, normal force and side force by using the force vectors in figure 1.26b.

Mendyka(2017) designed and manufactured a laboratory scale cutting stand for testing individual mining cutting tools. Mendyka performed undercutting tests and drag/pick cutting tool tests with the laboratory scale cutting stand. The laboratory scale cutting stand is shown in figure 1.27.



(a) Schematic view (Mendyka, 2017)

(b) Photograph (Mendyka, 2017)

Figure 1.27: Laboratory scale rock cutting stand by Mendyka

The numbers in figure 1.27a correspond to the following.

1. Rotary table.
2. Rock sample.
3. Cutting tool.
4. Slide support.
5. Horizontal platform for the slide support to move on.
6. Hydraulic motor.
7. Hydraulic motor.
8. Hydraulic actuator.
9. Vertical columns

The cutting tool can move up and down with the vertical columns. The cutting tool can also move horizontally with the slide support and the hydraulic actuator. The hydraulic motor 6 drives the rotary table. The laboratory scale rock cutting stand is intended for continuous cutting on the peripheral surface of rock samples. The flat top surface can also be cut by a symmetrical disk with the method of crushing.

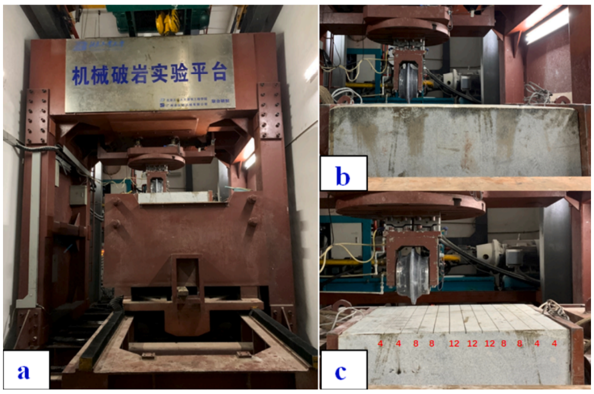
The laboratory scale rock cutting stand investigates tool wear for a continuous period. There are force measurement devices to determine cutting force, normal force or side force. Figure 1.28 shows some of the force measurement devices that were used for undercutting and cutting with a conical pick.

(a) Conical pick.

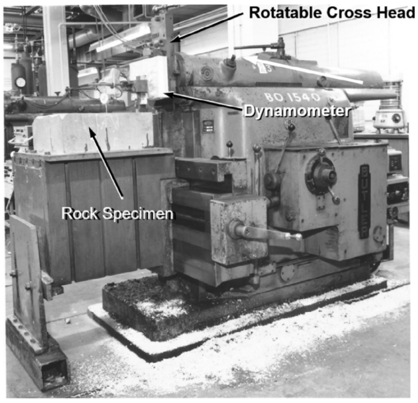
(b) Undercutting.

Figure 1.28: Fore measurement devices, load cells (Kotwica and Gospodarczyk, 2003).

There are numerous laboratory scale cutting equipment from different researchers as shown in figure 1.29. The different laboratory scale cutting equipment feature varied levels of complexity in operations and in the cutting toll design.

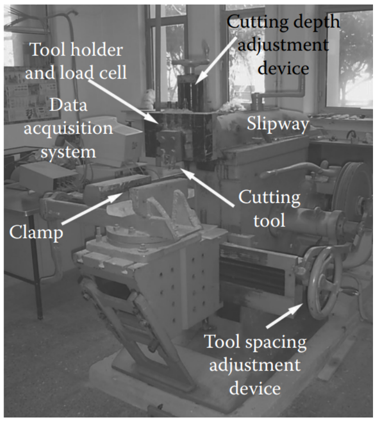


(a) LCM from (Li et al., 2022)



(b) LCM from (Hekimoglu, 2018)

(c) LCM from (Dehkhoda and Detournay, 2019)



(d) LCM from (Bilgin, Copur and Balci, 2013)

Figure 1.29: Numerous laboratory scale cutting equipment.

1.4.10 Numerical modelling of rock cutting

The advancements of technology and computational power allows for the simulation of rock cutting, determining tool forces, tool-rock interaction and specific energy. There are three main methods for numerically modelling rock cutting, finite-element method (FEM) (Huang et al., 2016; Jaime et al., 2015; Wicaksana, Jeong and Jeon, 2021), discrete-element method (DEM) (Kalogeropoulos and Michalakopoulos, 2021; Stopka, 2021; Su and Akcin, 2011; Van Wyk et al., 2014; Zou, Yang and Han, 2020) and a combination of both FEM and DEM (Zárate and Oñate, 2015).

