Numerical Investigation of PDC Cutter – Rock Interaction using LS-DYNA and Design of Experiment

By

Paulo Faife Inocencio Americo

22328

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University Teknologi PETRONAS

32610 Bandar Seri Iskandar

Perak Darul Ridzuan

Malaysia

CERTIFICATION OF APPROVAL

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A project dissertation submitted to the

Mechanical Engineering Programme

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in partial fulfillment of the requirement for the

BACHELOR OF MECHANICAL ENGINEERING WITH HONOURS

Approved by,

____

Dr Tamiru Alemu Lemma

UNIVERSITI TEKNOLOGI PETRONAS

Persiaran UTP, Perak

April 2020

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and the original work contained herein have not been undertaken or done by unspecified sources or persons.

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Paulo Faife Inocencio Americo

ABSTRACT

To be able to predict how a certain process will happen before it happens is the trend in all the industry, enables one to be prepared for the future. In this line of thinking the current work is an attempt to simulate the drilling operation to understand the rock-cutter interaction with the aim of optimizing the conditions to reduce the cutting force process. The Simulation was conducted in LS-DYNA, where the cutter was treated as rigid tungsten carbide and the rock as sandstone. The rock was stationary, and the cutter was treated to move at constant speed, with fixed rake angle and cutting depth. Variable such as cutting speed, bake rake angle, depths of cut and friction coefficient were being changed in a scientific manner to study the effect of the parameters on the cutting force. The result showed that LS-DYNA simulate the rock cutting process with accuracy. From the results the most important factors affecting the cutting force are rake angle and depth of cut. From examination of the results, the ones that uses the least force have rake angle of 0 and depth of cut of 0.5mm, the optimum combination of rake angle and depth of cut would optimize the drilling process. What makes this work unique is the application of Design of Experiment (DOE) to deeply study how the parameters affect the cutting force and which parameters affect the process the most.

ACKNOWLEDGMENTS

I wish to express my sincere gratitude to my supervisor, Dr Tamiru Alemu Lemma, who without tire helped me like a baby throughout this long journey, he guided me, corrected me and encouraged me to work hard. Without his immense help the objectives of this work would not be achieved.

I want to give a special thank you for the university staff, some research scientists at the university, who in difficult moment of this journey helped me solve some errors in the simulation, without their help this work would not materialize.

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CHAPTER 1

INTRODUCTION

1.1.Background

In oil and gas industry, drilling is a process where a drill bit is used to bore a hole in rocks containing oil and/or gas. PDC bits is the most used drilling equipment and uses polycrystalline diamond compact (PDC) cutters to cut rock.

The following figures shows both drilling bit and PDC cutter.

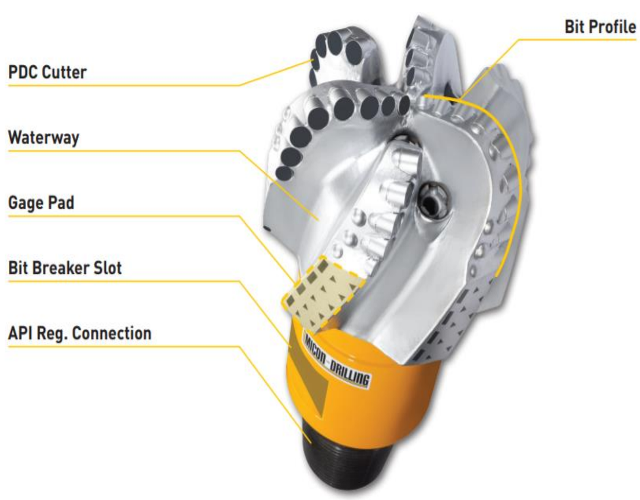


Figure 1.1: PDC Drill bit

Figure 1.1:PDC Cutter

In this project a single cutter rock cutting simulation is conduced, with model representing rock and cutter. The project focus is to validate rock cutting process in LS-DYNA and to analyse the cutting parameter with the aim of minimize the use of cutting force.

1.2.Problem Statement

To predict the condition that will maximize the efficiency of drilling process would be huge advantage because will save time and money needed in experiments. Doing rock cutting experiment is expensive and requires well equipped laboratory, the need to have a reliable numerical simulation to elucidate rock-tool interaction during rock cutting process is urgent. The rock cutting simulation field is quite new and without a well-established guide to conduct the drilling simulation. Most of the researches in this field does not follow a scientific method to study the interaction of drilling parameters such as cutting speed, depth of cut and rake angle.in this work a rock cutting simulation procedure will be developed and design of experiment will be used to study the effect of the variables in the force needed to cut.

1.3.Objectives

The objective is this project are:

i. To develop a model that properly simulates the rock cutting process;

ii. To analyse the effect of depths of cut, rake angle, cutting speed and dynamic friction on the force

iii. To identify the conditions that minimizes the required cutting force

1.4.Scope of Work

This project is limited to the following condition:

- Single cutter simulation
- The rock is sandstone
- The cutter will be considered as rigid object
- The simulation platform is LS-DYNA.
- The input variables to be considered are the speed, depths of cut, rank angle and Friction coefficient
- The simulation setup was done using Full Factorial Design of experiment (DOE).

CHAPTER 2

LITERATURE REVIEW

2.1.Rock-cutter interaction

After determining the rock properties, cutting parameters and cutter parameters, the only parameter that control the rock removal process is the cutting force [1].

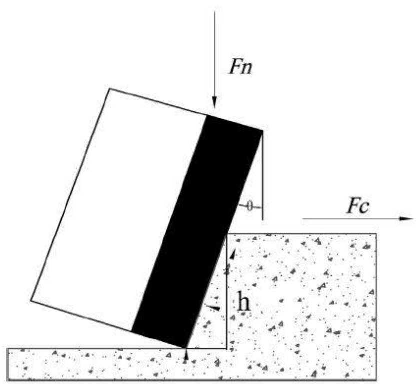


Figure1.2: Single cutting model

$$F_C = \frac{hl}{cos\Theta}\sigma_k$$

where F_C is the cutting force, h is the cutting depth, l is the width of cutter, θ is the cutting angle, σ_k is the cutting force per unit area.

2.2.Rock Failure Criteria

To conduct a rock cutting simulation is necessary a failure criterion, which is a mathematical model that represent the rock breaking behaviour. Huge number of failure criteria have been developed in the field of geo-mechanics and still being proposed by several researchers. As a user one should study the failure criteria to see if is suitable or nit. This review shows the most popular failure criteria used in geo-mechanics. The failure criteria are classified or based on stress, strain and energy [2].

Mohr-Coulomb failure criterion, this model is sorely used to model solid material and is most of the time represents sandy soils and other granular materials [3] . The Mohr-Coulomb criterion is a linear shear failure and according to [2] **is** characterized by two parameters: friction angle ∅ and cohesion *c*.

