**Numerical Simulation of Rock-Cutter Interaction in Drilling Operation Using ANSYS AUTODYN 3D**

by

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CERTIFICATION OF APRROVAL

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A project dissertation submitted to the
Mechanical Engineering Programme
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Approved by,

_______________________________

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TRONOH, PERAK
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## CERIFICATION 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 that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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CARTHIKRAJA N SETHAMBARAM

# Abstract

Minimized Rate of Penetration (ROP) and diminished drilling performance dependably been a major challenge for the drilling contractors. Optimizing the drilling process would help to reduce the time required to drill a well, thus directly reducing costs for drilling. Existence of critical interest for development in rock cutting innovation to achieve higher ROP and longer bit life is undisputable, which depends to an extent on the comprehension of the rock-cutter interaction. The main objective of this paper is to identify the essential parameters and its optimum value to increase the rock cutter efficiency. Efficiency of the rock cutter is defined in terms of Mechanical Specific Energy (MSE). The lower the MSE, the higher the efficiency of the rock cutter with the given parameter value. In this paper, numerical simulation of the rock-cutter interaction was performed in ANSYS AUTODYN and the results obtained were used to determine the optimum value of the identified parameters. The study was conducted in two phases. In phase 1, design parameters of the cutter were analysed. In the second phase, operational parameters were analysed using the optimum design values obtained from phase 1. The cutter is modelled as a solid cylinder of Polycrystalline Diamond and the rock is modelled as a solid cube. In the simulation only sandstone parameters were used for the rock properties. Response Surface Methodology was identified as the best tool to predict the optimum values by employing the Central Composite Design (CCD). Tests were run as per the DOE data. By setting minimal MSE as the objective, it was predicted from the results of the simulation that a back rake angle of $30^{\circ}$, side rake angle of $-3^{\circ}$ and DOC of 1.26 mm which performed the rock removal at the lowest MSE are the optimum design parameter values. These values were used in Phase 2 and optimum WOB and Bit Rotary Speed at different bottom hole pressure were identified.



**Key Words:** *Drilling; Single PDC cutter; Mechanical Specific Energy (MSE); AUTODYN; Numerical Modelling; Response Surface Methodology; Central Composite Design*

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# CHAPTER 1: INTRODUCTION

## 1.1 Background Study

Oil and gas remains the major source of fuel for energy generation in an ever power demanding world. Due to the presence of hydrocarbon sources below the ground, drilling operation is a major component which cannot be removed from the hydrocarbon extraction process. The drilling contractors work in accordance with a contract which specifies the well depth and be remunerated on per day rate [1]. Minimized Rate of Penetration (ROP) and diminished drilling performance have dependably been a major challenge for the drilling contractors. Optimizing the drilling process would help to reduce the time required to drill a well, thus directly reducing costs for drilling. Optimization of drilling shall be achieved by higher rate of penetration (ROP), better bit stability, better bit directional control, and better wear rate of the tool.

There are three types of drill bits used in the industry to drill a well. They are namely roller cone bits, fixed cutter bits, and hybrid bits. The selection and use of these bits depend on several factors such as formation to be drilled, projected operating parameters, the capabilities of rig and the operator's past experience in offset wells [2]. PDC bits are classified under the fixed cutter bit as the cutter is not displaced or rotated as the drilling progress. PDC bits gained wide usage in the upstream Oil and Gas industry for drilling formations of soft and moderately firm rocks. The shearing of rock performed by fixed cutters in the PDC bit is evidenced to be more efficient in penetrating rocks than crushing the rocks by the rolling cone bits. Recent developments in technology, prompt enhanced PDC wear, impact resistance and better vibrations comprehension of the PDC drill tool [3]. However, performance of PDC drill bit reduces drastically in hard formations even with the recent extensive bit performance study undertook by many researchers [7].

There is a critical interest for development in rock drilling innovation to achieve higher ROP and longer bit life, which depends to an extent on the comprehension of the rock-cutter interaction [4]. Cutter-rock interaction is very important in drill bit design due to its great effect on ROP, stability and bit steer-ability. Experimental investigation of rock cutter interaction can help to understand the effects of different parameters [2]. Modelling the cutter rock interaction will assist in estimating the bit drilling capacity with the formation nature to be drilled, compute the imbalance force for adjustment and decide the bit steering-capacity [5]. Single PDC cutter studies provide effective interpretation in intrinsic mechanisms during rock-cutting than full scale bit studies [6].

## 1.2 Problem Statement

As the search for reserves lead to greater depths in Oil and Gas industry, the importance in understanding tribology interaction between the rock and cutting tool is of much significance. The reason being, reaching deep reserves requires the cutter to perform cutting at exceptionally high pressure and high temperature (HPHT) environment. In this environment, low penetrations rate was identified by many drilling professionals as an important factor threatening future of deep well drilling [4]. There is an overwhelming demand for enhancement in rock drilling machinery, which rest on a large extent in the understanding of cutter-rock cutting process. It is almost impossible to predict exactly the interaction between cutting tool and rock before the drilling operation. Understanding the interaction between the cutting tool and the rock is important to optimize the drilling process through higher rate of penetration (ROP) and better tool life [2]. Cutter rock interaction model became a critical feature in the design process of the drilling bit. It is generally assumed in analytical and empirical models that the cutting force acting on the cutter is proportional to the cutting surface[5]. A better model has to be developed to overcome these assumptions to provide a clearer idea of the rock-cutter interaction.

A few experimental setup investigations performed by various researchers have helped in understanding the cutter-rock interaction during cutting utilizing single PDC cutter. But, high costs involved in performing physical experiments coupled with difficulties in directly observing the rock chip removal process in real time made it unfavourable to set up an experimental investigation. Numerical simulation is favoured against experimental investigation with regarding the before mentioned drawbacks to elucidate cutter-rock interaction during rock cutting. Despite the availability of wide-ranging work undertook by previous researches and in-depth evaluations in the areas mentioned, there aren't many researches on the simulation of rock-cutter interaction using Computer Aided Engineering (CAE) tools especially ANSYS AUTODYN. The most recent and relevant study to this project was in 2D. To the knowledge of author, there are least number of numerical studies where 3D geometry is considered. Furthermore, 3D models of previous works rock cutting have not completely provided accurate quantitative results [7].

To improve drilling operation through better drill bit execution which is the immediate capacity of the cutter-rock interaction, ideal variable parameters must be recognized [5]. It is generally assumed both in empirical and analytical models that the various parameters in rock-cutter interaction as a constant [5]. Optimization of cutter design through physical investigation is time consuming and expensive. Physical experiments are expensive and presence of difficulty in observing rock fragmentation process make it unlikely to pursued. Therefore, a simulation has to done to estimate the nearest possible data from the simulation output.

Furthermore, all the analysis done in previous works employed the One-Factor-at-a-Time (OFAT) analysis on investigating the parameters. This approach has many drawbacks, such as extra runs need to be conducted to get the same precision in effect estimation, interactions between multiple variable will not be analysed and can miss the optimal value of the input variable. No research has been done, to the knowledge of author, on the cutter-rock interaction using Response Surface Methodology (RSM).

## 1.3 Objectives

The objectives of this study are:

- To identify the different essential parameters affecting efficiency of a single Polycrystalline Diamond Compact (PDC) cutter.
- To develop, model and simulate dynamics of the single rock-cutter interaction in drilling operation using finite element method with ANSYS AUTODYN-3D.
- To estimate the optimum value of the parameters identified for an efficient drilling operation using results from the simulation utilising the Response Surface Methodology.

## 1.4 Scope of Study

The scope of study for this projects involves two parts where the first part is the studying the parameters involved in determining the efficiency of the rock cutters. Due to the absence of an experimental setup in the learning institution, the parameters will be identified from the past researches done by other researchers and other sources. While the second part is to develop a numerical model of the rock and cutter and simulate it in a simulation software. Finite Element Method (FEM) analysis will be employed in the simulation process. A physical model or working prototype of the cutter will not be made due to financial and time constrains. A physical experiment also shall not be conducted due to the absence of the experimental setup in the learning institution. Due to the availability of only one software provider in the learning institution, ANSYS, the service of that software developer will be used. The product that will be used in this project from that developer is ANSYS AUTODYN which employs the explicit finite element method. The created model shall be of three dimensional in order to generate more accurate results. Only the rock and cutter will be modelled, since modelling the PDC bit would consume time exceeding the time frame set for this project. Only one rock cutter will be modelled and no multi-arranged cutters will be modelled. Results of single PDC cutter could be used to predict the performance of multi-arranged cutters in the drill bit.

# CHAPTER 2: LITERATURE REVIEW

The underlying phenomena happening during rock cutting are fragmentation and fracturing of the rock under mechanical movement of the cutting tool. Rock cuttings are developed and removed due to the joint actions tensile fracture and shear initiated in the cutting zone near the tip and spreading into the unbroken rock [7]. Rock chips occur when the crack develops to the extent they network with other cracks created from neighbouring cuts or reach the free surface and is known as the rock fragmentation process [19].

Optimization of cutter design shall be done only once the knowledge on cutting process is obtained through physical experiment investigation. The whole rock-cutter interaction process shall be categorized into three groups. They are: (i) cutter design and properties, (ii) rock properties, and (iii) operational parameters. All these identified factors influence the efficiency and performance of rock cutter [7].

Various models have been developed to analyse and predict the cutting force for given rock properties and cutting tool properties. These models have been developed based on various experimental, numerical and analytical approach [7]. Experimental approach of rock cutting, helps to identify the parameters influencing the cutting efficiency by analysing the cutting force. In experimental setup, the experiment is performed in various environments such as confined pressures, different types of rocks and different operating parameters. Simple analytical models were developed to understand the rock-cutter interaction and provide necessary data for theoretical modelling. Numerical modelling has also been developed in the study of rock-cutter interaction.

For the analysis of optimum parameter values can be obtained through linear cutting or circular cutting process. One Study [23] explicitly stated that results obtained in their investigation proved that there is no significant difference between circular cutting and linear cutting. Despite experimental setup investigation research [13,21] used circular cutting, other numerical modelling works employed the linear cutting method [ 14,19,7] in performing their analysis.

## 2.1 Model Parameters

Gerbaud [3] studied and proposed another variant cutter-rock interaction model which includes build-up edge of crushed materials on the cutting face, forces applied on the back of the cutter and due to the rock deformation, chamfer on the cutter which affects the ROP significantly, and back flow of crushed materials. The research [3] stated previous models considered only three forces: normal force, drag force, and side force with the stated properties before were not considered. The results show that accurate use of this model can assist designer of drill bit to find the best application for the drill bit.

Hareland [8] developed a new analytical single PDC cutter force model. This paper [8] found that cutting efficiency is a function of rock property, back rake angle, and depth of cut. ROP was reduced as a result of increased rock hardness. Higher rpm and WOB will upsurge the ROP if cutting chips are detached efficiently. Design of cutter material and PDC cutter material influence the ROP all through the bit cutter life. Cutters made up from fine (10 µm) diamond grain size provides higher ROP and less abrasion than those from coarse (70 µm) diamond grains. Further, increasing the sintering pressure in building machine and chamfering the cutter edges during cutter production make them gives significantly enhanced bit performance in drilling hard formations and more thermally stable [9].

