STUDY OF THE CUTTER DESIGN OF PDC DRILL BITS ON EFFECT OF BACK RAKE ANGLE AND SIZE OF THE CUTTER ON WEAR RATE

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MECHANICAL ENGINEERING

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by

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Dissertation submitted in partial fulfilment of the requirements for the

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FINAL YEAR PROJECT DISSERTATION

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BACHELOR OF ENGINEERING (HONS) MECHANICAL

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CERTIFICATION OF APPROVAL

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Approved by,

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UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

May 2015

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 that the original work contained herein have not been undertaken or done by unspecified sources or persons.

MOHAMAD AZRIN BIN FAUZI

ABSTRACT

In the oil and gas industry, drilling is one of the most important aspects due to the economics and high demand. Reduction in drilling time is required to minimize the cost of operations. This study focuses on the Polycrystalline Diamond Compact (PDC) drill bit which is categorized as fixed cutter of drilling bit. Problem such as wear and tear of PDC cutter is one of the main factors in drilling process failure and this would affect the rate of penetration. Thus, an intensive study in drill bit design would save a lot of money if the efficiency of drill bit can be improved. The objective of this project is to finding optimal design of PDC cutter and study the effect of design improvement to the wear rate. Derive an analytical model of PDC Cutter. Developing simulation modelling the PDC cutter and to determine the optimal characteristic of PDC cutter. The analytical model will be developed to collect the required results. Author will proceed with the simulation modeling using Autodesk Inventor for 3D drawing, which is based on the results of the analytical model. The modeling varies based on the back rake angle and the size of cutter. Subsequently, the experiment modeling will be conducted using ANSYS Explicit Dynamic by certain parameters and constant for the drilling simulation based on the cutter parameters. After that, the result from the experiment will be analyzed, in which the optimal characteristic of the cutter is obtained.

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In the name of ALLAH the most graceful and the most merciful, all the praises to ALLAH who rules the world.

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NOMENCLATURE

PDC = Polycrystalline Diamond Compact

ROP = Rate of Penetration (m/h)

WOB = Weight on bit

TOB = Torque on bit

CAD = Computer Aided Drawing

F_N = Normal Force

F_H = Horizontal force

σ = normal stress

τ = shear stress

θ = angle made by failure plane with horizontal

d = depth of cut

F = resultant force from the wedge acting on the chip

ϕ = angle of resultant force with the normal

α = back rake angle

β = side rake angle

W = Wear Rate

CHAPTER 1: INTRODUCTION

1.1 Background of Study

Oil currently the dominant source of energy. It is not only used for transport but also for industry and homes. Oil is the main source of liquid energy where a naturally occurring liquid, gas, semi-solid or solid mixture of hydrocarbons and non-hydrocarbons molecules as mentioned by Bourgoyne *et al*. (1986). Oil is formed from accumulated naturally from thousand feet below the Earth's surface. In order to extract the oil it begins with the exploration work.

An exploration work start from gravity or magnetics acquisition, geological field work, seismic acquisition and reprocessing, seismic interpretation, geological model, well proposal and well drilling. Gravity or magnetics acquisition are perform by airbone gravity survey and geological field work aims at gathering data for sedimentology, structural, regional and geochemical analyses. Seismic data acquisition performs once an interesting site is located. The seismic data is recorded to see the subsurface. The raw data need mathematical and physics wave theory processing before anything can be seen on seismic sections. Sophisticated computing systems are used in seismic processing and interpretation.

Formation evaluation is the process used to determine if rock layers contain hydrocarbon. This process can determine if sufficient quantities of hydrocarbons are present and if the rock has enough permeability to allow a commercial completion of the drilling process using a drill rig.

1.1.1 Drill rig

A production well is drilled with a drilling rig located on the production platform or with a rig close to platform and production equipment. A drilling rig is a machine which creates holes in the earth sub-surface. A drilling rig comes in varieties depending on requirements and needs. The types of drilling rig are shown in Figure 1.1.

Figure 1.1: Types of Rigs
Source: *maersk.com*

Land rigs as the name implies, these rigs are primarily used on land. It is the most common used for exploration. Drilling barge operates in shallow water consists of a barge with a complete drilling rig and ancillary equipment constructed on it in Offshore Operations Subgroup (2011). Jack-up rig is a floating barge containing outfitted with long supports legs drilling structure that can be raised or lowered independently as mentioned by Tanaka (2005). Semi-submersible rigs are floating vessels supported on large pontoon-like structure that submerged below the sea surface. Drillship is used for farther offshore exploration mounted on ship that can drill a well in water up to 12,000 feet. Drillship is not as stable in rough sea compared to semi-submersible but having more storage capacity.