Another method similar to the Mohr-Coulomb is Drucker-Prager failure criterion and according to [2] it is often used because it creates a cone as failure envelope in the 3-D stress space instead of a six-sided pyramid in case of the Mohr-Coulomb criterion.

The next criterion which is very popular and simple is the Von-Mises failure criterion and according to [2] The criterion is often used in material sciences, especially as reference value for graphical presentations.

Mat_Damage_2 is failure criterion model ,available in LS-Dyna and characterized as an is an elastic viscoplastic material model combined with continuum damage mechanics (CDM)[3].

The Johnson/Cook model is normally (employed in cases where strain rate vary largely and adiabatic temperature increases due to plastic heating cause material softening.When the model is applied to solid material requires an equation of state [4].

Johnson-Holmquist model is mostly used for modelling material such as glass, ceramics, and other brittle materials [3].The model is available in LS-DYNA as Johnson-Holmquist Concrete and Johnson-Holmquist Ceramics , MAT_111 and MAT_110 respectively.

Continuous Surface Cap Model, is a visco-elastic-plastic damage model, used to model rock such as concrete and sandstone and other geologic materials[5]. Is available for solid elements in LS-DYNA as Mat_159**.** The advantage of this model if the fact that element erosion is incorporated in the model, excluding the need to manually add erosion option.

Table 1.2: Literature review on rock cutting simulation

Authors	Numerical method	Findings	Failure criterion	DOE
[6]	FEM rock cutting simulation	FEM simulates rock cutting and the fragmentation process very well	MAT_DAMAGE_2	Yes
[7]	FEM rock cutting simulation	There is no significant difference of simulated results between linear and circular cutting for all cutting regimes	Johnson-Cook in Ansys Explicit	No
[8]	FEM rock cutting simulation	Is advisable to used rake angle of +10° to get higher ROP with lower mean force	Drucker-Prager model in Autodyne	No
[9]	Discrete and finite element Method Simulation	DEM can be used to model tools in rock cutting operations and allows to reproduce simulation of tool wear	Mohr-Coulomb criterion	no

Authors	Numerical method	Findings	Failure criteria	DOE
[10]	Explicit FEM	keeping rake angle constant, the fragmentation of the rock decreases with increment of cutting speed.	Mat_Damage_2 in LS-DYNA	No
[11]	Explicit FEM	The simulation reflects the damage of coal-rock. Simulation and experiment are in perfect agreement	elastic-brittle-plastic constitutive model in Ansys/LS-DYNA	No
[5]	Explicit FEM	The result of cutting forces and the fragmentation process are reasonable	CSCM in LS-DYNA	No
[12]	Explicit FEM	fragmentation is observed, however chip separation did not occur in the simulation	(SPH)-based model in LS-DYNA	No

2.3.Rock cutting Simulation

Following are the commonly used numerical technique to model numerical simulation: The Finite Difference Method (FDM), Finite Element Method (FEM), Discrete Element Method (DEM), and the Boundary Element Method (BEM). Author in [15] investigated rock-cutter interaction using DEM (2D) ,where he analyzed failure behavior in cutting of rocks and indentation, he arrived to the conclusion that the rock fragments can be simulated using the DEM.

Investigation in paper [16] used a Boundary Element Method (BEM) to simulate cracks and chips formation process . The results showed that chips were being formed by either tension or shear, or their combinations. However, the limitation of the methods used by both investigators is the fact that they could not detect chip separation. In this project FEM (Finite Element modelling) will be used because according [6], explicit FEM method is widely used and is more advanced than the other methods. The advantage of FEM method is that the chip formation and separation can be seen [6].

LS-dyna is an FEM based numerical code, which can simulate dynamic, non-linear failure [6]. An assortment of mathematical models and simulation codes have been utilized in other researcher's work to the study cutter-rock interaction. LS-DYNA is a popular FEM software, used in [6], [10], [17], [18] to study rock fragmentation. LS-DYNA assimilate the usage of explicit non-linear finite element code. Author in paper [6] was able to simulate the single cutter simulation and the rock fragmentation was successful observed using LSDYNA. His Simulations were conducted by changing the rake angles at different cutting velocities and cutting depths. He also investigated the variation of cutting forces, stresses, rock fragment morphology and the character of fragment formation. The author of the study based on the results he obtained and compared with real data, he concluded that, the explicit FEM is a powerful tool for simulating rock cutting and the fragmentation process. The numerical model predicted the separation of rock fragments from the base rock slab more accurately. The cutting forces and rock fragment characteristics were strongly influenced by rake angle when compared to cutting tool velocities for a given depth of cut.

CHAPTER 3

METHODOLOGY/PROJECT WORK

3.1. Project Methodology

The current work is a simulation of rock cutting process by using Finite Element Method codes, LS-DYNA. Simulation of rock cutting process with single PDC cutter is conducted. There is quite a number of numerical simulation techniques, as mentioned in the literature review section of this project and the reason Finite Element is chosen over others is the fact that the chip formation mechanism can be observed, FEM method better method than the other methods [6].

In the current project the simulation is conducted by orthogonally move the cutting tool against stationary rock materials made of sandstone. The simulation setup is determined by Design of Experiment (DOE), and studies the effect of cutter velocity, cutter angle, depth of cut, and dynamic friction on the cutting Force.

Following are the assumptions used in this project.

- Single cutter simulation
- The rock is sandstone (damage 2)
- The cutter is tungsten carbide (rigid object)