Rafatian et. al. found that a standout amongst the most critical variables influencing the rate of penetration (ROP) is the downhole pressure environment. This paper produced results using high pressured testing facility with a single cutter to cut two types (Indiana Limestone and Carthage marble) of stone with different ranges of depth of cuts and different confining pressure. This paper suggests that there is a remarkable increase observed in mechanical specific energy (MSE) compared to the tests done at atmospheric pressure even though with low pressures (100–200 psig) and coupled with permeable rocks. This paper proposed a new theory, based on the cutting mechanism under pressure and frictional force. Few reasons for the increase in MSE are suggested by this paper are that downhole pressure strengthens the rock, difference between the bottomhole mud column pressure (borehole pressure) and the pressure inside the pore spaces of the rock (pore pressure) that strengthens the rock matrix, produced rock chips which are held down by the mud column pressure increases the work needed. It was also acknowledged by this paper that even under perfect hydraulic conditions, the MSE that they gauged amid drilling a rock under pressure was greater than the CCS of that rock under the same binding pressures [10].

In the study of Akbari et. al. A different element rock cutting model was actualized where rotary speed and weight on bit would be simulated and the resulting penetrating rate was logged. This paper also simulated the effect of the presence of bottom-hole pressure. Micro properties of the rock distinct element model are rarely available compared to macro properties such as elasticity and plasticity parameters [11].

In the study of Rajabov et. al. Experiments with three different rock types; Carthage marble, Mancos shale, and Torrey Buff sandstone, were done that at both atmospheric and elevated confining pressures, PDC cutters with different back rake angles. Results show that a cutter with low back rake requires less horizontal cutting force in order to cut the same volume of rock. Lower back rake angles require less torque in order to drill at the same ROP. The paper suggests compressive strength of some rocks such as shale cannot be used alone as a reference rock property for accurately evaluating and comparing drilling efficiency. A new 3D mechanistic PDC cutter-rock interaction model was also developed which incorporates the effects of both back rake and side rake angles in the study [12].

During rock cutting, temperature at rock-cutter interface considerably affects the PDC cutter's efficiency, including its drill-ability, wear rate, and impact resistance in field conditions [13]. In the study [13], a model rock-cutter model which takes the friction into account for the assessment of temperature effect on the ROP, was created.

## 2.2 Finite Element Model

The model in this study is based on the fundamental equation of rigid body point motion, which is shown in ***Eq.1***. The effective stress, $'\Omega$, which is the stress calculated over the section that effectively resist the force on the boundaries and is related to damage variable (D) and stress tensor (Ω). The boundary conditions are inclusive of displacement occurring at boundary zone, forces on the border of the body and body forces on the boundary of contact zone.

$$'\Omega = \frac{\Omega}{1 - D}$$

*Equation 1: Effective Stress*

The evolution equation for the damage variable is defined as:

$$\dot{D} = \begin{cases} \frac{Y}{S(1-D)}\,\dot{r} & for\ r > r_d \quad and\ \ \Omega_1 > 0 \\ 0 & for\ \ r \le r_d \end{cases}$$

*Equation 2: Damage Variable*

Where $r_d$ is the damage threshold, $\dot{r}$ is damage governed by plasticity, S is a damage strength, Y is the damage strain energy release rate, and $\Omega_1$ is the maximum principal stress. The damage strain energy release rate (Y) is given as:

$$Y = \frac{\Omega^2{}_{vm} R_v}{2E(1 - D)^2}$$

*Equation 3: Damage Strain Energy Release Rate*

Where $\Omega_{vm}$ is the equivalent Von Mises stress, and E is the Young's Modulus. The tri-axiality function $R_v$ is defined as:

$$R_v = \frac{2}{3}(1 + v) + 3(1 - 2v)\left(\frac{\Omega_H}{\Omega_{vm}}\right)^2$$

*Equation 4: Triaxiality Function*

## 2.3 Model Simulation

Simulation is one of the major way to understand the rock properties during rock-cutting other than physically conducting an experiment. The heterogeneous nature of rocks leads to various mechanical behaviour and failure mechanisms from the general homogenous materials. Therefore, behaviour of rock cutting in numerical codes poses a big challenge in monitoring. Anyhow, field and laboratory tests are needed to verify and modify the numerical models.

Complex properties of rock and downhole conditions make the modelling hard to achieve. The study [6], has classified research methods into three parts which are analytical method, numerical method, and experimental method. Analytical models and numerical models are the widely used methods in assessing rock-cutter interaction [6]. The codes used in the literatures study all fall under the numerical and analytical models.

In 2D simulations, chipping fragmentation and crack propagation can only be simulated by vertical indentation; horizontal mechanism cannot be analysed. Furthermore, rock debris cannot be analysed by just taking into account one dimensional crack development. AUTODYN 3D is an FEM based numerical code, which can simulate dynamic, non-linear failure [14]. The study [7] stated that most of the works done previously were of 2D models. There are very few model employ 3D models. Furthermore, the 3D models have not given accurate quantitative results.

An assortment of mathematical models and simulation codes have been utilized in other researcher's work to the study cutter-rock interaction. ANSYS AUTODYN has been utilised by the studies [14-16] to simulate the similar kind of rock-cutter interaction, the tunnel boring machine (TBM) and the cutter efficiency is evaluated. Where else, LS-DYNA has been used by other researchers [4, 17] to study rock fragmentation. LS-DYNA assimilate the usage of explicit non-linear finite element code. Unlike LS-DYNA, simulation in AUTODYN-3D is made simplified where the cut rock volumes were identified by usage of the erosion option readily available in the setup whereby rock particles which approached failure level were immediately eliminated. The work by [7] has simulated both a 2D model and a 3D model. To compare the results, even a physical experiment has been conducted by the research team.

The most common method employed by the researchers [ 4, 16, 18, 19] in numerical analysis is the finite element method (FEM). However, few literatures [7,11] used discreet element method (DEM) stating that finite element method (FEM) consists of certain weakness. The study [7] argued that FEM which was based on the continuum mechanics theory has serious problem in representing the discontinuities of material occurring during cutting process. The study also stated that previous research which utilised the LS-DYNA code which was based on FEM couldn't provide quantitative results of the fragmented rock materials (rock chips). It further argues that, DEM can take into account most kind of discontinuities and material failure characterized with multiple fractures. FEM of the rock cutting remains difficult as due to the complexity of rock properties and non-linear behaviour of roc, rock-fracture and chipping phenomenon.

In addition to that work [11] stated explicitly that early attempts of the simulation were made using different finite element software packages which utilize an explicit solution scheme but the results were unsatisfactory due to the limitations of these packages in simulation of large strain phenomena and post failure behaviour and contact modelling. When Discrete Element Method is employed [7, 20], the rock is modelled as many cylindrical elements and the cutter is modelled as straight line elements. Work by [20] shared similar sentiment as [7], as the researchers stated that FEA has serious problems in demonstrating properly the discontinuities of material during rock cutting process.

## 2.4 Model Efficiency Definition

Study [8] suggested that to enhance PDC cutter performance, cutting efficiency shall be related to the volume of rock detached by a cutter and the force exerted in the removal process. The study introduced the term specific volume with the given equation as shown in equation 1.

$$Specific\ Volume = \frac{Volume\ of\ rock\ removed\ in\ one\ major\ chip}{Maximum\ force\ exerted\ to\ remove\ the\ volume\ of\ rock}$$

*Equation 5: Specific Volume*

On the other hand Rafatian [21], suggested the concept of Mechanical Specific Energy (MSE). MSE is defined as value of mechanical energy required to extract a unit volume of rock. Equation 2 defines the above statement.

$$MSE = \frac{Mechanical\ Energy\ Required}{Volume\ of\ Rock\ Removed}\ (\frac{N}{m^2}\ or\ psi)$$

*Equation 6: Mechanical Specific Energy*

In addition to that, [3] stated that cutter efficiency can be evaluated when the cutter is classified as minimised specific energy (MSE) and maximized rate of penetration (ROP).

## 2.5 Response Surface Methodology

The main objective of this study is to determine the optimal design parameter values. In order to achieve that goal, Response Surface Methodology (RSM) was utilised. RSM is a statistical technique for empirical model building which uses a set of equation in determining the plots. In order to generate the RSM, a careful Design of Experiments (DOE) is done. The objective of optimisation is achieved through the response (output) maximisation or minimisation which is influenced by several independent variables (input). The experiments are called a set of runs where the input variables are varied in order and output is analysed where which input, value of the input, and output variation (positive or negative) caused the change in response.

The main factor controlling the RSM is the DOE. The strategies developed originally for the model fitting of physical experiments but applied to numerical experiments too as the methodology is the same. The purpose of DOE is the selection of limiting points of inputs and determine where should the response be assessed.

The usual model constructed using RSM is the Central Composite Design (CCD). A second-order model can be constructed efficiently with central composite designs. CCD are first-order designs augmented by additional centre and axial points to allow estimation of the tuning parameters of a second order polynomial.

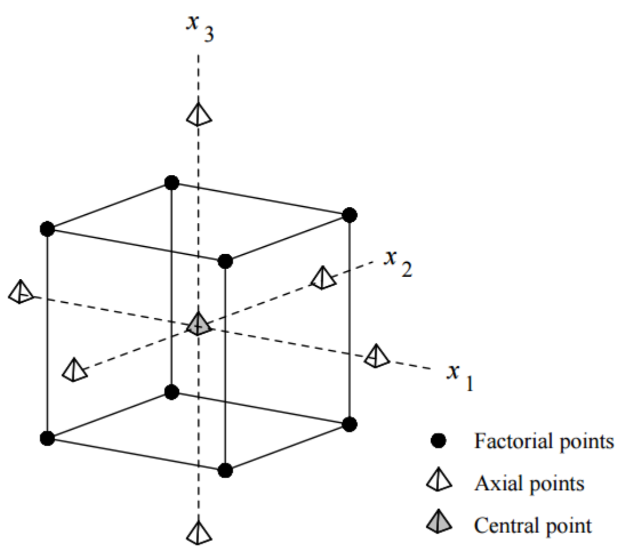


Figure 1: CCD for 3 design variables at 2 levels

# CHAPTER 3: METHODOLOGY

This paper will present the numerical modelling and simulation of rock cutting process with a single PDC cutter. The model developed will be of a cutter-rock system. The rock modelled will be of using the finite element method analysis which was studied in-depth in the literature review part. A 3D model will be developed in this work to display the accuracy of the results obtained. The models will be developed in ANSYS AUTODYN. The results obtained shall be validated with the numerous experimental results available from past researches.