Drill rig consist of five main components as shown in Figure 1.2, where derrick is the main parts which is a structure with four supporting legs resting on a square base. Rotating equipment from top to bottom consists of swivel, Kelly, drill string and bit. Swivel is a component which attached to the hoisting equipment to carries the entire weight of the drill string but allows it to rotate freely. In addition, the swivel is not rotate but allows everything below it to rotate. Kelly is a short piece of pipe. The Kelly is approximately 40 feet long, square or hexagonal on the outside and hollow throughout to provide a passage way for the drilling fluid. The drill string is made up of the drill pipe and drill collar which come in sections or joints. The purpose of the drill collars is to put extra weight on the bit. The drill bits are located at the bottom end of the drill string and responsible for actually making contact with the subsurface layers and drill through them. Detail processes are elaborated as follows.

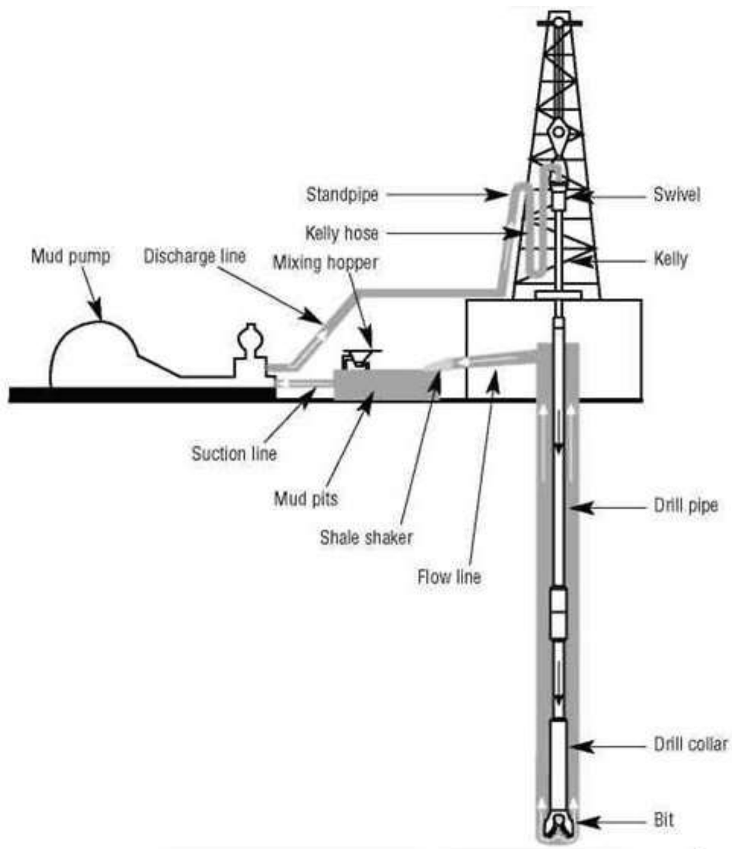


Figure 1.2: Drill Rigs components
Source: piping-engineering.com

1.1.2 Drilling Process

Once the operation of the drilling process begins, the drill bit is lowered into the hole by adding sections of drill pipe at the surface. This pipe is pumped full of drilling fluid, or "mud," which travels down the pipe, through the bit, and back to the surface, carrying rock pieces, called cuttings in Marathon Oil Corporation (2010). The mud has several functions. As it passes out of the drill bit, it lubricates the cutting surface, reduces friction and wear and keeps the drill bit cooler. Additionally, it carries rock cuttings away from the drill bit and back to the surface for separation and disposal. According to Bourgoyne *et al. (*1986), while traveling back up the hole, the mud also provides pressure to prevent the hole from caving in on itself.

1.1.3 Drill Bits

The drill bits are located at the bottom end of the drill string. The drill bits responsible for making contact with the subsurface layers and drilling through them for breaking up and dislodging rock and sediment that may encountered while drilling.

The drill bits can be categorized into three types which is fixed cutter bits, roller cone bits and percussion hammer bits, each designed for different subsurface drilling condition. Different rock layer experienced during drilling may require the use of different drill bits to achieve maximum drilling efficiency. Hammer bits are not widely used since the hammer bits act as only for crushing the rock and not to drill the formation. Fixed and roller types are the mostly used in drilling process.

Roller cone bits usually have three cone-shaped steel devices that are free to turn as the bit rotates. This type of bit work by gouge chip and crushing the rock and it is divided into two categories which is Tungsten Carbide Insert bit (TCI) and Milled Tooth Bits as shown in Figure 1.3. Tungsten Carbide is one of the hardest material and capable of drilling hardest abrasive formation. Milled Tooth bit are also called as tube bit and best is softer formation sensibly less expensive than other type of bits.