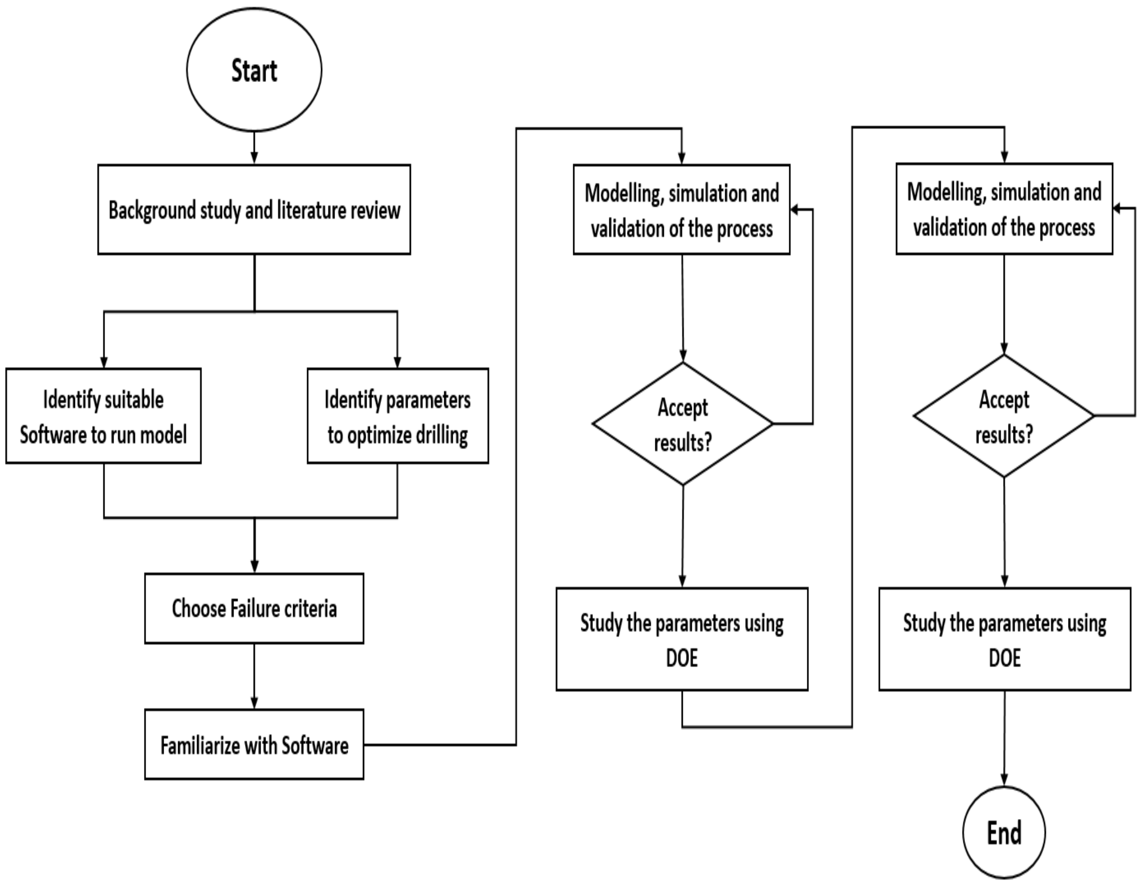


Figure 1.3: Project workflow

3.2.SIMULATION PROCEDURE

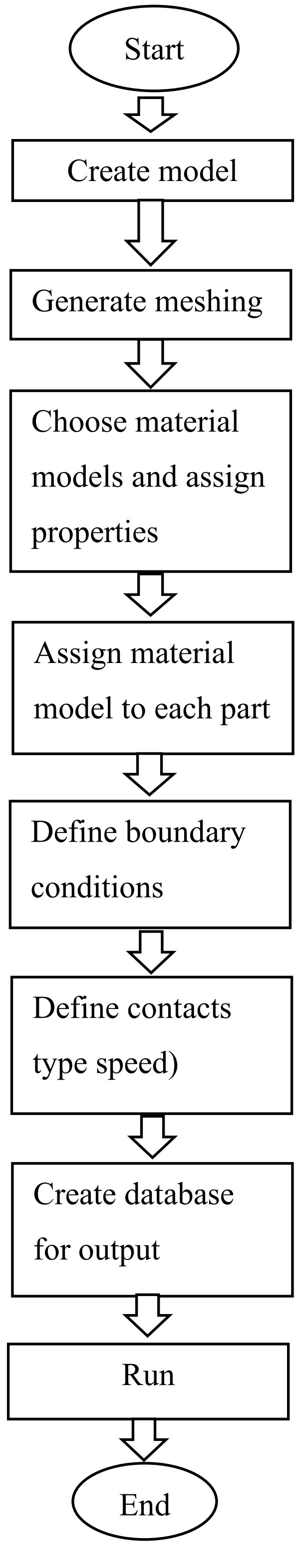


Figure 2.3: Simulation procedure

3.3.Gant Chart

Tasks	Weeks													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Selection of Project title	■													
Data gathering and literature review		■	■	■	■	■	■	■						
Proposal defence presentation									■					
Familiarization with Simulation software (LS-DYNA)									■	■				
Set material database as per the model parameters											■	■	■	
Interim report														■

Table 1.3:FYP-1 Gantt chart

Tasks	Weeks													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Literature review	■	■												
Simulation of the 2D rock cutting process			■	■	■	■								
Validation of the results						■	■							
Design of experiments								■						
Simulation of model using (DOE)									■	■				
Validation of the results											■			
Optimization of values												■	■	
VIVA														■
Dissertation submission														■

Table 2.3:FYP-2 Gantt chart

3.4.Key Milestones

- Milestone #1: Setup material database for cutter and rock. Due: 30/11/2019
- Milestone #2: Completion of the LS-DYNA model for single cutter simulation. Due: 14/02/2020
- Milestone #3: Completion of the DOE and simulation. Due: 25/02/2020
- Milestone #4: Completion of the final report and video presentation. Due: 9/04/2020

3.5.Model setup

3.5.1. The cutter

The cutter used in this simulation is from an actual PDC bit specification

Blade quantity	6
Primary cutter size	13.44mm
Total cutter	44
Rotary Speed	60-240RPM
Bit Weight on Bit	30-120KN

Table 3.3: PDC Bit Specification

The cutter material is tungsten carbide and is treated as Rigid body

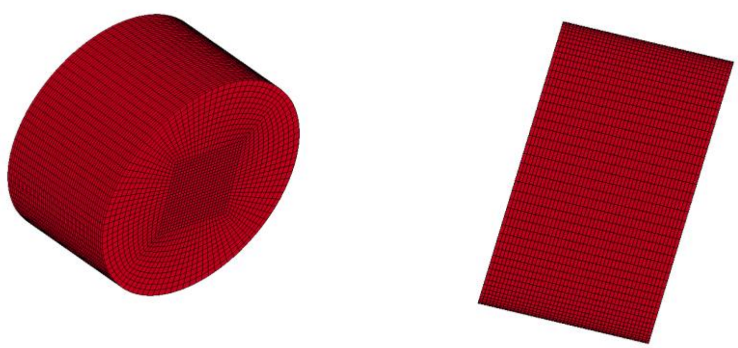


Figure 3.3: Cutter model

Diameter of the cutter: 13.44mm

Length of the cutter: 13.44mm

The meshing of the cutter generated: 51200 elements and 53833 nodes

The cut is assumed to be a rigid body with properties of tungsten carbide as the normal drilling cutter.

Cutter	Density(Kg/m^3)	Young modulus(GPa)	Poisson ratio
tungsten carbide	15630	615	0.31

Table 4.3: Input parameter for cutter in LS-DYNA(MAT_RIGID).