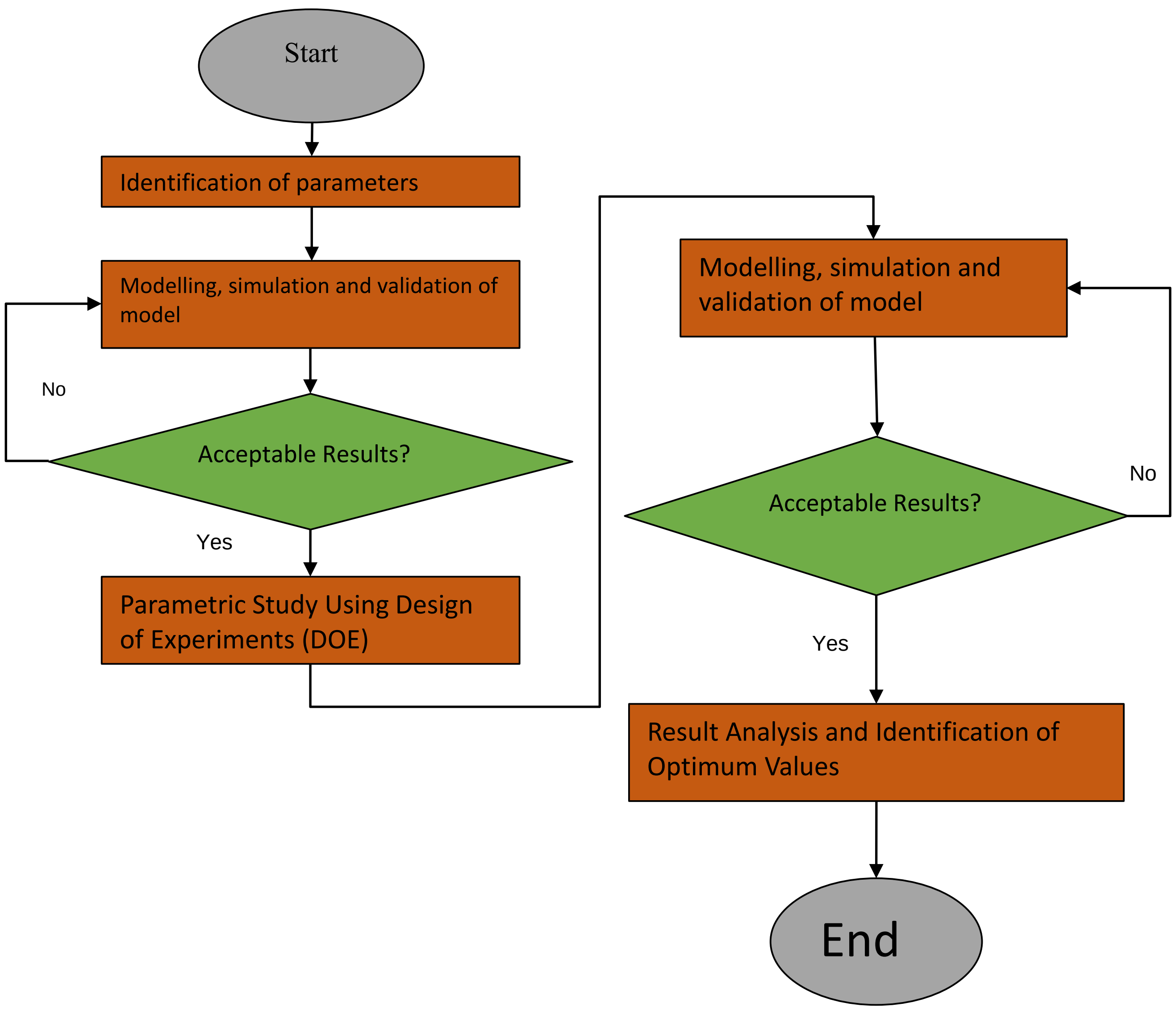


Figure 2: Flow Chart of the Project

| No. | Activities / Week | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **FYP 1** | | | | | | | | | | | | | | |
| 1 | Literature Analysis on Rock Cutter Mechanism | | | | | | | | | | | | | | |
| 2 | Knowledge Acquisition on Simulation Software (ANSYS AUTODYN) | | | | | | | | | | | | | | |
| 3 | Determination of Rock Model Parameters | | | | | | | | | | | | | | ▲ |
| 4 | Determination of Rock Cutter Model Parameters | | | | | | | | | | | | | | ▲ |
| | **FYP 2** | | | | | | | | | | | | | | |
| 1 | Development & Simulation of the 2D model using Software | | | | | | | | | | | | | | |
| 2 | Development & Simulation of the 3D model using software | | | | | | | | ▲ | | | | | | |
| 3 | Validation of the results (2D & 3D) | | | | | | | | | | | | | | |
| 4 | Design of Experiments | | | | | | | | | | | | | | |
| 5 | Simulation of Model using Design of Experiment (DOE) Method | | | | | | | | | | | ▲ | | | |
| 6 | Validation of the results (3D, DOE) | | | | | | | | | | | | | | |
| 7 | Identification of optimum values of the parameters identified | | | | | | | | | | | | | ▲ | |

Figure 3: Gantt chart ▲Milestones

Based on the literature, the input parameters (i.e. back rake angle, side rake angle, etc.) which produced the least Mechanical Specific Energy (MSE) as an output are regarded as the optimum value of the input parameter. Due to the high number of levels involved in the factors identified, RSM is employed in designing experiments.

The numerical modelling will be done in two phases in identification of optimum parameters. In the first phase, only the cutter design parameters would be analysed as input parameters. The varying factors (cutter design parameters) would be back rake angle, side rake angle, and depth-of-cut. The response generated from this experiment would be the MSE and mass of rock removed. After identifying the optimum values of the design parameters, in the second phase, those optimised input parameters would be used to analyse the operational parameters which effect the efficiency of the cutter. The varying factors (operational design parameters) are bottom hole pressure (BHP), cutter velocity ($V_c$), and Weight-On-Bit Effect (WOB).

The DOE method would also be employed to analyse the interaction in both the phases. The results will be analysed from there to find the optimum values in varying operational parameters which gives the least MSE.

## 3.1 Cutter-Rock Model

A 3D model was developed using the literature reviewed. The model is based on balancing of static forces acting externally on a single PDC cutter during cutter-rock interaction. The model is shown in Figure 4.

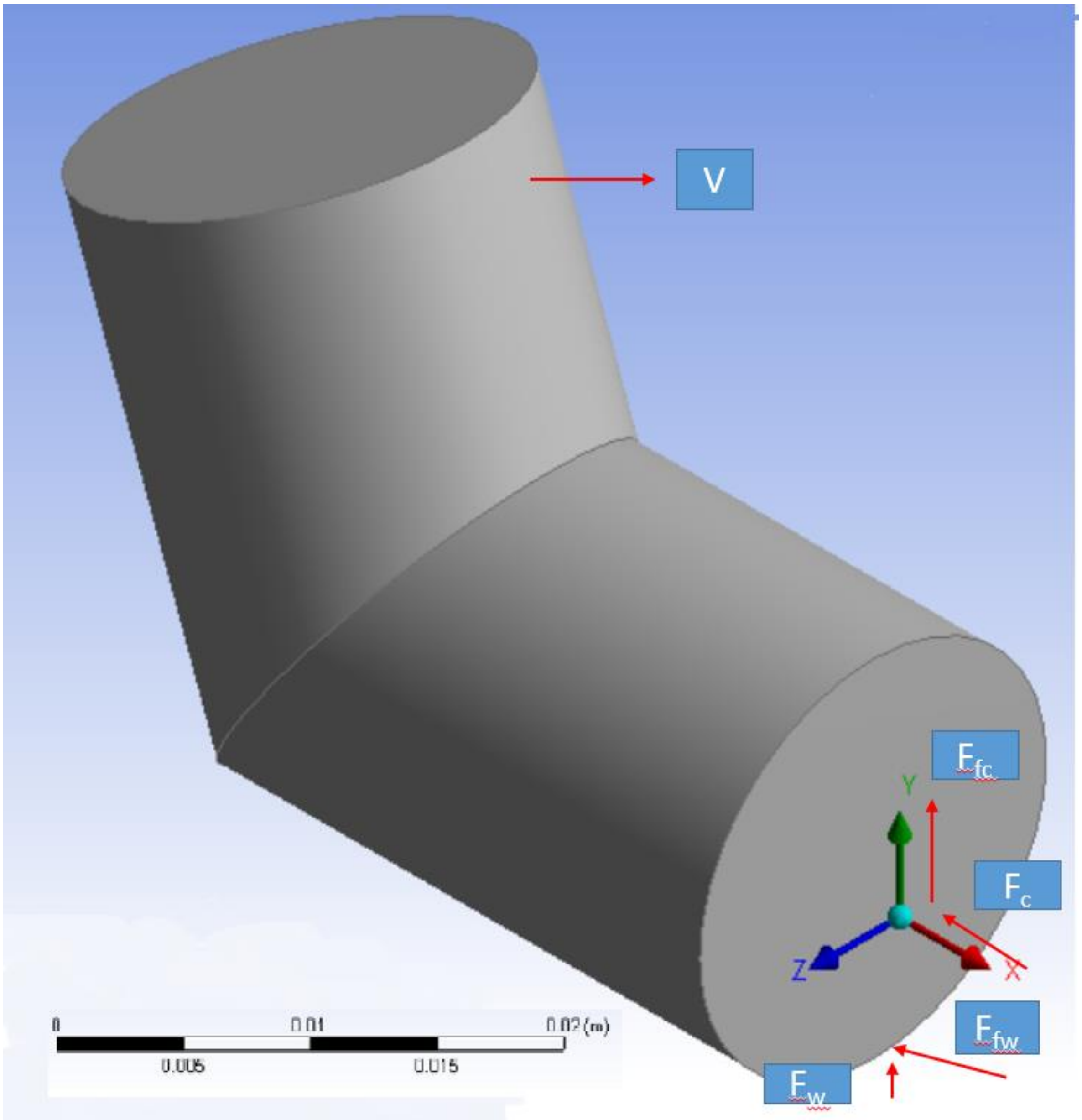


Figure 4: Free Body Diagram of a Single PDC Cutter and Forces Acting on It

Table 1: Forces Acting on Single PDC Cutter

| Force Symbol | Definition |
|---|---|
| $F_c$ | Cutting force perpendicular to surface of cutter ($F_c = R_c A_c$) |
| $F_{fw}$ | Friction force at the cutter-rock interface ($F_c = \mu R_c A_c$) |
| $F_w$ | Wear force perpendicular to the wear flat ($F_w = R_p A_w$) |
| $F_{fw}$ | Wear frictional force between wear flat and rock ($F_{fw} = \mu R_p A_w$) |

**Wear flat refers to the area of cutter which is in contact with rock*

* $A_c$ = *Cutter Rock Contact Area* * $A_w$ = *Cutter Wear Flat Area at the bottom of cutter*

$$F_H = F_c \cos\alpha \cos\beta - F_{fc} \sin\alpha \cos\beta + F_{fw}$$

$$F_s = F_c \cos\alpha \sin\beta - F_{fc} \sin\alpha \sin\beta$$

$$F_N = F_c \sin\alpha + F_{fc} \cos\alpha + F_w$$

Equation 7: FBD Equations

Where α and β are cutter back rake angle and side rake angle respectively. Table 2 lists the parameters identified that affect the performance of the cutter and the method of assimilation into the numerical modelling in this paper.