Fixed-head bits rotate as one piece and contain no separately moving parts and it work by shearing and scraping through rock. Fixed-head bits are divide into three categories which is Natural Diamond bit, Impregnated bit and Polycrystalline Diamond Compact (PDC) bit as shown in Figure 1.4. When fixed-head bits use PDC cutters, they are commonly called PDC bits. Natural Diamond bit have industrial grade diamond set in the butt surface to create an abrasive cutting face and primarily used in hard abrasive formation and does not effective in soft formation due to their smoother surface profile. An impregnated bit have PDC cutter protruding straight out of bit body thus increases cutter ability in lateral cutting and keeps the cutter sharp as their wear. PDC bits have a tungsten carbide cutter topped with hard cap of diamond composite material. Since this project focusing on PDC drill bits, further discussion on this matter will be given.

Figure 1.3: Roller Cone Bits
Source: downhole drilling tools

Figure 1.4: Fix-Head Bits
Source: hughes christensen

1.1.4 PDC Drill Bit

Polycrystalline diamond compact (PDC) bits have been significant contributors to the great improvement in efficiency and economics of oil and gas drilling as mentioned by Bellin *et al.* (2010). PDC bits are designed and manufactured in two structurally dissimilar styles which are matrix-body bit and steel-body bits. According to Bourgoyne *et al.* (1986), the two provide significantly different capabilities, and because both have certain advantages, a choice between them would be decided by the needs of the application. PDC are best performing in soft, firm and medium-hard non-abrasive formation.

The main parts of the PDC drill bits are shown in Figure 1.5. The nozzle located near the center of the bit act as cleaning and cooling of cutters. The main functions of nozzle are to remove and sweep the chip while drilling process. Blades are one of the main parts of drill bits. Blades are the one who hold the cutter. Lastly the most important parts of drill bits is the cutter itself. Cutters are the part that contacts a formation by shearing the formation.

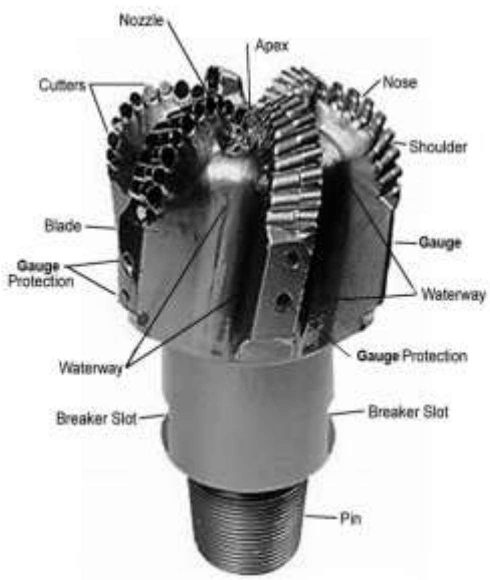


Figure 1.5: PDC drill bit components
Source: petrowiki.org

1.2 Problem Statement

Failure of PDC drill bit often happen during drilling operation due to cutter damage such as chipped cutter, lost cutter, broken cutter and junked damage. This problem leads to low rate of penetration which consequently affects the drilling performance and cost. Hardness of formation is one the factor that leads to cutter damage. However, low rate of penetration also caused by the design of the drill bit for example the back and side rake angle, size of cutter and shape of cutter.

Drilling high compressive strength rocks that are highly abrasive has always been a challenge for PDC cutters. When a rock has a high compressive strength, high force is required for the cutter to penetrate the rock. High cutting forces cause problems. When the high cutting forces are transmitted to the drill string, drilling problems occur. For example, the drill string can buckle or bow causing unwanted deviation of the well as mentioned by Islam (2008). High forces cause problems within the cutter. The higher forces cause more frictional heating. The heating causes rapid wear of the PDC cutter. Heating of the cutter causes thermal stresses within the cutter and subsequent cracking. These problems make drilling the formation with PDC cutters uneconomical.

Currently high compressive strength abrasive formations can be drilled with impregnated drill bits. Impregnated drill bits can resist the higher heat of high bit weights. However, it takes small depths of cut. To drill sufficiently fast, they must be turned at a high rpm according to Islam (2008). Turning at a high rpm requires special equipment, increasing the cost of drilling operations.

High abrasive formations can be also drilled with insert rock bits. These bits require high levels of weight to drill efficiently. The high WOB increases the risk of the drilling problems mentioned above by Islam and Khan (2008). It also causes rapid wear of the seals and bearings of the rock bit. This shortens bit life requiring the operator to frequently change the bit.