The various methods offer different advantages and disadvantages. Most of the numerical modelling for rock cutting are either for conical picks or symmetrical disk cutting used for TBM (Stopka, 2021). There is little numerical modelling for rock cutting using asymmetrical disk.

The level of complexity of numerically modelling rock cutting using FEM can be changed by using different rock failure models. The basic model is Mohr-Coulomb failure criteria, whereas more advanced models are Concrete damage model, Johnson Holmquist concrete model, or the continuous surface cap model. Jaime used all the advanced models and found that the continuous surface cap model performed the best (Jaime et al., 2015). Commercial FEM software implements some of these models of failure. Simulations of rock cracks and fragmentation can be conducted by using the basic or advanced models.

DEM is an assembly of discrete particles that can move independent of one another and can interact with one another.

Various researchers have used both FEM and DEM to model rock cutting to optimize the tool parameters and determine required tool forces. The difference between the approaches used by researchers was how they used the method in terms of failure criteria, tool geometry, verification of results, parameters used, parameter calibrations and the commercial software used.

Huang et al. (2016) and Su and Akin (2011) compared FEM and DEM models for rock cutting using a conical pick. Huang et al.(2016) performed the FEM analysis and Su and Akin (2011) the DEM analysis. They compared the mean cutting force and the peak cutting force obtained from the simulations to one another and to theoretical values, that was determined by using the equation of Evans (1962) and Goktan (1997), and experimental values.

The results showed that both the DEM and the FEM simulations were in good agreement with one another. Both simulations were closer to the theoretical values of Goktan. The simulations did not predict the experimental values accurately as can be seen in table 1.1.

In this table FN is the mean normal force, FD is the mean drag force, FN' is the mean peak normal force, FD' is the mean peak drag force, FD'_{Evans} is obtained from using Evans' equation and FD'_{Goktan} is obtained from using Goktan's equation.

Table 1.1: Numerical, theoretical and experimental results for Sandstone-1 (Huang et al., 2016; Su and Akcin, 2011).

d (mm)	FEM Simulations				DEM Simulations				Theoretical		Experimental results			
	FN	FD	FN'	FD'	FN	FD	FN'	FD'	FD'_{Evans}	FD'_{Goktan}	FN	FD	FN'	FD'
3	0.46	0.58	0.67	0.96	0.24	0.37	0.7	1.07	0.3	0.63	4.4	3.9	8.8	9.1
6	1.62	2.06	2.27	3.14	1.19	1.34	1.92	3.08	1.18	2.53	6.7	6.7	14.5	18.2
9	1.91	3.66	3.6	8	1.84	3.18	3.16	6.23	2.66	5.69	8	8.8	21.5	28.1

The error between the numerical and theoretical values and the experimental values are due to the geometry of the conical pick and the wear of the conical pick. In the numerical simulations and theoretical calculations it is assumed that the tool is perfect with no tool wear and has a perfectly sharp tool point as shown in figure 1.30. The conical pick used in the experiment had a rounded point and had some tool wear.

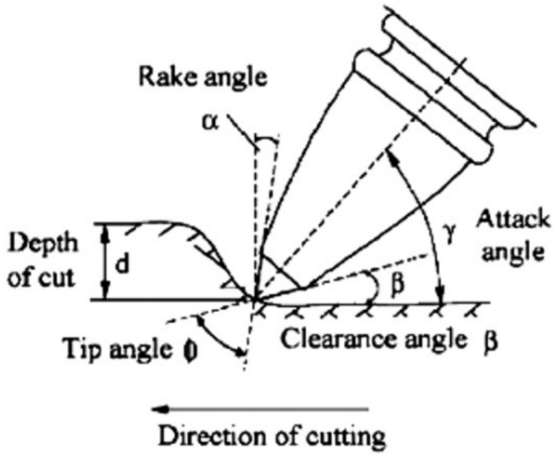


Figure 1.30: Tool geometry used for numerical simulations and theoretical calculations (Su and Akcin, 2011)

Su and Akin (2011) used PFC^{3D} to conduct the DEM simulations, Van Wyk (2014) also used PFC^{3D} to model tool-rock interaction for different tool types. Van Wyk found that the simulations took from one to five days to simulate 20 mm of cutting. Su only modelled unrelieved cuts for a conical pick and just changed the depth of cut. The rest of the parameters such as skew angle and attack angle remained the same. The micro-properties were calibrated by modelling the uniaxial compressive strength test in PFC^{3D} to get the required macro-properties. Because only an unrelieved cut was modelled a graded particle assembly was used as in figure 1.31. This graded particle assembly was used to lower computational power used.