Table 2: Parameters Identified and Method of Assimilation in The Model

| Parameters Identified | Method of Assimilation in The Model |
|---|---|
| Back Rake Angle, α (˚) | Geometry Modification (Translation & Rotation of the Cutter in the model) |
| Side Rake Angle, β (˚) | |
| Depth-of-Cut, (mm) | |
| Weight-On-Bit Effect, (kN) | Application of Force on Cutter |
| Bit Rotary Speed, (RPM) | Linear Velocity of Cutter |
| Down Hole Pressure (Pa) | Pressure Application on the Rock |

### 3.1.1 Cutter Modelling

PDC bits available in market are of matrix body or made up of fully steel. Selection of the material depends on the application of bit. Polycrystalline diamond cutters (PDC) comprise a polycrystalline diamond (PCD) top layer intrinsically sintered onto a tungsten carbide material using a high-pressure, high-temperature process. In this paper, the cutter is modelled as a solid cylinder of Polycrystalline Diamond with the dimensions of 20 mm length and a diameter of 13 mm (0.512 in) as Diamond is the only material of cutter that interacts in the cutter-sandstone contact area. This is in line with other works [8, 20, 22] on the dimension of the cutter used in this study as 13.005 mm (0.512 in) is the widely used cutter in the industry. The PDC cutter is modelled as per the available cutter in the market. The material property of Diamond has to be created and the properties of the material has to defined in AUTODYN since it is not available in the material library of the software. In selecting the cutter material, the distortion of the cutter is unimportant contrasted with the material being cut, and the wear or deformation of the cutter is immaterial. Therefore, failure mode or yield for the cutter is ignored which is defined as none and the cutter is assumed to be rigid.

### 3.1.2 Rock Modelling

Only one type of rock is considered for this study as the rock properties column is not being investigated in this study. The properties entered in the material library is listed in Table 3. As this material also was not pre-defined in the material, the material has to be defined like the diamond properties. The rock model is defined with linear Equation of State (EOS). The Drucker-Prager model to define strength model is used as a representation of the rock behaviour which portrays the increasing shear resistance due to the compaction and cohesion during failure of rock chips. Therefore, the rock will be modelled by Drucker-Prager yield surface combined with the erosion criterion being set failure at maximal shear strain of 1.1. The wizard in material library required compressive and tensile strength of the rock (sandstone). Uniaxial tension and compression were taken to be 90% of the Brazilian tensile strength and uniaxial compressive strength respectively. Principal stress failure which was used in other works [217] to represent brittleness in materials used is also used for the failure model. Brazilian tensile strength was defined for the failure stress.[2]. The rock is modelled as a 3D rectangular block with a dimension of 30mm x 50 mm x 20 mm.

Table 3: Material Properties Data

| Material | Density, **ρ** (Kg/m$^3$) | Brazilian Tensile Strength, $S_T$ (MPA) | Uniaxial Compressive Strength, $S_c$ (MPA) | Young's Modulus *E* (GPa) | Poison's Ratio, *v* | Bulk Modulus B (GPa) | Shear Modulus, *s* (GPa) |
|---|---|---|---|---|---|---|---|
| Diamond | 3520 | >1200 | >110000 | N/A | N/A | N/A | N/A |
| Sandstone | 2000 | 15 | 170 | 15 | 0.14 | 6.94 | 6.58 |

## 3.2 Model Setup and Boundary Conditions (Phase 1)

In real performing environment, the drill bit along with the cutter moves in a circular path as the drill-bit rotates. But as stated in the literature, linear cutting technique gives nearly the same value of output. Therefore, to simplify the model, the cutter is dragged along a linear path along the static rock plane in this simulation. The model is virtually designed in Explicit Dynamics first for the 3D model building. Initial condition and material is defined in Explicit Dynamics Model setup. A 3D model sketch is shown in Figure 5. The cutter will be tilted and rotated according to the specified back rake angle, α and the side rake angle, β and translated to specific depth of the cut.

The initial velocity of the cutter is set at 100 m/s and defined in the model block of Explicit Dynamics. The AUTODYN solver is utilised for the simulation. The boundary condition set for the sandstone is clamped static with providing X, Y and Z component of velocity equivalent to zero at the bottom nodes. Where else, the Y and Z velocity component of the cutter is set to be zero. The initial 100 m/s boundary condition is also specified for the simulation of the actual experimental setup and to eliminate a trajectory response which neglects the force applied on the rock. The sliding contact between the cutter tip and the rock was assumed to be frictionless. The depth of cut, $d_c$, back rake angle and side rake angle was set at various values as specified in Table 4 during simulation. A gauge node was defined at the tip of the cutter to measure the different parameters such as force and strains during the cutting process. The Lagrange/Lagrange interaction is selected between the cutter and the rock is defined with small external gap before the simulation starts. The Global Erosion is set to erode of geometric strain with the coefficient of 1.1 to simulate the actual condition where the rock chips are removed after the cutting process.

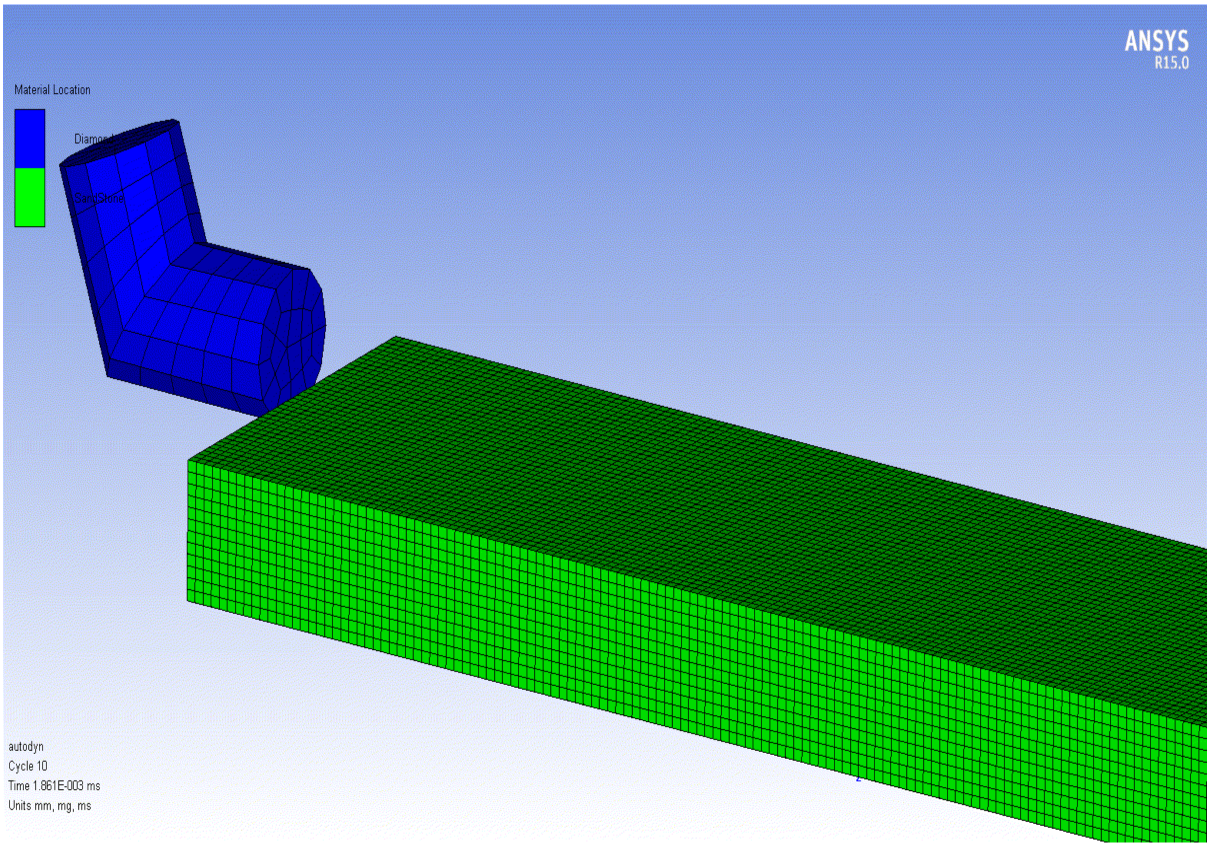


Figure 5: The 3D model in AUTODYN

The design of experiment method was utilised to develop tests with various values of the parameters. The limits of the inputs were specified beforehand in the software code Design Expert™ as stated in Table 4. In line with the literature reviewed, to find optimum values, the Response Surface Methodology (RSM) was used from the software options. A simple model constructed using RSM is the Central Composite Design (CCD) with two centre points. A total of 12 runs were designed. These limits were chosen from the literature reviewed [7, 14, 15].

Table 4: Design of Experiments Limit (Phase 1)

| Parameter | Lower Limit | Upper Limit |
|---|---|---|
| Back Rake Angle | -15˚ | 35˚ |
| Side Rake Angle | -3˚ | 3˚ |
| Depth of Cut | 1 mm | 4 mm |

## 3.2 Model Setup and Boundary Conditions (Phase 2)

The cutter orientation is fixed as the operating parameter is fixed in phase one. The values for the cutter orientation is obtained from the results of phase 1. The cutter and rock has the same dimension and criterion as stated in phase 1. The varying parameters are the cutter velocity, BHP effect and WOB effect. Method of assimilation is already specified in Table 2.

The design of experiment method also was utilised as in phase 1 to develop tests with various values of the parameters. The limits of the inputs were specified beforehand in the software code Design Expert™ as stated in Table 5. In line with the literature reviewed, to find optimum values, the Response Surface Methodology (RSM) was used from the software options. A simple model constructed using RSM is the Central Composite Design (CCD) with one centre points. A total of 11 runs were designed. These limits were chosen from the literature reviewed [23]. For BHP assimilation in model, conversion factor is utilised to obtain the value. FOR WOB effect, first the foot-pounds are converted into kN using the conversion factor. After that, it was assumed that the WOB will be distributed equally to all the cutters in the bit. The usual bit cutter density is from the range of 40 - 50 cutters per bit [12]. The average value of 45 cutters per bit is take into consideration. For cutter velocity, Equation 8 is utilised and the values are determined from there. The average Diameter of a drill bit is around 12 in [9].

$$Linear\ Velocity = 2\pi \frac{rad}{revolution}\ X \frac{1}{60}\left(\frac{min}{sec}\right) X\ RPM\ X\ Bit\ Radius$$

*Equation 8: Linear Velocity – Revolutions per Minute Relation*

Table 5: Design of Experiments Limit (Phase 2)

| Parameter | Lower Limit in Literature | Upper Limit in Literature | Lower Limit in Model | Upper Limit in Model |
|---|---|---|---|---|
| BHP | 0 psi | 1000psi | 0 Pa | 6.895 MPa |
| WOB | 5000 lb | 30000 lb | 0.494 kN | 2.965 kN |
| Cutter Velocity | 55 RPM | 190 RPM | 0.86 m/sec | 2.985 m/sec |

# CHAPTER 4: RESULTS AND DISCUSSION

## 4.1 Phase 1 Results

Based on the failure criterion, EOS and parameters specified, the simulation of the numerical model was implemented using the AUTODYN code. Table 6 compiled the data obtained from test runs done in simulation using design parameters specified by the DOE Code.