Therefore, this project will focus on the wear characteristics of PDC cutters. In addition, this research involves the analysis of suitable characteristic of the cutter in reference to reduce its wear reduction rate. It is well known that different formation comprises of different hardness level of rocks, and therefore different type of formation requires different characteristic of the cutter in order to shear the rocks. Selecting a proper cutter characteristic for drillings in medium abrasive formation are very vital because the selection of parameters helps to prolong the cutter life as well as maximize the rate of penetration (ROP).

1.3 Objectives

The aim of this study of PDC Drill bit cutter is as stated below:

- To derive analytical model of PDC Cutter in hard abrasive formation drilling.
- To develop simulation modeling the PDC cutter in hard abrasive formation.
- To determine the optimal characteristic of PDC cutter in hard abrasive formation.

1.4 Scope of study

The scope of study based on objectives can be simplified. Firstly by deriving analytical model of PDC cutter and analyze the mechanical characteristic of the cutter such as size, material type, cutting angle, shape, expose value and parameter on cutting efficiency and also their effect to the behavior of hard rock formation. 3D modeling by using CAD software which is Autodesk Inventor will be utilized in the study. This study will also integrate drilling simulation software using ANSYS Explicit Dynamic for the analysis of the cutter parameters.

1.5 The Relevancy of the Project

This project is relevant to the author since it is involves a very comprehensive study on theory and the application. The theory and calculations used comprises of general oil and gas as well as mechanical knowledge which can be applied in the industry.

1.6 Feasibility of the Project within the Scope and Time Frame

This project is within the capability of a final year student to be executed with the help and guidance from the supervisor or co-supervisor. Solid Mechanic and Computer Aided Engineering courses is one of the compulsory subjects a Mechanical Engineering student in order to perform this project. Therefore, the author has a knowledge that are useful and can be implemented for this project. The time frame is also feasible and the project can be completed within the allocated time.

CHAPTER 2: LITERATURE REVIEW

2.1 Overview/Introduction

This chapter will review the past study of PDC drill bit cutter and also covered on materials used in cutter, shape of the cutter, size of cutter, cutter back rake angle and PDC design.

2.1.1 PDC cutter

A PDC cutter utilizes the combination of an elliptical shape with higher thermal resistance obtained through leaching. A tungsten carbide portion includes protrusions which extend from a surface thereof in a pattern. The diamond volume is mounted to the surface wherein the protrusions allow for better attachment as well as for the diamond volume to be larger about a perimeter edge of the cutter and smaller/shallower in a center region of the cutter.

In an embodiment, a PDC cutter comprises a tungsten carbide substrate having a top surface including a protrusion pattern formed in a center portion of the top surface and a diamond table mounted to the top surface of the tungsten carbide substrate. The diamond table is thicker at a perimeter of the top surface and thinner at the center portion of the top surface, and the diamond table is leached.

The invented configuration of PDC cutter seeks to increase drilling efficiency by the shape of the PDC cutter requires less weight on bit than conventional PDC cutters, lessening wear and cracking due to frictional heating as mentioned by Cuillier *et al.* (2007). It is composed of preferred PDC materials to increase the cutters resistance to heat. The shape of the cutter is optimized for high strength to reduce damage from high down whole forces. The shape of the cutter is optimized for easier cooling from the flow of the surrounding fluid. These combined factors enable the economical drilling of formations that were not previously drillable by PDC cutters. The PDC cutters increase the rate of penetration beyond impregnated or rock bits.

Figure 2.1: example of PDC cutter
Source: pdccutters.com

2.1.2 PDC Cutter Materials

Diamond is the hardest material known. This hardness gives it superior properties for cutting any other material. PDC is extremely important to drilling, because it aggregates tiny, inexpensive, manmade diamonds into relatively large, inter grown masses of randomly oriented crystals that can be formed into useful shapes called diamond tables by Kerr (1988). Diamond tables are the part of a cutter that contacts a formation. Besides their hardness, PDC diamond tables have an essential characteristic for drill-bit cutters and they efficiently bond with tungsten carbide materials that can be attached to bit bodies.

Diamond grit is commonly used to describe tiny grains of synthetic diamond used as the key raw material for PDC cutters. In terms of chemicals and properties, manmade diamond is identical to natural diamond. According to Sun *et al.* (2000), making diamond grit involves a chemically simple process: ordinary carbon is heated under extremely high pressure and temperature.

Individual diamond crystals contained in diamond grit are diversely oriented. This makes the material strong, sharp, and, because of the hardness of the contained diamond, extremely wear resistant. In fact, the random structure found in bonded synthetic diamond performs better in shear than natural diamonds, because natural diamonds are cubic crystals that fracture easily along their orderly, crystalline boundaries.