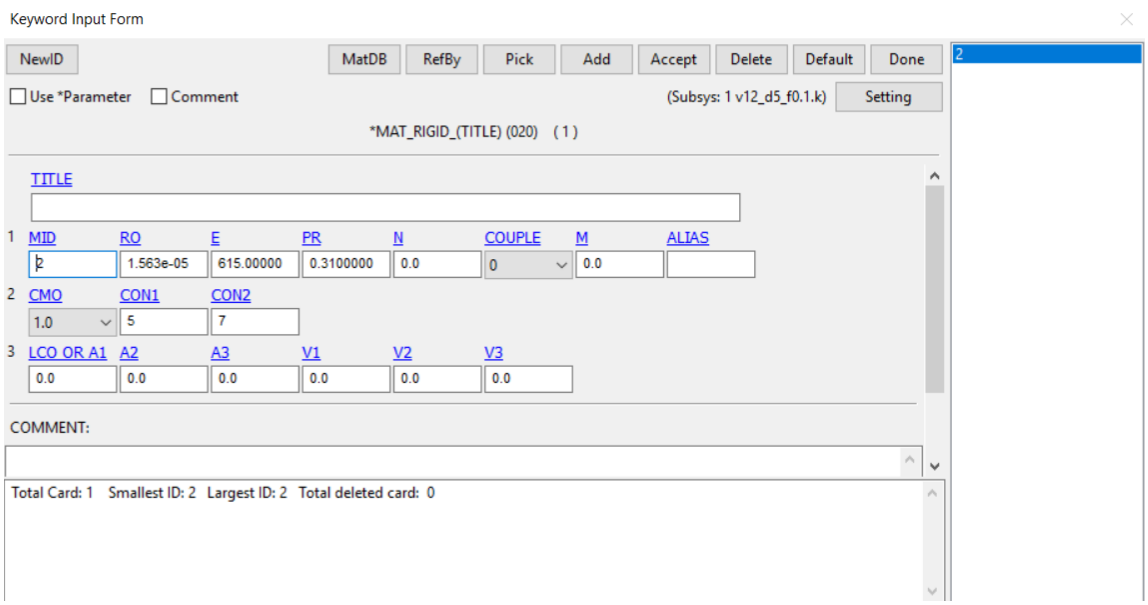


Figure 4.3: Ls-dyna keyword input mat-rigid

3.5.2. The Rock

The rock model is 42mm long, 12.6mm high and 8.4 mm wide. In order to save computational time a moderate meshing is done, with a smaller number of elements without compromising the accuracy of the results. The meshing below has 51200 elements and 53833 Nodes.

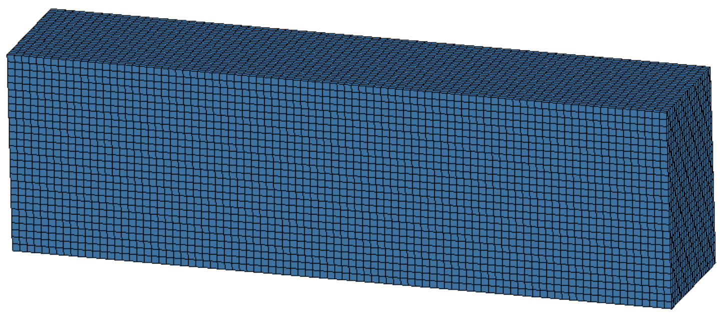


Figure 5.3: Rock meshing

Mat damage 2 model description

From literature review it was found that material model mat_damage_2, is ideal to model the rock because is possible to see the fragmentation of the rocks and is relativity faster than model such as Johnson Holmquist and Drucker Prager.

The effective stress is identified by:

$$\bar{\sigma} = \frac{\sigma}{1 - D} \quad (2)$$

Where σ is the stress tensor and D is the Damage Variable; the evolution equation for the damage variable is defined as below:

$$\dot{D} = \begin{cases} \frac{Y}{S(1-D)}\dot{r} \; for \; r > r_D \; and \; \sigma_1 > 0 \\ 0 \qquad for \qquad r \leq r_D \end{cases} \quad (3)$$

Where "r" is the damage accumulated plastic strain, "r_D" is the damage threshold, Damage effective plastic strain when material softening begins. "**S"** is the damage material constant, σ_1 is the maximum principal stress and Y is the called damage strain-to-energy release rate and $\dot{r}$ is damage governed by plasticity and is calculated from the following equation:

$$\dot{r} = \dot{\varepsilon}^{p}_{eff}(1-D) \quad (4)$$

$\dot{\varepsilon}^{p}_{eff}$ represents the effective plastic strain rate, Y is calculated with the following formula:

$$Y = \frac{\sigma_{eq}^2 R_v}{2E((1-D)^2} \quad (5)$$

Where the σ_{eq} is the equivalent von mises stress and **E** is the elastic modulus, R_v is the triaxiality variable and is defined as a function of the Poisson's ratio and hydrostatic pressure p

$$R_v = \frac{2}{3}(1+v) + 3(1-2v)\left(\frac{p}{\sigma_{eq}}\right)^2 \quad (6)$$

According [3] strain rate may be accounted for using the Cowper and Symonds model .

$$1 + \left(\frac{\dot{\varepsilon}}{C}\right)^{1/p} \quad (7)$$

Where $\dot{\varepsilon}$ is the strain rate and is calculated from $\dot{\varepsilon} = \sqrt{\dot{\varepsilon}_{ij}\dot{\varepsilon}_{ij}}$ (8),

C and p are user defined.

Damage parameters	Values
Damage threshold (r_D)	0.003
Damage strength (S)	1.0
Critical damage value (D_c)	1.0x10^{-3}

Table 5.3:Damage parameters Values to input in LS-DYNA Mat_105[19]

The rock is assumed as sandstone

Rock materials	**ρ(kg/m^3)**	**E(GPa)**	**v**
Sandstone	2200	29.9	0.31

Table 6.3:rock properties[20]