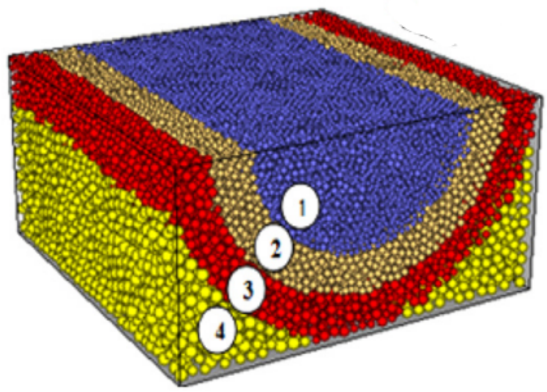


Figure 1.31: Graded particle assembly (Su and Akcin, 2011)

The layers numbered 1 to 4 has different particle radii were 1 has the smallest and 4 the largest. As shown in table 1.1 the DEM simulation performed well compared to the theoretical values. Su found that although the numerical and experimental values differed, they displayed a good linear relationship (Su and Akcin, 2011). Thus the tool-rock interaction can be properly modelled using DEM but special attention must be given to ensure that all the factors such as geometry and tool wear are accurately simulated in the DEM model.

Kalogeropoulos and Michalakopoulos (2021) used Yade, a DEM software, to model tool-rock interaction. The cutting tool was a drag pick tool that resembles a chisel pick. They used a different method of calibration to optimize the rock properties. They determined lower-and-upper bounds for the micro-properties. The lower-and-upper bounds were used with a Plackett-Burman design to construct a dataset of different micro-properties and their associated mean cutting force. The dataset was used to determine a linear equation for the mean cutting force. A non-linear equation was determined with only the micro-properties that had the highest effect on the mean cutting force.

The error between the non-linear equation and the experimental result was used as the objective function and an inequality error constraint was applied with the linear equation. Sequential least squares programming (SLSQP) was used to optimize the micro-properties so that the micro-properties were optimal to predict the tool-rock interaction for the rock used in the experiment. This method of calibration gave extremely good results. But the numerical results were compared to the experimental results that were used to optimize the micro-properties. Thus it showed that using linear and no-linear equations to optimize the micro-properties gives micro-properties that can be used to interpolated accurately to the experimental results. But Kalogeropoulos did not change the depth of cut in the numerical simulation and experimental simulation to see if the optimized micro-properties will still work for the change in cutting depth.

Jaime et al. (2015) and Haung et al. (2016) used LS-DYNA3D software to FEM model tool-rock interaction, figure 1.32 illustrates the FEM simulation. Both used an algorithm of contact with erosion to model the tool-rock interaction. Haung et al. (2016) used hexahedron elements to discretize the model were Jaime et al. (2015) used tetrahedron elements to discretize the model. Jaime et al. (2015) found that using tetrahedron elements introduced randomness in the discretization that gave better fragmentation patterns, because hexahedron elements gave a mesh of regular pattern, and force history (Jaime et al., 2015). Both studies obtained good results that showed that FEM can be used to model tool-rock interaction.

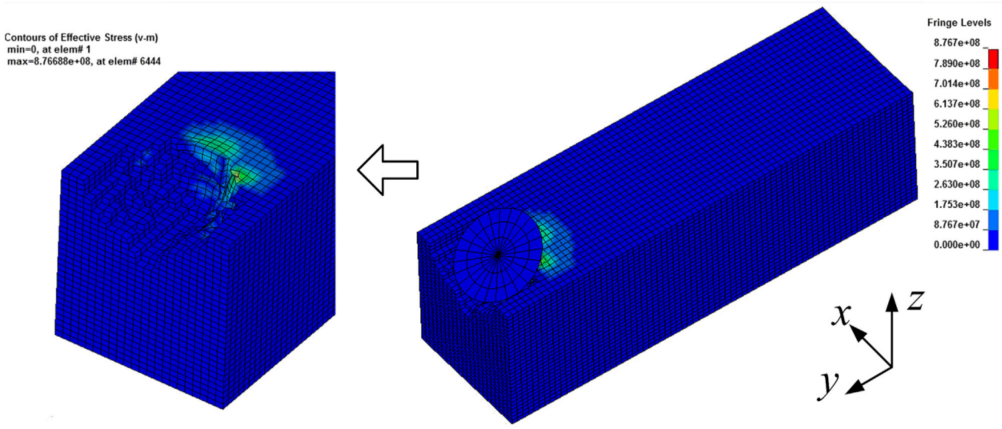


Figure 1.32: Transient stress nephogram for 3 mm of cutting depth of rock (Huang et al., 2016)