2.1.3 Cutter Shape

The most common PDC shape is the cylinder, partly because cylindrical cutters can be easily arranged within the constraint of a given bit profile to achieve large cutter densities. Electron wire discharge machines can precisely cut and shape PDC diamond tables as shown in Figure 2.2. Non-planar interface between the diamond table and substrate reduces residual stresses. According to Sun *et al.* (2000), these features improve resistance to chipping, spalling, and diamond table. Other interface designs maximize impact resistance by minimizing residual stress levels.

Figure 2.2: PDC shape
Source: New Cutting Structure Design Improves the Performance of the PDC Bit

Certain cutter designs incorporate more than one diamond table. The interface for the primary diamond table is engineered to reduce stress. A secondary diamond table is located in the high-abrasion area on the ground-engaging side of the cutter. This two-tier arrangement protects the substrate from abrasion without compromising structural capability to support the diamond table.

Highly specialized cutters are designed to increase penetration in tough materials such as carbonate formations. Others include engineered relief in the tungsten carbide substrate that increases penetration and reduces requirement for WOB and torque, or beveled diamond tables that reduce effective cutter back rake and lower bit aggressiveness for specific applications by Kerr (1988).

2.1.4 Cutter Size

From a previous test at the CTF by Sinor *et al.* (1998) indicated that a PDC bit with smaller cutters diameter wore faster. The objective of the test was to determine if smaller diameter cutters would minimize cutter wear and possibly drill harder stringers since the depth of cut was smaller. However the smaller depth of cut could possibly improve cutter strength, especially through nonhomogeneous formations opposite to the theory that bigger chips resulted less wear.

Sinor *et al.* (1998) prove that 8 mm cutters are shown to be worn much higher than the 13mm. The bit with 8mm cutters had wear past the end of the carbide pockets on a number of cutters. Out toward the O.D. taper, the usable diamond was worn into the matrix of the blades. Wear and temperature reached a point that one cutter actually became debrazed from the cutter pocket.

PDC bits with four blades each were designed and built for testing to further evaluate the effect of cutter size on wear rate. The bits were designed to have 7° back rake on the cutters inside the cone, 10° angle at the nose, and 15° on the taper of the bit versus the standard 20° back rake. The variable of these three bits was the size of the PDC cutters which is 19mm, 13mm, and 8mm respectively. Figure 2.3 shows the top and side view of the three four bladed bits.

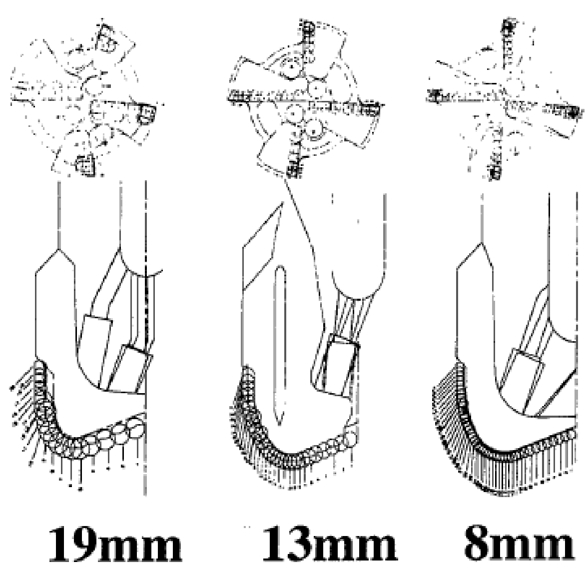


Figure 2.3: Cutter Size
Source: SPE International

2.1.5 Cutter Back Rake Angle

The cutter back rake angle used on most commercial PDC bit designs is 20°. Cutter back rake angle is defined as the angle the cutter face makes with respect to the rock as shown in Figure 2.4 below. First, we need to understand why the use of 20° back rake angle became standard on PDC Bits to know are the use of one back rake angle the best solution for all drilling conditions.