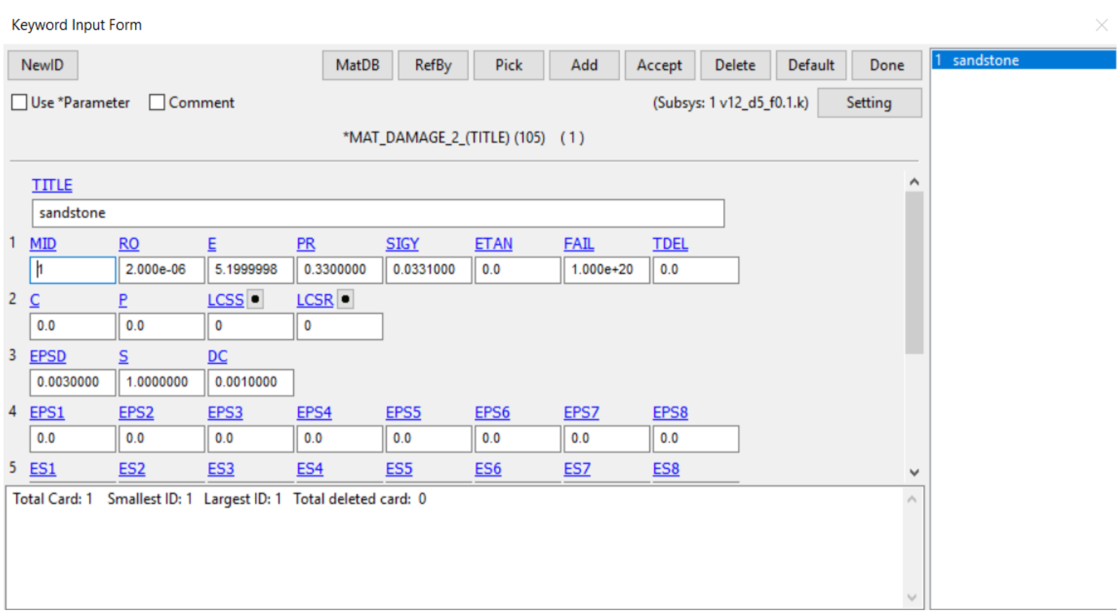


Figure 6.3:LS-DYNA keyword input MAT-105

3.5.3. Important factors to simulate rock cutting process

In LS-DYNA keyword CONTACT is used to setup the interaction between different parts. In this case the parts are cutter and the Rock. Both Eroding Nodes to Surface and Automatic Nodes to surface contact can be used to treat the cutter-rock interaction, but since erosion is needed to simulate the fragmentation, the eroding nodes to surface was chosen to treat the rock and the cutter interaction in this investigation. The cutter was set as the master and the nodes created at the top portion of the rock as the Slave as implemented in [20].

According to [20] is necessary to add a contact option to treat the rock-rock interaction in order to update the contact surface. The suitable contact to treat the interaction is eroding single Surface. Since the interaction is among rocks, only the rock was set to be slave.

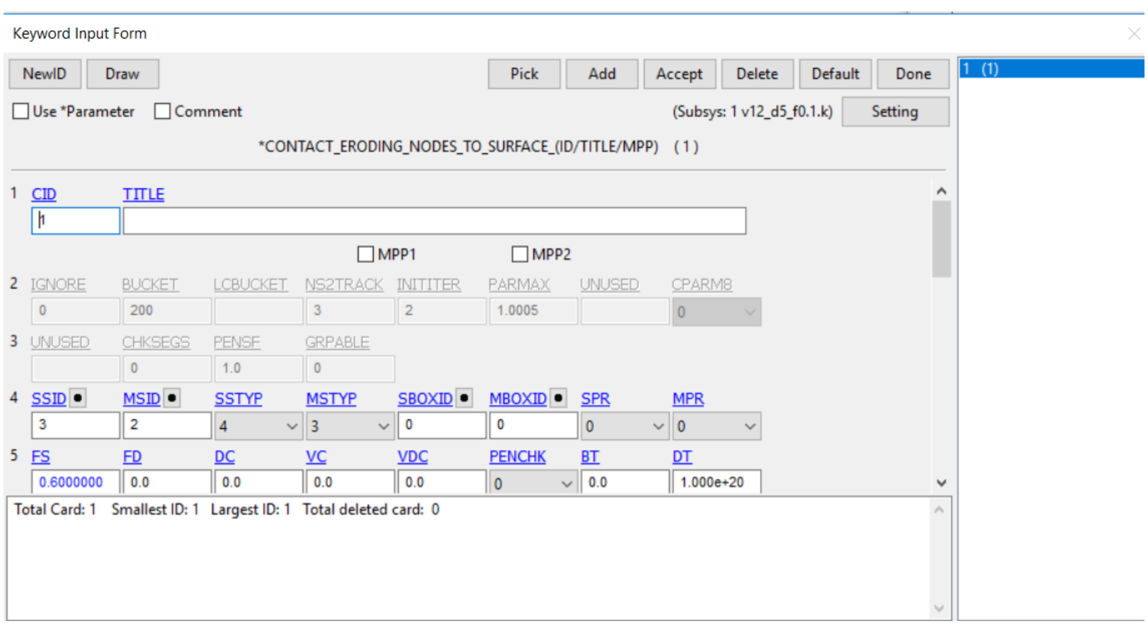


Figure 7.3: LS-DYNA Contact keyword

In LS-DYNA most of the rock material model does not automatically enables the erosion of the elements, in order to have the fragmentation it is necessary to activate Mat Add Erosion from and choose the erosion criteria, Minimum principal Strain was chosen and set -0.5.As can be seen in the figure.

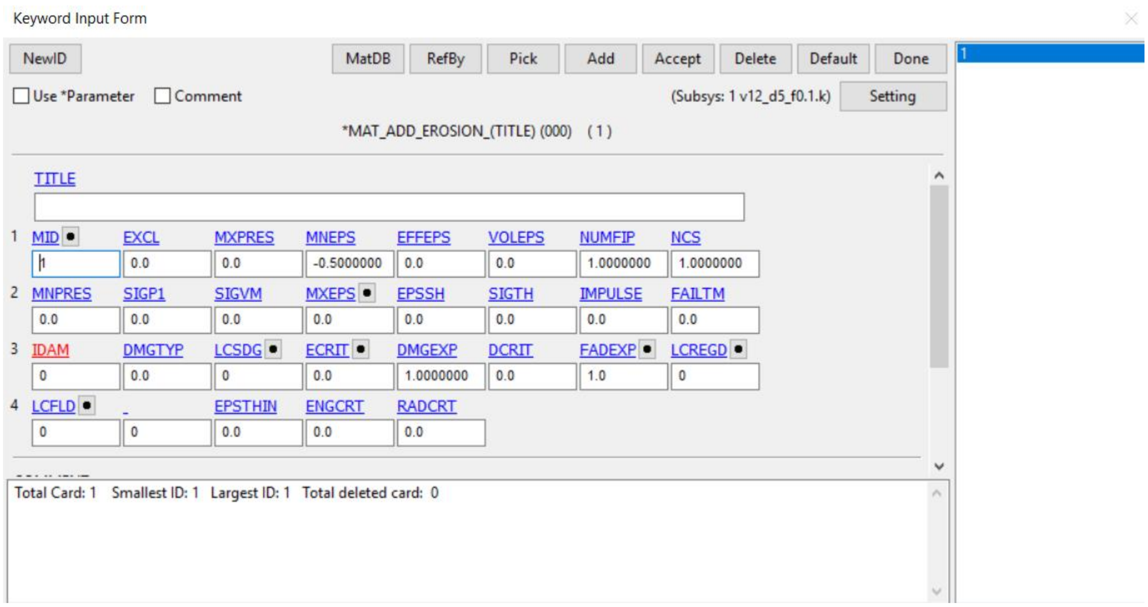


Figure 8.3: LS-DYNA Erosion keyword

3.6.VALIDATION

For validation purpose an additional simulation was carried out with rake angle of -15º , cutting speed of 4mm/s, and depth of cut of 1mm, same parameters from experimental and simulation work in [21] and [10] respectively, the result is shown.