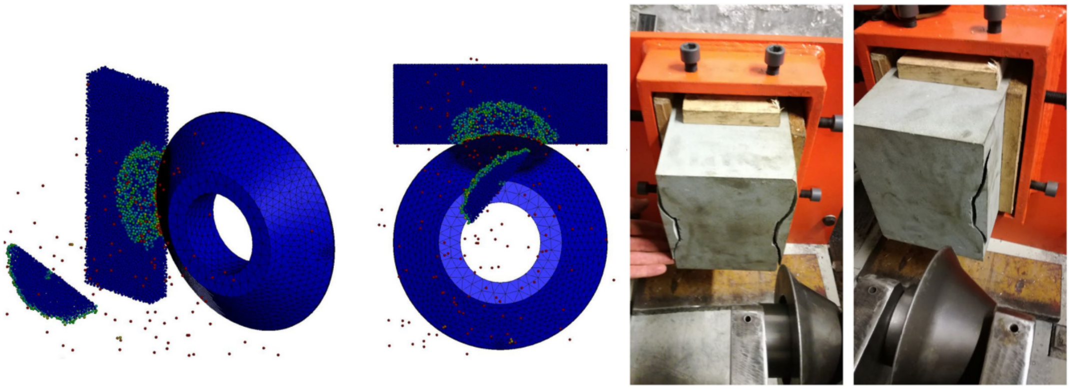
Both studies had shortfalls. In the study by Haung et al. (2016) deficiencies were that in the first part of the study, were FEM was compared to DEM, tool geometry error were made. In the second part of the study Haung adapted both Evans' and Goktan's equations to take lateral forces into account. The equations were compared to FEM simulations and experimental results. No geometrical errors were made in the second part of the study. Jaime et al. (2015) had the shortcoming of not adequately modelling the width of the rock that was being cut large enough which led to most of the element eroding at ones leading to zero forces being observed. When the width was increased the erosion problem vanished.

Wicaksana et al. (2021) modelled tool-rock interaction for conical picks on ANSYS AUTODYN, FEM software. They considered dynamical properties and quasi-static properties to determine which is more accurate. They also modelled unrelieved and relieved cuts. They concluded that rock cutting is a dynamic problem and should be modelled from a dynamic perspective (Wicaksana, Jeong and Jeon, 2021).

Using dynamic properties, the simulations gave better results and were closer to the experimental values. The study also showed good results for modelling relieved cuts which shows that it can be used to simulate a full scale cutter, but it will be computationally expensive. The values obtained from the numerical simulations were lower than the experimental values but the relationship remained the same. Thus, the numerical simulations can be used to make decisions such as ratio of cut spacing to cut depth, because although the value, obtained is smaller than the actual value the relationship remained the same.

Stopka (2021) used LS-DYNA, DEM software, to model tool-rock interaction for asymmetrical disk tools (Stopka, 2021). Stopka used the uniaxial compressive strength and Brazilian tensile strength to calibrate the model. The uniaxial compressive strength and Brazilian tensile strength were simulated with LS-DYNA and compared to the experimental results. Through trial and error, the micro properties were determined. The radius of the particles were made as large as possible, but still gave good results to lower the computational power required.

After the calibration, the disk rock interaction was modelled numerically and experimentally as shown in figure 1.33.



(a) Numerical modelling **(b)** Experimental modelling

Figure 1.33: Stopka numerical and experimental model (Stopka, 2021)

Two different rocks were modelled at different depths, sandstone at 20 mm and concrete at 15 mm. The simulation time for sandstone was between 65-70 hours and for concrete between 3-4 hours on a HP Z840. The results of the study showed that the numerical model performed well. Therefore the tool-rock interaction of a asymmetrical disk can be numerically simulated using DEM and that the simulations would provide good estimations of the tool forces.

1.5 Scope of research

The broad aim of the research presented here is to enhance the feasibility of mechanical cutting of hard rock such as UG2 reef. UG2 reef was selected as the test rock, as it is becoming the primary platinum reef being explorated. The Merensky reef is already mined out in many areas at shallow depths. While mechanized mining is already the favoured approach in soft rock environments, such as coal mines, it has not achieved the same success in hard rock environments.

If successfully implemented in hard rock settings, it has the potential to enable continuous mining operations, eliminating the cyclic nature of the current drilling and blasting process. This could not only contribute to more productive mining but will also improve safety for both personnel and equipment.