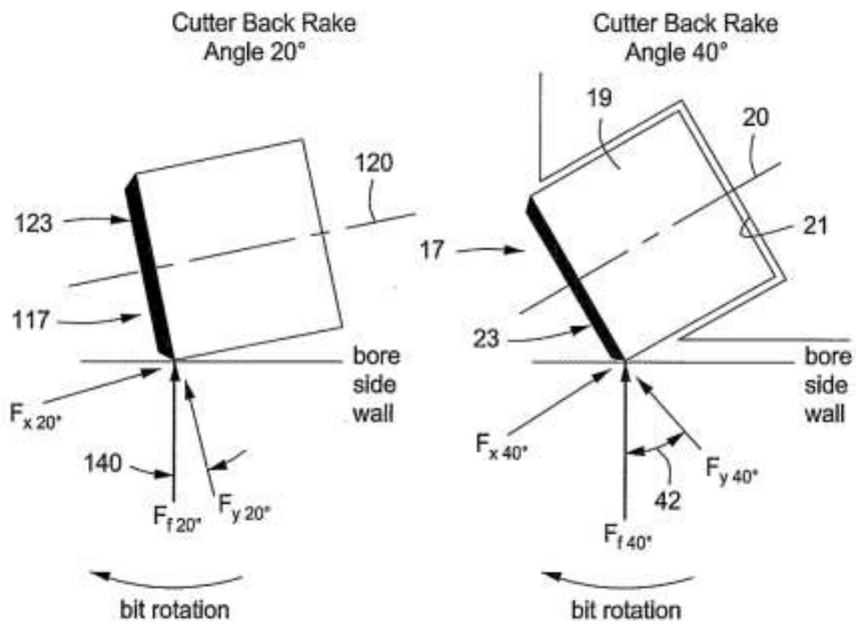


Figure 2.4: PDC Cutter showing back rake angle
Source: Bracewell and Giuliani LLP

Reported by Hibbs (1978) that the forces required to cut Jack Fork sandstone with 8.1mm cutters were minimized at rake angles between 10° and 20° regardless of speed. Followed up by Hough (1986), the work with the analysis of cutter back rake angles 7°, 15°, 20°, and 25° while cutting Mancos shale under atmospheric conditions. He concluded that the mean penetration rate for bits with 15°, 20°, and 25° back rake were statistically the same and superior to the bit with 7° back rake. The bit with 20° back rake gave the highest mean rate of penetration although it was not statistically superior to the bits with 15° or 25°. Hibbs (1978) also reported that the bit with 7° back rake gave the lowest torque. In conclusion of Hibbs (1978) report, 20° of back rake angle gave the maximum rate of penetration and would be the best choice for drilling in shales if other factors were properly considered.

2.1.6 PDC design

Drill bit design is one of the factors affecting the rate of penetration. According to Gerbaud *et al.* (2006), to obtain required drilling performance, drill bit designer adjusts some features in the drill bit. There are three main design feature affecting PDC bit performance according to Kerr (1998) in his journal entitled "PDC Drill Bit Design and Field Application Evolution". The features are number of cutter, back rake angle and side rake angle.

The cutter of a PDC bits are mounted on a bit body. There are two types of bit body used for PDC drill bits which are steel and matrix body bit. Steel body bits in Figure 2.5 use a stud cutter that is interference-fitted into a receptacle on the bit body. The advantage of using a stud is it can be removed or replaced if the cutter is damaged and the body of the bit is not damaged. However, erosion of the cutter often happens when using this type of bit body. Kerr (1998) stated that matrix bit body in Figure 2.6 used cylindrical cutter that is brazed into a pocket after the bit body has been furnace by conventional diamond contact bit techniques. The advantage of this type of bit is both erosion and abrasion resistant. However, matrix body bit has economic disadvantages because raw materials used in their manufacture are more expensive.