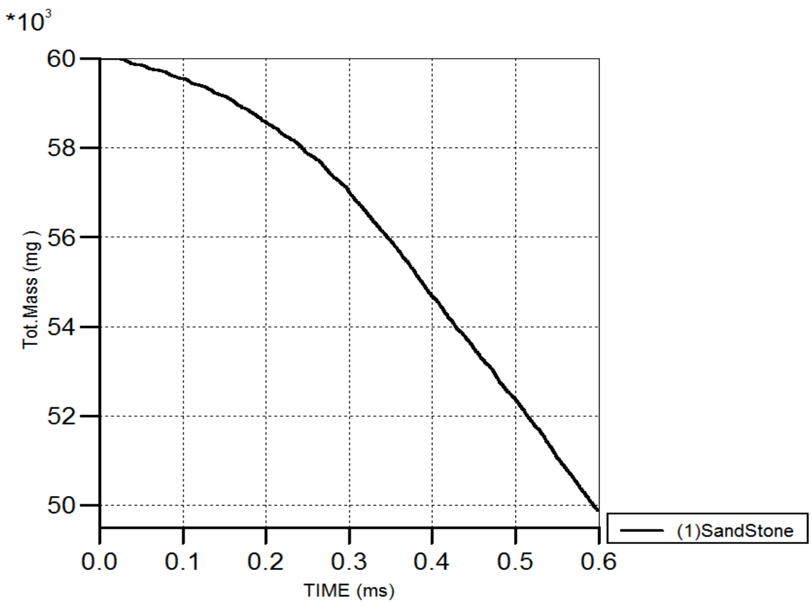


Figure 6: Total Mass of Sandstone as a Function of Time (Test 1)

$$Volume(m^3) = \frac{Mass\ (g)}{Density\ (\frac{g}{m^3})}$$

*Equation 8: Volume-Mass-Density Relation*

Using Equation 8 relation, the total volume removed from the rock is obtained as shown in Table 5.

Table 6: Mass and Volume Removed from the Rock (Test 1)

| Initial Mass (g) | Final Mass (g) | Total Mass Removed (g) | Volume of Rock Removed ($m^3$) |
|---|---|---|---|
| 60.00 | 49.488 | 10.512 | 5.26E-06 |

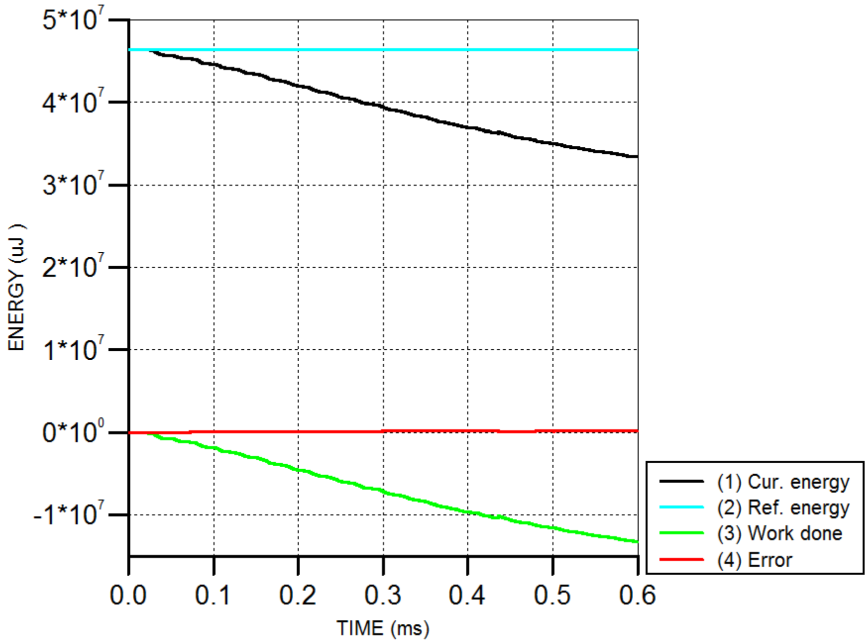


Figure 7: Energy Curves of the system as a Function of Time (Test 1)

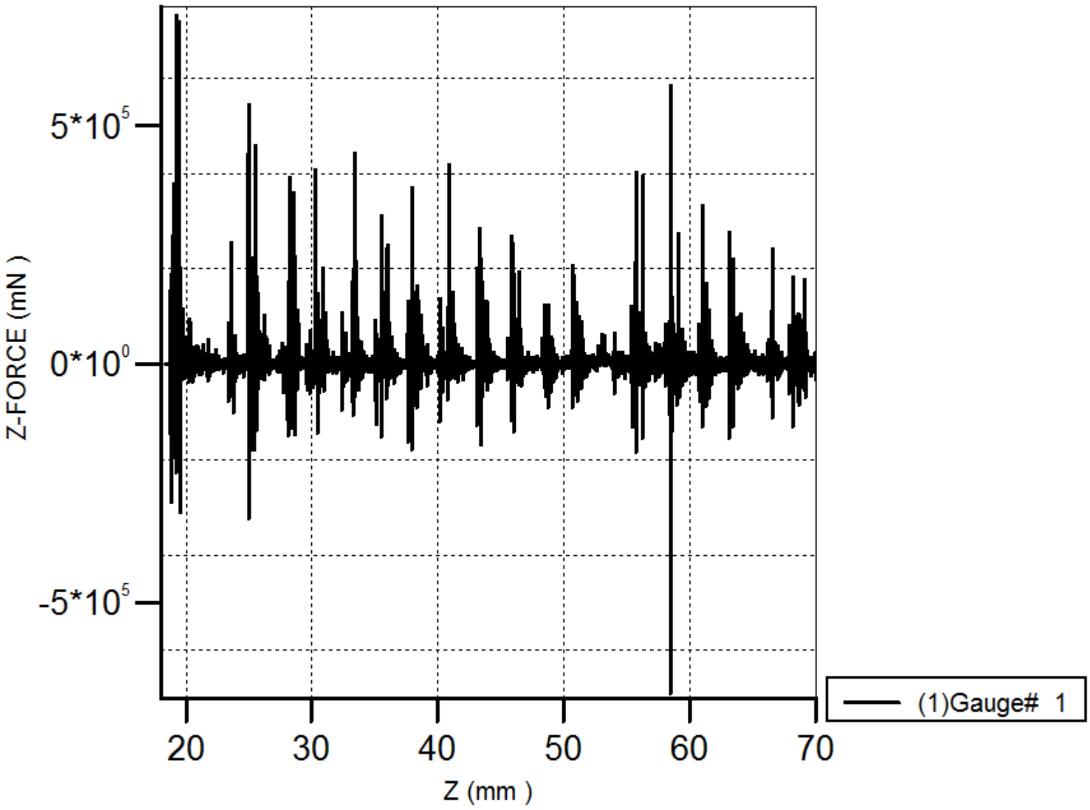


Figure 8: Force Applied on the Rock as a Function of Time (Test 1)

Table 7: Data Set for the Experiment Conducted (Phase 1)

| Test | Depth of Cut (mm) | Back Rake Angle (˚) | Side Rake Angle (˚) | Mass Removed (g) | Work Done (J) | Volume of Rock Removed ($m^3$) | MSE |
|---|---|---|---|---|---|---|---|
| 1 | 2.500 | -24.320 | 0.000 | 10.512 | 20.362 | 5.26E-06 | 3874048.71 |
| 2 | 2.500 | 39.320 | 0.000 | 4.986 | 4.646 | 2.49E-06 | 1863658.24 |
| 3 | 0.379 | 7.500 | 0.000 | 6.100 | 10.390 | 3.05E-06 | 3406557.38 |
| 4 | 4.621 | 7.500 | 0.000 | 8.238 | 14.849 | 4.12E-06 | 3605001.21 |
| 5 | 4.000 | 30.000 | -3.000 | 9.738 | 12.865 | 4.87E-06 | 2642226.33 |
| 6 | 1.000 | 30.000 | 3.000 | 5.435 | 8.756 | 2.72E-06 | 3222079.12 |
| 7 | 1.000 | -15.000 | -3.000 | 5.180 | 9.383 | 2.59E-06 | 3622934.36 |
| 8 | 2.500 | 7.500 | 0.000 | 10.512 | 20.362 | 5.26E-06 | 3874048.71 |
| 9 | 2.500 | 7.500 | 0.000 | 10.512 | 20.362 | 5.26E-06 | 3874048.71 |
| 10 | 2.500 | 7.500 | 4.243 | 5.214 | 9.490 | 2.61E-06 | 3640161.10 |
| 11 | 2.500 | 7.500 | -4.243 | 6.152 | 12.100 | 3.08E-06 | 3933680.10 |
| 12 | 4.000 | -15.000 | 3.000 | 9.918 | 16.827 | 4.96E-06 | 3393224.44 |

Based on Table 7, the data set was used as input into the Design Expert™ Code and the surface response was generated for both the outputs (MSE and Mass Removed). The study type was of Response Surface and the design type was of Central Composite. The RSM design data is further summarised in Table 7. The response surface is generated from the design as shown in Figure 8 & 9 for both the output.

Table 8: The RSM Design Summary (Phase 1)

| Factor | Minimum | Maximum | Mean | Standard Deviation | |
|---|---|---|---|---|---|
| Depth of Cut (mm) | 0.37868 | 4.62132 | 2.5 | 1.2792 | |
| Back Rake Angle (˚) | -24.3198 | 39.3198 | 7.5 | 19.1881 | |
| Side Rake Angle (˚) | -4.24264 | 4.24264 | 0 | 2.55841 | |
| Response | Minimum | Maximum | Mean | Standard Deviation | Model |
| MSE ($J/m^3$) | 1.86366E+006 | 3.93368E+006 | 3.41264E+006 | 608484 | Quadratic |
| Mass of Rock Removed (g) | 4.986 | 10.512 | 7.70808 | 2.39444 | |

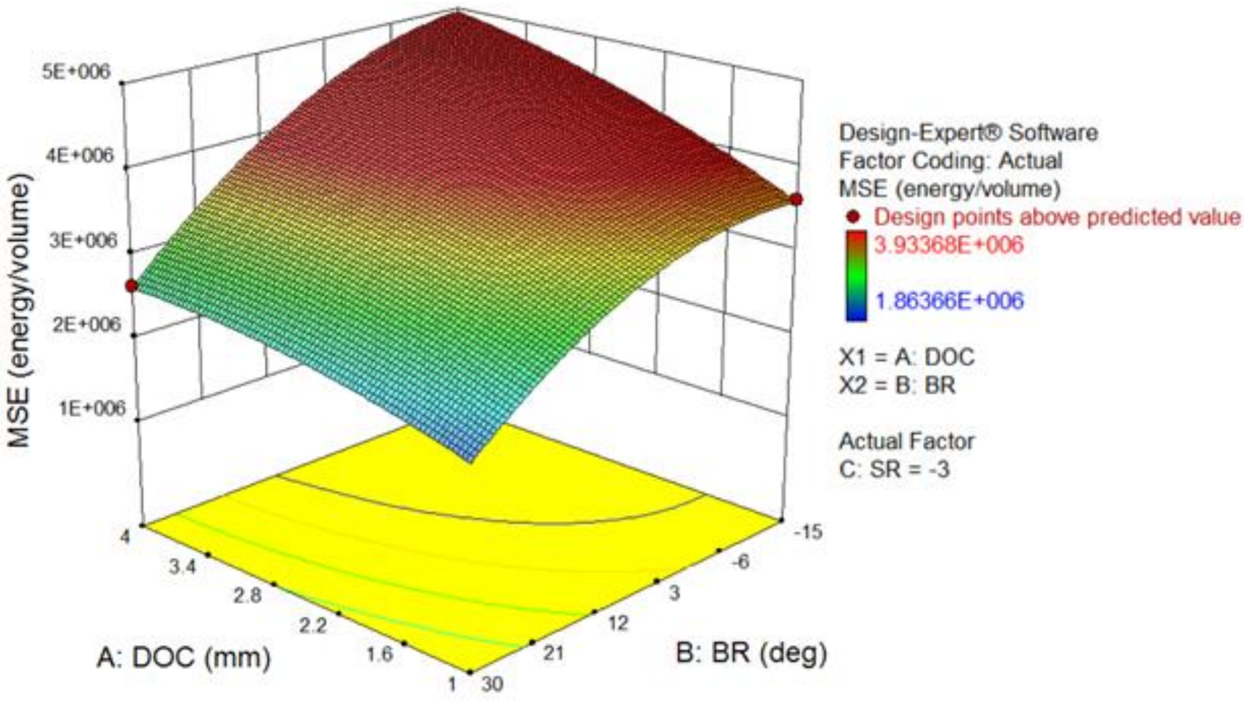


Figure 9: Response Surface for MSE (Actual Factor = Side Rake @ -3˚)