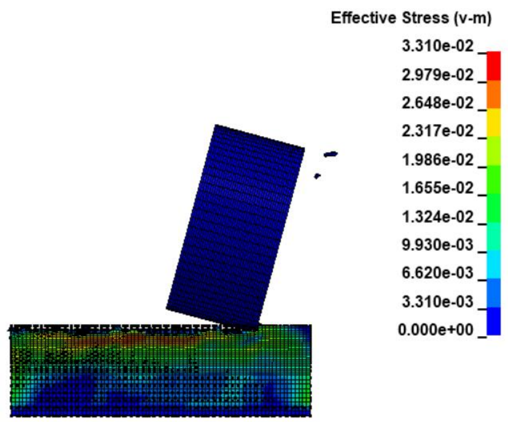


Figure 1.3: Stress distribution

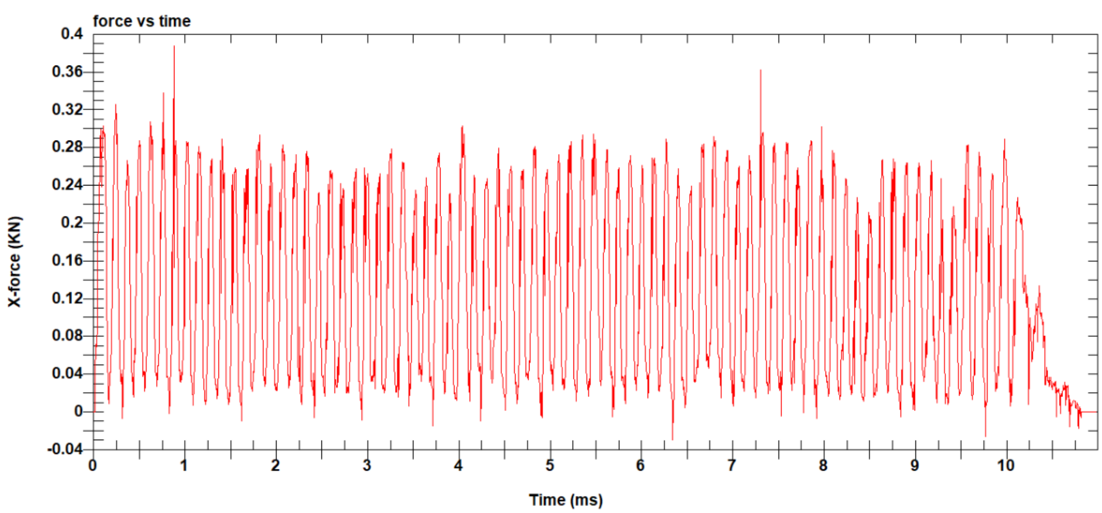


Figure 10.3: Force vs time

variable	Validation simulation result	Simulation [22]	Experiment [21]
Depth of cut	1 mm	1mm	1mm
Rock type	Sandstone	Sandstone	Sandstone
Rake angle	-15	-15	-15
speed	4mm/s	4mm/s	4mm/s
friction	0.6	-	0.6
Mean cutting force	132	140	128

Table 7.3: Validation

3.7.Design of experiment (DOE)

The following DOE was generated in statistical software called JMP. Full factorial design with two level was set. The DOE as a statistical tool will be used to study the effects of the variables rake angle, velocity, depth of cut and friction coefficient on the cutting Force.

Variable	Levels	
Rake angle	0	30
Cutting Speed	2	12
Depth of cut	0.5	5
Friction	0.1	0.8

Table 1.3: Full factorial DOE Setup

	Pattern	rake angle	cutting speed (m/s)	depth of cut (mm)	friction coefficient
1	+−−+	30	2	0.5	0.8
2	−−−−	0	2	0.5	0.1
3	+−+−	30	2	5	0.1
4	++−+	30	12	0.5	0.8
5	−+−−	0	12	0.5	0.1
6	+++−	30	12	5	0.1
7	++−−	30	12	0.5	0.1
8	−−−+	0	2	0.5	0.8
9	−++−	0	12	5	0.1
10	−−+−	0	2	5	0.1
11	−+−+	0	12	0.5	0.8
12	−−++	0	2	5	0.8
13	−+++	0	12	5	0.8
14	+−++	30	2	5	0.8
15	+−−−	30	2	0.5	0.1
16	++++	30	12	5	0.8

Figure 11.3: Simulation runs design

CHAPTER 4

RESULTS AND DISCUSSION

4.1. RESULTS

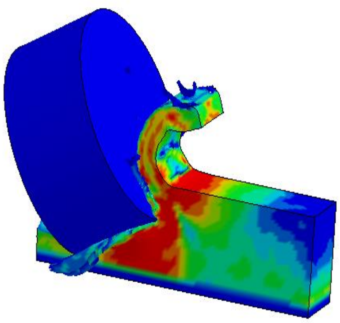
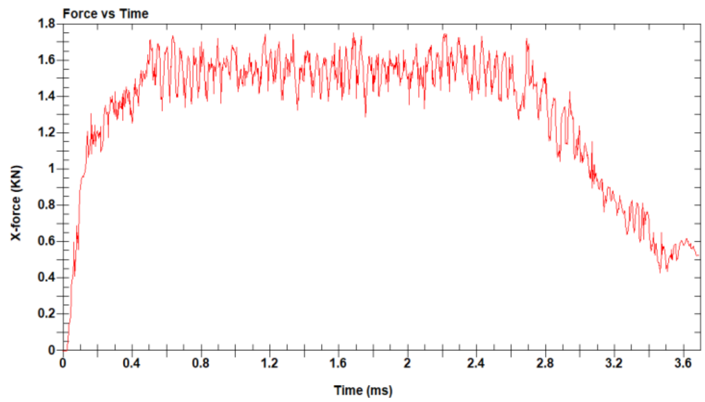
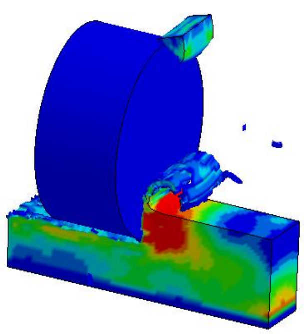
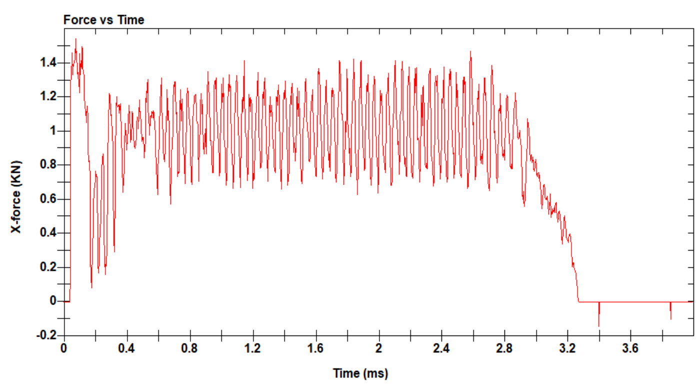
 Run 16	 velocity =12m/s; rake angle= 30° depth of cut 5mm; friction = 0.8
 Run9	 velocity =12m/s; rake angle= 0° depth of cut 5mm; friction = 0.1