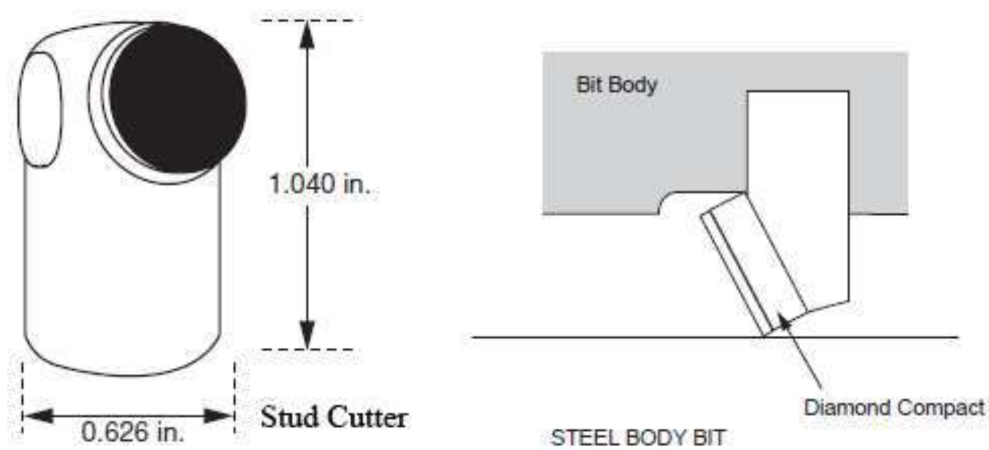


Figure 2.5: Steel Bit Body & Stud Cutter

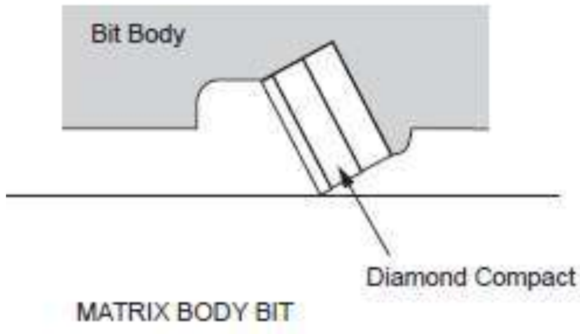


Figure 2.6: Matrix Body Bit

There are two rakes angle can be set for PDC cutters which are back rake and side rake. Both these rakes angle affect performance of PDC drill bit. Back rake angle is determined the size of cutting that is produced. Meanwhile, side rake is used to direct the formation cutting towards the flank of the bit and into annulus. According to previous research conduct by Rajabov *et al.* (2012), indicated that a cutter with low back rake angle requires less horizontal cutting force. PDC with lower back rake angle drill more efficiently. Side rake angle affect the cleaning of a PDC bit in that a cutter that uses side rake mechanically directs cuttings towards the annulus. In addition, Kerr (1998), states that a greater depth of cut is achieved with a smaller back rake angle, which generally produces a larger chip. In addition, the smaller the rake angle, however, makes the cutter more vulnerable to impact breakage should a hard formation be encountered.

Pain *et al.* (1985) indicated that as cutter density or the number of cutters of PDC but increase, ROP will decrease. Adding more cutters to the bit face reduces the efficiency of cleaning, which directly affects ROP's. However, increasing cutter density of a given PDC drill bit will reduce the effective load per cutter. Kerr (1998) explains the work rates and wear rates of individual cutters will be decreased, which extend bit life.

2.2 Critical Review

This section will discuss analysis and experimentation of PDC cutter. Different analysis of PDC cutter will be discussed. This chapter will show from which journals/articles the author gets from and sort according to general themes such as numerical, computational, and experimental, the critical review process is depicted in Figure 2.7, the overview of the critical review.