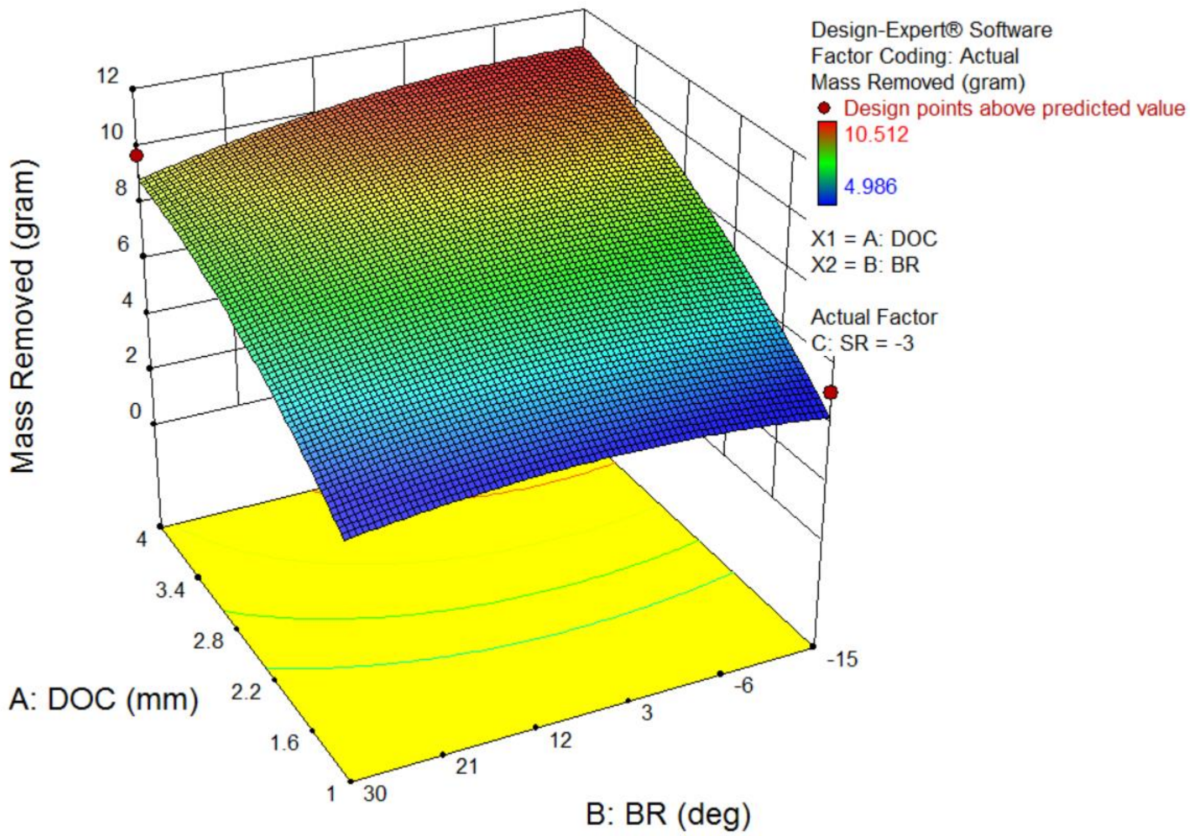


Figure 10: Response Surface for Mass Removed (Actual Factor = Side Rake @ -3˚)

## 4.2 Phase 2 Results

Based on the results obtained from phase 1, the cutter design is fixed to have a back rake angle of 30˚, side rake angle of -1.97˚, and depth of cut of 4 mm. Table 10 compiled the data obtained from test runs done in simulation using design parameters specified by the DOE Code.

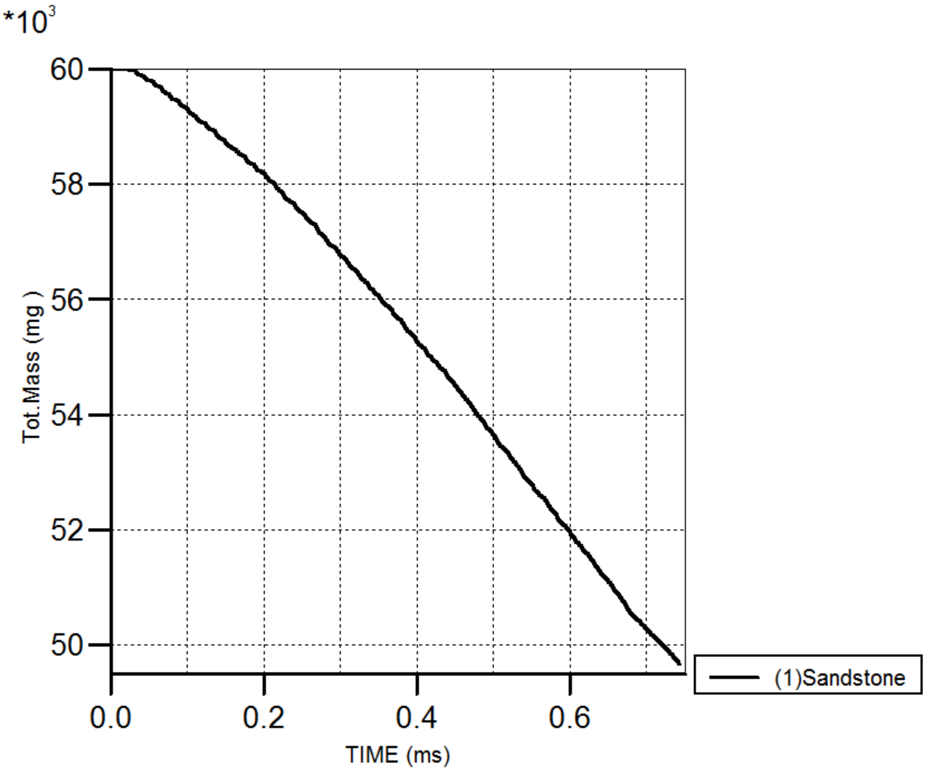


Figure 11: Total Mass of Sandstone as a Function of Time (Run 1)

Table 9: Mass and Volume Removed from the Rock (Run 1)

| Initial Mass (g) | Final Mass (g) | Total Mass Removed (g) | Volume of Rock Removed ($m^3$) |
|---|---|---|---|
| 60.00 | 49.66 | 10.34 | 5.17E-06 |

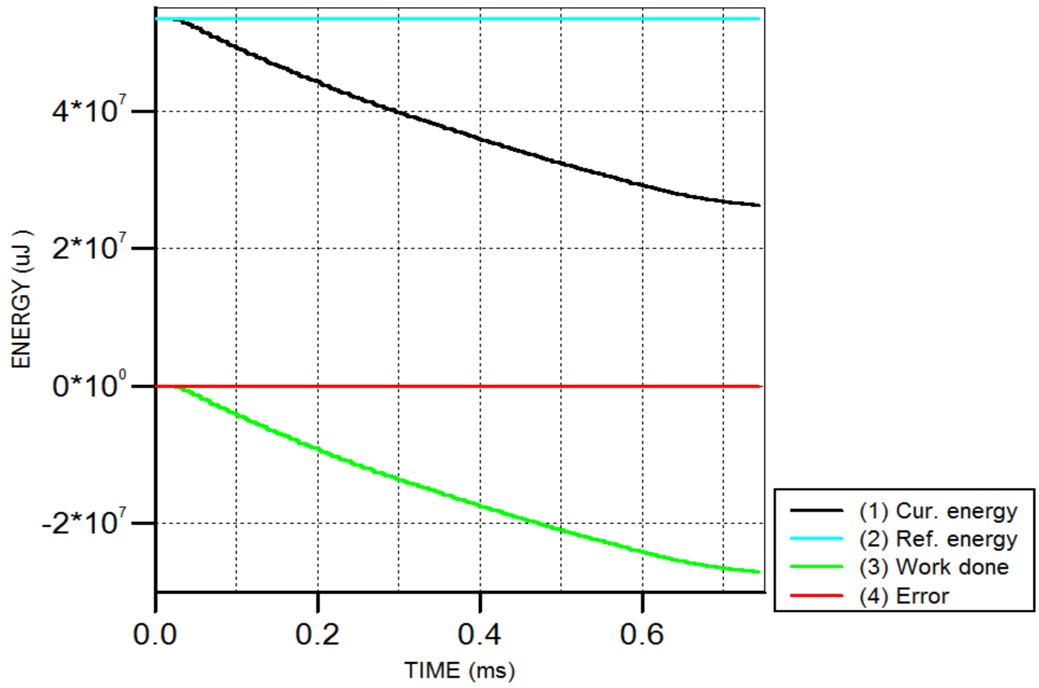


Figure 12: Energy Curves of the system as a Function of Time (Run 1)

Table 10: Data Set for the Experiment Conducted (Phase 2)

| Test | Cutter Velocity (m/s) | Weight-On-Bit (kN) | Bottom Hole Pressure (Pa) | Mass Removed (g) | Work Done (J) | Volume of Rock Removed (m3) | MSE |
|---|---|---|---|---|---|---|---|
| 1 | 0.864 | 0.494 | 0.000E+00 | 10.34 | 27.09 | 5.17E-06 | 5239845.26 |
| 2 | 2.985 | 0.494 | 6.895E+06 | 16.05 | 186.73 | 8.02E-06 | 23271435.69 |
| 3 | 0.864 | 2.965 | 6.895E+06 | 3.25 | 5.77 | 1.62E-06 | 3555144.79 |
| 4 | 3.424 | 1.730 | 3.448E+06 | 14.65 | 273.78 | 7.33E-06 | 37368456.97 |
| 5 | 2.985 | 2.965 | 0.000E+00 | 16.50 | 218.95 | 8.25E-06 | 26532961.71 |
| 6 | 1.925 | 1.730 | 8.323E+06 | 18.65 | 58.74 | 9.33E-06 | 6298627.49 |
| 7 | 1.925 | 3.477 | 3.448E+06 | 10.08 | 92.01 | 5.04E-06 | 18255952.38 |
| 8 | 0.425 | 1.730 | 3.448E+06 | 13.52 | 78.62 | 6.76E-06 | 11630177.51 |
| 9 | 1.925 | 1.730 | 3.448E+06 | 15.64 | 91.34 | 7.82E-06 | 11680306.91 |
| 10 | 1.925 | -0.018 | 3.448E+06 | 14.82 | 90.85 | 7.41E-06 | 12260458.84 |
| 11 | 1.925 | 1.730 | -1.428E+06 | 0.00 | 0.00 | 0.00E+00 | 0.00 |

Based on Table 10, the data set was used as input into the Design Expert™ Code and the surface response was generated for both the outputs (MSE and Mass Removed). The study type was of Response Surface and the design type was of Central Composite. The RSM design data is further summarised in Table 11. The response surface is generated from the design as shown in Figure 14 and 15 for both the output.