Table 1.4: results run 16 and 9

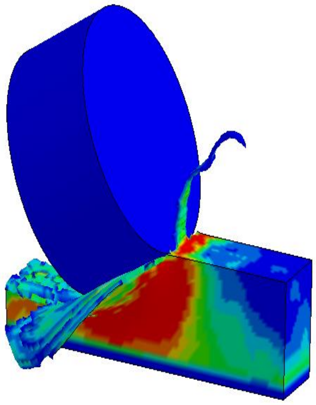
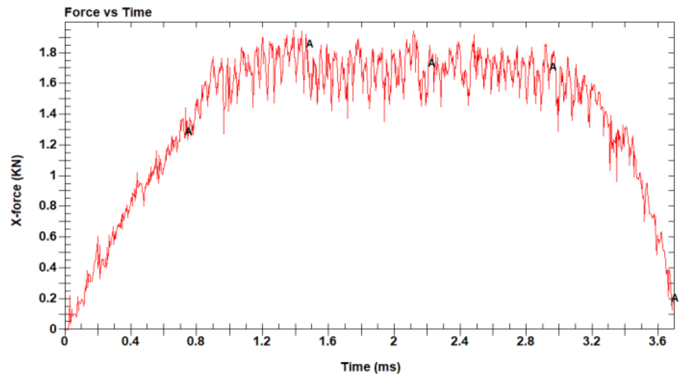
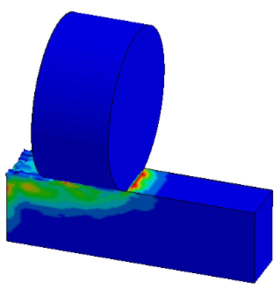
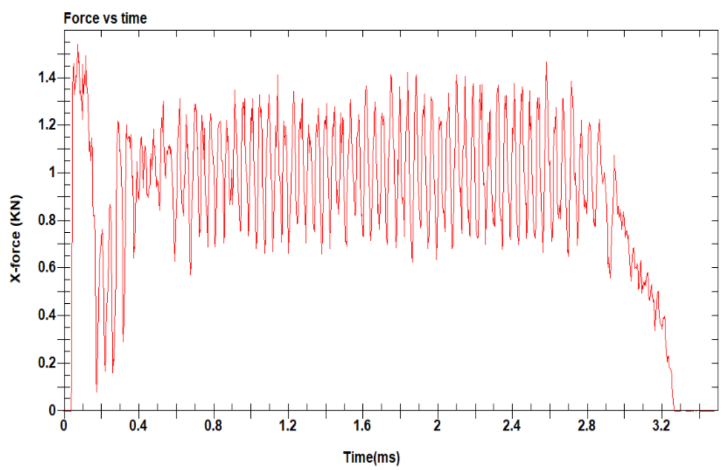
 Run 4	 velocity =12m/s; rake angle= 30° depth of cut 0.5mm; friction = 0.8
 Run 5	 velocity =12m/s; rake angle= 0° depth of cut 0.5mm; friction = 0.1

Table 2.4: results run 4 and 5

	Pattern	rake angle	cutting speed (m/s)	depth of cut (mm)	friction coefficient	Cutting force (N)
1	+−−+	30	2	0.5	0.8	1650
2	−−−−	0	2	0.5	0.1	79.5
3	+−+−	30	2	5	0.1	1500
4	++−+	30	12	0.5	0.8	1710
5	−+−−	0	12	0.5	0.1	95.5
6	+++−	30	12	5	0.1	1510
7	++−−	30	12	0.5	0.1	1700
8	−−−+	0	2	0.5	0.8	80.8
9	−++−	0	12	5	0.1	1010
10	−−+−	0	2	5	0.1	959
11	−+−+	0	12	0.5	0.8	95.8
12	−−++	0	2	5	0.8	963
13	−+++	0	12	5	0.8	1030
14	+−++	30	2	5	0.8	1560
15	+−−−	30	2	0.5	0.1	1640
16	++++	30	12	5	0.8	1550

Figure 1.4: Result of Design of Experiment

4.2. DISCUSSION

The effect of each variable on the cutting force can be analysed by keeping the other variables as constant and just change the desired variable.

4.2.1. Effect of rake angle

As full factorial design of experiment, the rake angle used are 0^o and 30^o, which are low and high level respectively. The effect can be clearly seen by comparing runs where all the variables are constant except for rake angle. It is observed as the rake angle is changed from 0 to 30, the cutting force have drastically changed, as can be seen from the table which compares run 1 to run 8 and run 6 to run 9.

variable / runs	Rake angle	speed	Depth of cut	Friction	Force
1	30	2	0.5	0.8	1650
8	0	2	0.5	0.8	80.8
6	30	12	5	0.1	1510
9	0	12	5	0.1	1010

Table 3.4: Rake angle comparison

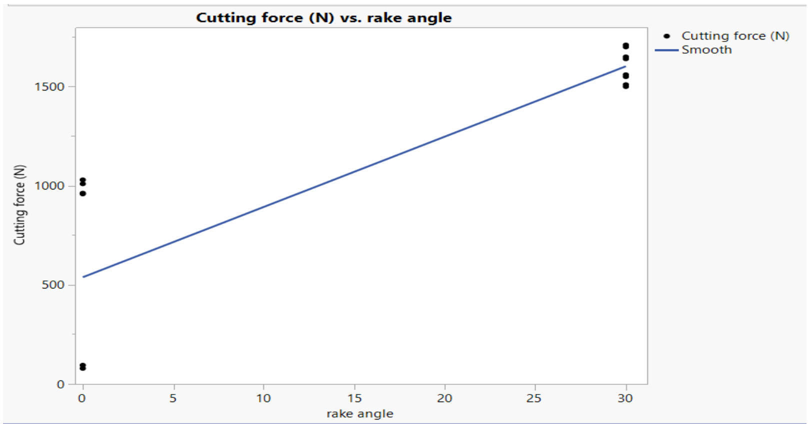


Figure 1.4: Cutting force vs rake angle

4.2.2. Effect of the Depth of cut

Keeping all the variable constant and only varying the depth of cut is observed that the force increases linearly as the depth of cut increases, author from [23] arrived at the same conclusion.