Mechanized mining can be done in various ways as evident from sections 1.4.3 and 1.4.4. In this work rock cutting with conical picks is investigated. As discussed in section 1.4.4 conical picks are common drag/pick type of tools. Section 1.4.6 shows that there is more research about rock cutting with drag/pick tools than other for methods such as undercutting. No research related to cutting UG2 reef samples with conical picks could be found. It is specifically in this area where the current work aims to add value to the understanding of mechanized mining in deep hard rock environments.

Section 1.4.6 shows, that in abrasive rock conical picks last longer, has less wear and if designed properly, even wear can be achieved. This is important in the light of section 1.4.6 which highlights the fact that drag/pick type tools mill the face of the rock, causing generation of dust, which is a safety hazard. The amount of tool wear can cause more tool wear and inefficiency of the equipment. Due to the large bending forces radial picks get damaged. Thus, conical picks are preferred over radial picks.

In this work the modelling of rock cutting with conical picks is therefore investigated numerically and experimentally.

For the numerical simulation, the student used the finite element method since he is focusing on the cutting process itself, rather than on the movement of the rock fragments directly after rock fracture. Section 1.4.10 underscores that the cutting forces represent the main results required from the numerical simulations.

The finite element analyses were done using the ANSYS LS-DYNA software with the continuous surface cap model. Section 1.4.10 determined that from all the basic and advanced material models to simulate rock cutting, the continuous surface cap model performed the best.

The linear cutting machine was designed to allow for change in cutting parameters such as cutting depth, cut spacing, skew angle and attack angle. Section 1.4.6 showed that these are the cutting parameters that can be changed to optimize rock cutting using conical picks. The results of the experimental cutting tests allow inference of the optimal cutting parameters for cutting rock samples found in deep hard rock environments.

Section 1.4.9 discusses various laboratory scale rock cutting testing equipment that has been used by previous researchers. It shows that the results required of the cutting process is the cutting forces and the volume of material cut.

For this study a radial arm drilling machine was modified so that it allows for all the changes in cutting parameters as well as recording the cutting forces and collection of the cut material. The recording of the cutting force was done by using a load cell that uses strain gauges to determine the forces.

Initial testing and commissioning of the machine was done using sandstone. Sandstone sample with little to no variance in strength on a millimetre scale could readily be purchased, and this made the sandstone ideal for initial troubleshooting and tests. An added advantage of the sandstone was that the uniaxial compressive strength was lower than the expected uniaxial compressive strength of UG2 and allowed some experience with the machine to be developed before commencing with the very limited number of UG2 rock samples.

Results from the experimental cutting tests are used to validate the numerical simulation results. For the numerical simulation one cutting depth is used to calibrate the material model parameters. A second cutting depth is then used to determine if the model extrapolates accurately. This demonstrates the extent to which the numerical simulation can be used to predict cutting forces. Results like these are required for future design investigations for mechanized mining equipment in South African deep hard rock environments.

This work represents an important building block towards mechanized mining in deep hard rock environments. It presents new knowledge about the cut-ability of UG2 when mined using conical picks. It also contributes to the plausibility of using finite element simulations for investigation of rock cutting in deep hard rock environments.

This study serves as a pivotal steppingstone in the journey toward mechanized mining within challenging deep hard rock environments.

1.6 Document overview

The dissertation comprises 5 chapters. Chapter 1 introduces the problem at hand and what is required to address the problem. A literature review shows what equipment and tools are currently being used in underground mines. It also identifies important design parameters to consider when designing underground mining equipment. The literature review gives an overview of both previous laboratory scale linear cutting machines that were used and the numerical simulations that were performed using different numerical simulation methods and software.

Chapter 2 covers the numerical simulation side of the dissertation. The chapter gives an overview of the material model that will be used and the parameters that can be changed of the material model. A validation study was done to show that the numerical simulation, with the material model, gives similar results as previous studies. The different parameters that can be changed in the model set-up was investigated to determine the effect of the parameter on the final result of the simulation.

Chapter 3 covers the design, manufacturing and testing of the linear cutting machine that are used in this dissertation. The chapter identifies the requirements of the linear cutting machine and how the actual machine full fills the requirements. The design and calibration of the load cell used is presented in the chapter. Lastly the chapter covers the testing of the linear cutting machine on sandstone. The testing ensures that the linear cutting machine operates as expected before UG2 reef samples are tested.

Chapter 4 covers the results obtained of cutting UG2 reef samples. The results are compared to the results obtained of cutting the sandstone samples. Conclusions are draw about the similarities and the differences between the two samples. Lastly, the chapter covers the set-up of the numerical simulation so that the numerical results resembles the experimental results.

Chapter 6 concludes the research. The chapter gives recommendations of future work towards more reliable modelling of rock cutting in deep hard rock environments.