Table 11: The RSM Design Summary (Phase 2)

| Factor | Minimum | Maximum | Mean | Standard Deviation | |
|---|---|---|---|---|---|
| Cutter Velocity (m/s) | 0.424727 | 3.42427 | 1.9245 | 0.94854 | |
| WOB (kN) | -0.0177609 | 3.47676 | 1.7295 | 1.10506 | |
| BHP (Pa) | -1.428E+006 | 8.323E+006 | 3.4475E+006 | 3.08354E+006 | |
| Response | Minimum | Maximum | Mean | Standard Deviation | Model |
| MSE ($J/m^3$) | 0 | 3.73685E+007 | 1.41903E+007 | 1.12339E+007 | Quadratic |
| Mass of Rock Removed (g) | 0 | 18.652 | 12.1366 | 5.81671 | |

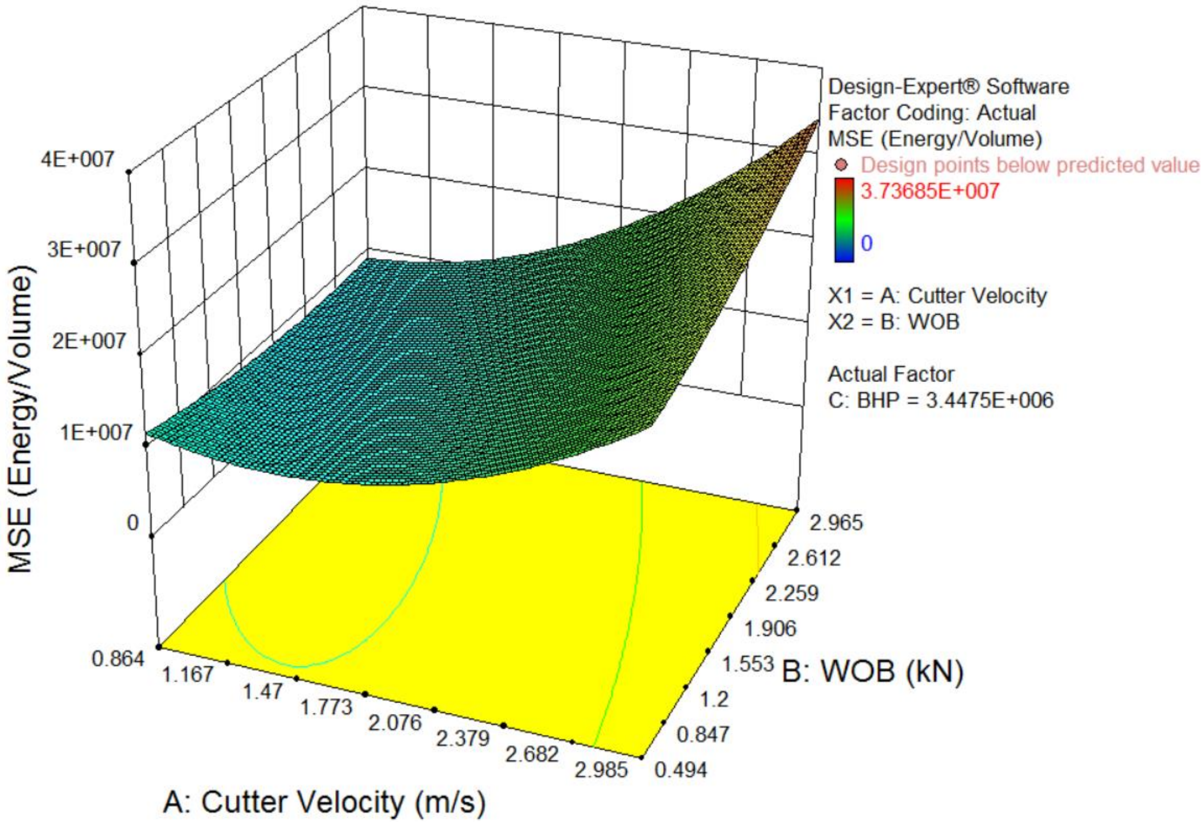


Figure 13: Response Surface for MSE (Actual Factor = BHP@3.4475E+06, Mean)

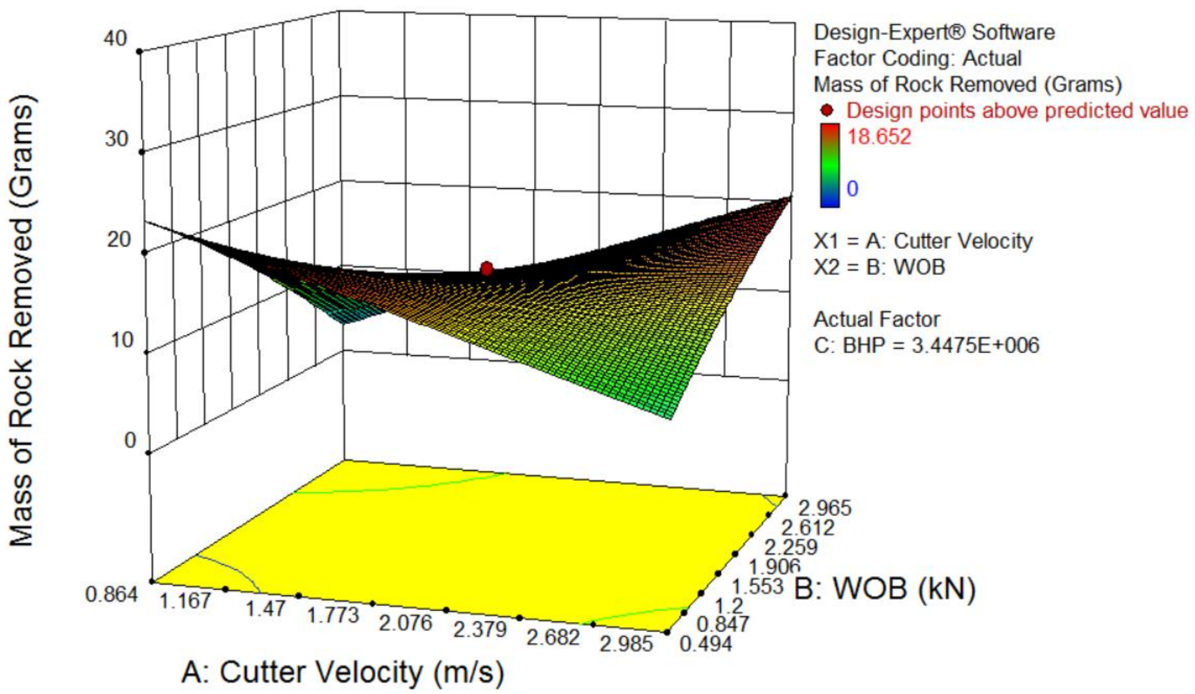


Figure 14: Response Surface for Rock Removed Mass (Factor = BHP@3.4475E+06, Mean)

## 4.3 Discussion and Analysis

### 4.3.1 Phase 1

After the response surface generation, the numerical analysis tool in the software is utilised and the best parameters is identified. Minimised MSE is stated as the condition. In addition, the input parameters should also be in the range of earlier specified limits. The result obtained is shown in Figure 9 with the desirability index.

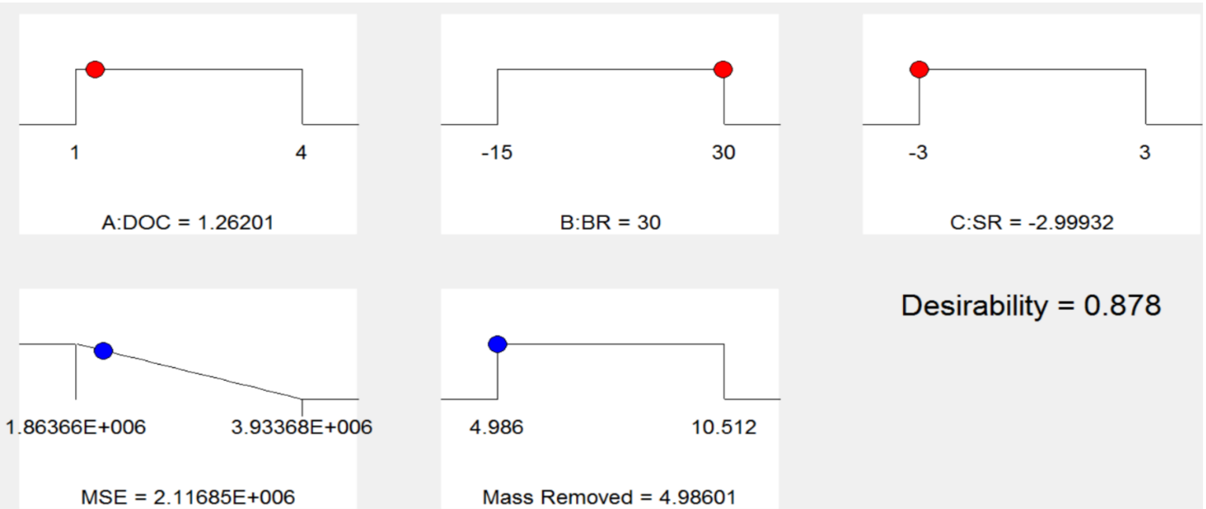


Figure 15: Ramp Graph of Optimisation with desirability index

Back Rake Angle Effect

From the analysis it was shown that, the largest back rake angle, +30˚, in the limit defined gave the lowest MSE by taking into consideration of side rake angle and DOC. The most basic idea one can get is that the surface area in contact is increased as the back rake angle is increased. As this will enable the cutter to engage with more mass being removed, thus volume. As per the equation defined in literature, MSE will decrease if the volume of rock cut is increased or the work done to remove the volume is decreased. Our objective is to decrease the MSE as low as possible. The phenomenon is in line with our objective. According to the theory, as more volume being removed, more work will be done which will increase the MSE. But the ratio of volume being removed was grater compared to the work done, thus resulting in lower MSE compared to other back rake angles. The value obtained shared similar outcome as per the study where work [8] reported that largest back rake angle used in the study is the most efficient back rake angle.