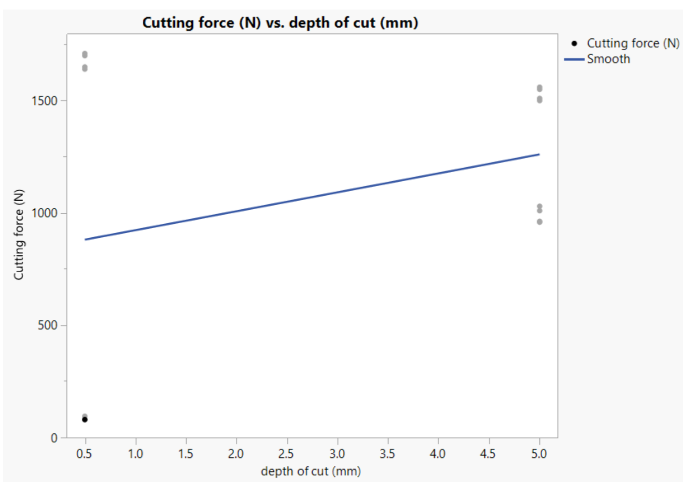


Figure 3.4: cutting force vs depth of cut

4.2.3. Effect of cutting speed

Keeping the other variables constant, and changing the cutting speed, it is checked that the cutting force increases as the speed increases.

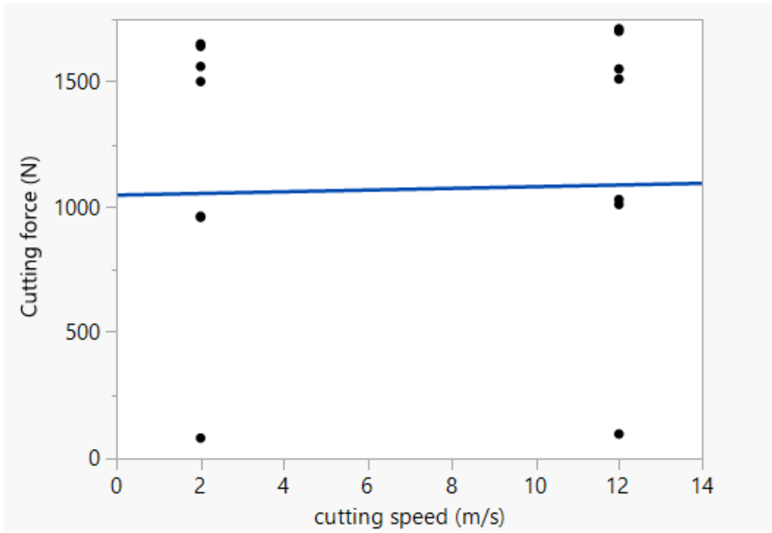


Figure 4.4: Cutting force vs cutting speed

4.2.4. Effect of dynamic friction coefficient

Observing the dynamic friction coefficient, which was varied between 0.1 and 0.8, it was concluded that rough rock needs more force to cut the rock however the effect is very small, nearly linear.

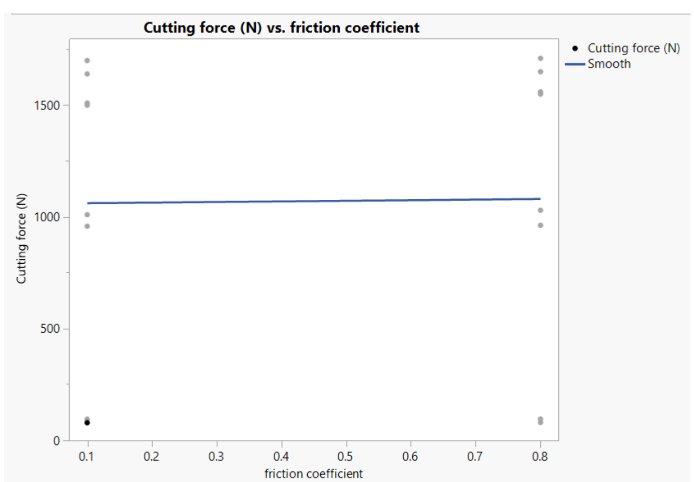


Figure 5.4: Force vs dynamic friction

From the results the most important factors affect the cutting force are rake angle and depth of cut, followed by the speed and the friction with least effect. The optimum condition based on the result is to keep the rake angle close to zero and the minimum depth of cut.

The main goal of the DOE is to show the combination that produces or minimizes the cutting force the most. Runs 2, 5,8 and 11 used least force to break the same rock. Analyzing the result that produced the least force, they have two things in common which are rake angle of 0 and depth of cut 0.5mm.

variable / runs	Rake angle	speed	Depth of cut	Friction	Force
2	0	2	0.5	0.1	79.5
5	0	12	0.5	0.1	95.5
8	0	2	0.5	0.8	80.8
11	0	12	0.5	0.8	95.8

Table 4.4: Runs that used minimum force

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1. CONCLUSION

The rock cutting simulation process was successfully developed and convergence was observed in validation of the current simulation process compared to experimental and simulation work of [21] and [19] respectively. It can be concluded that LS-DYNA Software is good tool to simulate rock cutting process, mostly because of the option of add erosion which make it possible to see the fragmentation process. The material model chosen to do the simulation was damage 2, which is fast to converge and require less computational time when compared with material model such as Johnson Holmquist.

As the rake angle is changed from 30 to 0 the cutting force increases sharply, leading to the conclusion that rake angle close to zero is good to have least force and consequently decrease the use of energy. Small depth of cut needs less force, due to small amount of rock mass being removed.

The main goal of the DOE is to find a combination of conditions that minimizes the cutting force. From the results the most important factors affect the cutting force are rake angle and depth of cut. From examination of the results the ones that used the least force have rake angle of 0 and depth of cut of 0.5mm, the optimum combination of these two variables would optimize the drilling process and reduce the energy consumption.

5.2.RECOMMENDATION

From the project my recommendation will focus on my limitations and things I could not do because of time restriction. Firstly, for future studies I suggest using different software like Hyperworks to compare the accuracy with Ls-dyna, would be very interesting, to see if it affects the results and which one is closer to experimental results. If possible both Laboratory and simulation work should be done in parallel in order to study the accuracy and validate the result without needing to rely on external work.

Other thing that could affect the result is the material model assigned to the rock, in this project mat damage 2 was used and if time allowed using other material model such Johnson Holmquist, drucker-prager, CSCM, etc. would be important to see which model give better result.

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