Side Rake Angle Effect

From the analysis, it was favoured to use -3˚ while taking into consideration of BR angle and DOC. This also shall be related to area of contact. As side rake angle is increased, in terms of value, more area come into contact. Therefore, it shared the same sentiment as the effect of back rake angle.

Depth of Cut Effect

From the response generated, it was to be noted down that, the DOC favoured is nearest to the lowest limit of the experiment. It can be reasoned as that increase in ratio of work done with volume removed is exceeding the lower level. The mass of rock removed is not take into consideration for analysis as computation of MSE has included the effect of mass removed, through the volume removed in calculation. As MSE is defined as Energy needed to remove a unit of volume, lower MSE will result in less energy consumed in drilling for the same amount of volume removed. The value obtained shared similar outcome as per the study where work [8] reported that smallest DOC used in the study is the most efficient DOC.

### 4.3.1 Phase 2

After the response surface generation, the numerical analysis tool in the software is utilised and the best parameters for specific bottom hole pressure is identified. Maximised rock removal and minimised MSE is stated as the condition at a specified BHP. In addition, the input parameters should also be in the range of earlier specified limits. The result obtained is analysed in Figure 16 & 17.

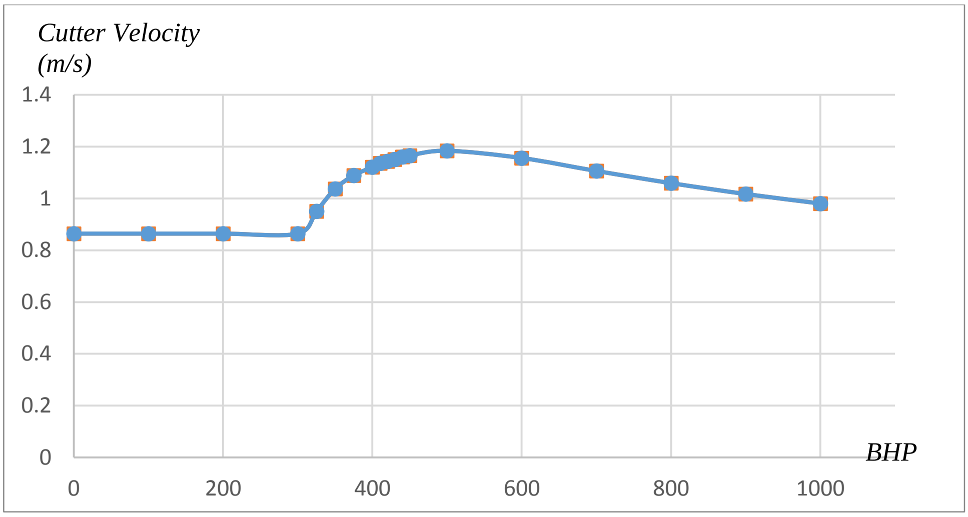


Figure 16: Optimum Cutter Velocity for Varying Bottom Hole Pressure

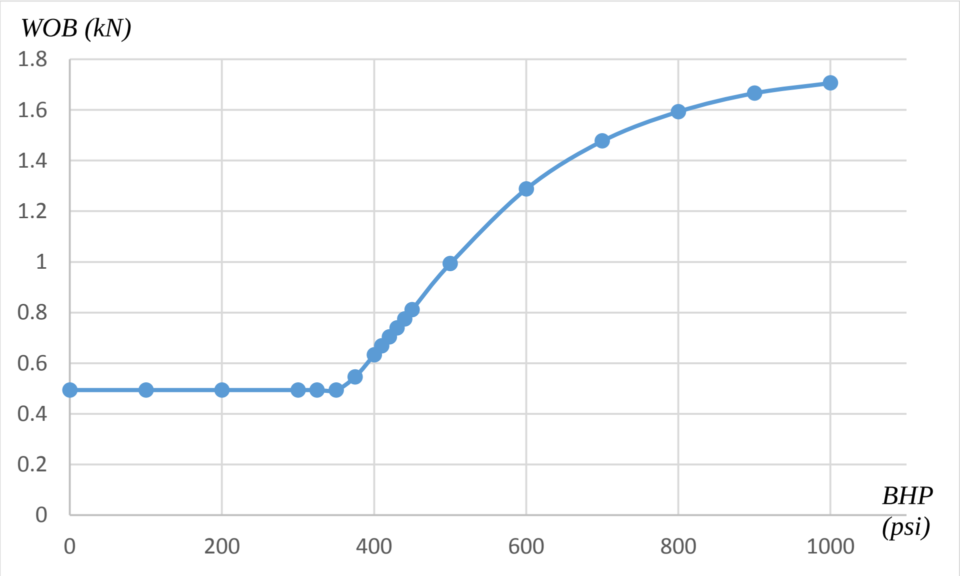


Figure 17: Optimum Cutter WOB for Varying Bottom Hole Pressure

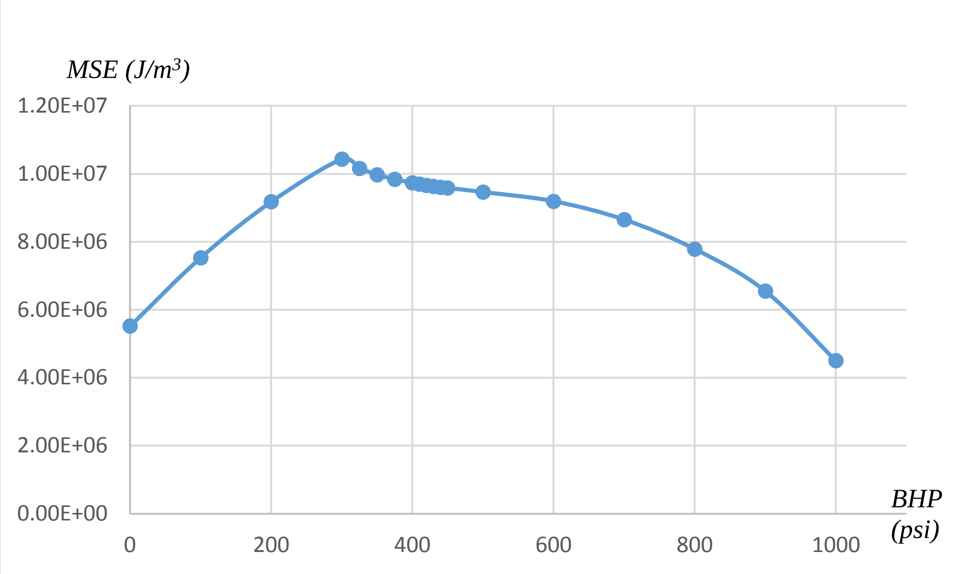


Figure 18: MSE Response for Varying Bottom Hole Pressure

Table 12: Optimum Output Table (Phase 2)

| BHP (PSI) | BHP(Pa) | Optimum Velocity (m/s) | Optimum WOB on Cutter (kN) | Optimum WOB (kN) | MSE | Optimum RPM |
|---|---|---|---|---|---|---|
| 0 | 0.00E+00 | 0.864 | 0.494 | 22.23 | 5.52E+06 | 123.7588837 |
| 100 | 6.89E+05 | 0.864 | 0.494 | 22.23 | 7.53E+06 | 123.7588837 |
| 200 | 1.38E+06 | 0.864 | 0.494 | 22.23 | 9.17E+06 | 123.7588837 |
| 300 | 2.07E+06 | 0.864 | 0.494 | 22.23 | 1.04E+07 | 123.7588837 |
| 325 | 2.24E+06 | 0.951 | 0.494 | 22.23 | 1.02E+07 | 136.2207158 |
| 350 | 2.41E+06 | 1.037 | 0.494 | 22.23 | 9.97E+06 | 148.5393084 |
| 375 | 2.59E+06 | 1.089 | 0.546 | 24.57 | 9.84E+06 | 155.9877597 |
| 400 | 2.76E+06 | 1.121 | 0.633 | 28.485 | 9.74E+06 | 160.5714221 |
| 410 | 2.83E+06 | 1.136 | 0.668 | 30.06 | 9.70E+06 | 162.7200138 |
| 420 | 2.90E+06 | 1.143 | 0.704 | 31.68 | 9.66E+06 | 163.72269 |
| 430 | 2.97E+06 | 1.151 | 0.739 | 33.255 | 9.63E+06 | 164.8686055 |
| 440 | 3.03E+06 | 1.160 | 0.774 | 34.83 | 9.60E+06 | 166.1577606 |
| 450 | 3.10E+06 | 1.166 | 0.811 | 36.495 | 9.58E+06 | 167.0171973 |
| 500 | 3.45E+06 | 1.184 | 0.993 | 44.685 | 9.46E+06 | 169.5955074 |
| 600 | 4.14E+06 | 1.156 | 1.288 | 57.96 | 9.19E+06 | 165.5848028 |
| 700 | 4.83E+06 | 1.106 | 1.477 | 66.465 | 8.65E+06 | 158.4228304 |
| 800 | 5.51E+06 | 1.059 | 1.593 | 71.685 | 7.78E+06 | 151.6905763 |
| 900 | 6.20E+06 | 1.017 | 1.666 | 74.97 | 6.55E+06 | 145.6745194 |
| 1000 | 6.89E+06 | 0.980 | 1.706 | 76.77 | 4.50E+06 | 140.4176316 |

Referring to Fig 16 & 17, it is to be noted that the optimum cutter velocity and WOB remains the same as this proves that at low confining pressures, there is no effect on the energy required to remove the rock. But as soon as BHP exceed the threshold of 350 psi, the optimum WOB and cutter velocity increases. An interesting phenomenon occur where the optimum cutter velocity after 500 psi threshold. This might be reasoned with the increasing optimum WOB as it helps to offset the reduction in cutter velocity. It is also to be noted that, past the 300 psi threshold, referring to Fig 18, the MSE output decreased with the optimised cutter velocity and optimised WOB. From fig 18, it can be noted that downhole pressure decreased the MSE as it can be reasoned as the downhole pressure assisted the cutter in crushing the rock. The optimum WOB and Optimum RPM for the specified bottom hole pressure is given in Table 12. This values can be included in the power calculation for the drilling contractors.

# CHAPTER 5: CONCLUSION & RECOMMENDATION

The results obtained are in agreeing terms of the past researches. The parameters taken into consideration are the back rake angle, side rake angle and depth of cut for the phase 1 simulation. In phase 2, the operating parameter were taken into account to find the optimum value utilising the optimum design values identified in phase 1. The factors affecting the cutter performance from the design point of view and operational parameter view is analysed. After all the data input, it has been found out that a cutter design with depth of cut 1.26 mm, back rake angle of 30˚, and side rake angle of -3˚ produces the output of lowest MSE. In phase 2, optimum values of WOB and Bit Rotary speed is identified under various bottom hole pressure which are the operational parameters identified affects the cutter efficiency. The list of optimum values is listed in Table 2. The objectives of this study is met.

In future work, the parameters affecting from the rock properties factors will be taken into consideration such as various rock densities, micromechanical properties and rock UCS. Different designs of cutter also shall be considered in future works. It will be best to use the results of the tests for calibration of model which will be allowed for tuning better model parameters and consequently enhance qualitative results in the analysis of rock-cutter interaction. Usage of this results will also be used to set up an experimental setting for validating the output obtained from this work.

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