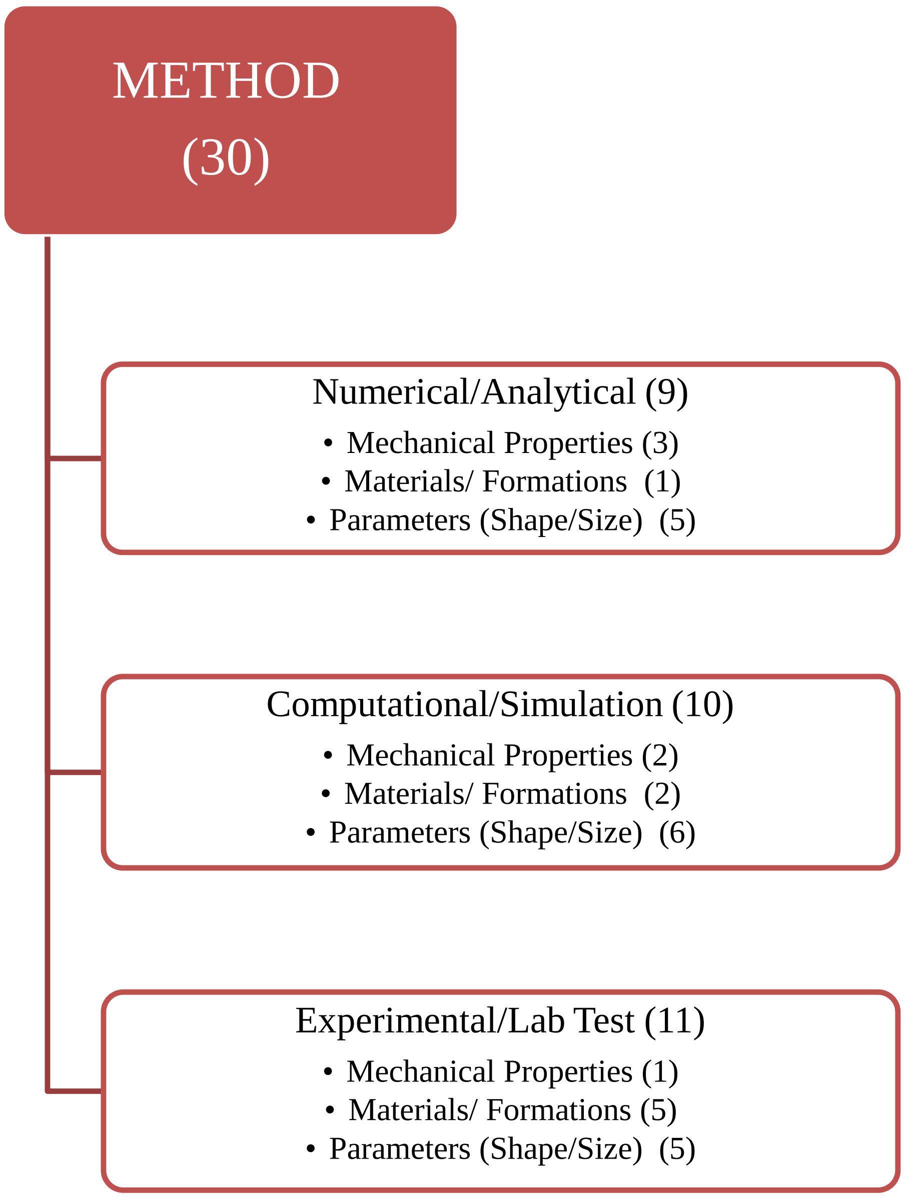


Figure 2.7: Overview of Critical Review

2.2.1 Computational and Simulation test of PDC Cutter

The chamfer modeling allows direct estimation of the chamfer shape and size on the PDC forces. According to Gerbaud *et al.* (2006) the introduction of the back cutter forces provides a good evaluation of the cutter forces and adds more optimization possibilities. The innovations incorporated into this model and described in this paper provide a number of benefits in terms of ROP improvement, bit stability, bit wear and bit directional control.

The primary mechanism involved in rock cutting is chip formation which is a discontinuous process and involves formation of minor chips until a major chip forms. Akbari *et al.* (2011) found the primary mechanism involved in rock cutting is chip formation which is a discontinuous process and involves formation of minor chips until a major chip forms. The test criteria are modeling and simulations which is focusing on Rate of Penetration using Distinct Element Method. Distinct Element Method has been proven to be a powerful tool in the study of bit rock interaction and failure and penetration mechanism. Its methodology allows observing failure and posting failure behavior of the granular material such as rock in contact with cutters clearly.

2.2.2 Numerical and Analytical test of PDC Cutter

The mechanical properties of rock and their modeling provide the essential fundamental knowledge required to explore rock removal mechanisms and rock cutting theories. Qualitative explanations have made quite a lot of progress in describing several important phenomena like crushed zone evolution, built-up edge formation, cutting shape variation, and so on. However, quantitative criteria and analytical methods still need to be developed to better describe the PDC cutter. Chet *et al.* (2012) mentioned some current studies on rock drilling using PDC bits attempt to replace roller cone bits with PDC bits in hard-rock formations. Progress in this area will impact the development of petroleum and gas engineering, not only in technology but also in economics. Numerical modeling associated with analytical and experimental modeling will likely play an important role to explain the mechanism of the PDC cutter/rock interaction and to predict PDC cutter performance.

The development of a parametric FLAC 3D model of a single PDC cutter are interacting with a rock specimen and the initial numerical tests investigating the effect of various geologic and drilling parameters. The FLAC code has also been used for numerical modeling of drilling. According to Tulu and Heasley (2008) the FLAC 3D cutter-rock model developed is designed to support the Extreme Drilling Laboratory (EDL) currently being constructed at DOENETL. The objective is to understand the mechanisms of rock failure and chip formation under a drill bit. The initial runs of the model worked well and show an increase in thrust and torque associated with increasing cutting depth and rock strength, as expected. The effects of fluid pressure and temperature on the cutting process will be investigated in detail with the single cutter model.

A basic single cutter analytical model was developed that predicts forces in single cutter tests on two representative shale over a large range of confining pressure as long as there are no dysfunctional phenomena. According to Rahmani *et al.* (2012) the Discrete Element Model (DEM) indicated that the energy spent in plastic deformation of already sheared rock is far more than the energy consumed in failing the intact rock. Descriptive models developed to explicitly account for the effects of cutter balling indicate that flow behavior of produced cuttings during the occurrences of balling phenomena can have significant and distinctive effects on cutting forces.

2.2.3 Experimental and Lab test of PDC Cutter

The walk angle of a PDC bits depends not only on the bit profile but also on the active and passive gauges. Directional lab test have demonstrated that the various bit tested with a passive gauge had a left tendency, despite their bit profiles and PDC setup. Menand *et al.* (2003), founded that the walk angle of a PDC cutting structure is calculated with a simple equation that link the inner cone and outer structure heights and the PDC back rake angle. The active and passive gauges dramatically affect the walk angle of PDC bits. The directional tests enable observation of spiraling problems and define the minimum requirements for avoiding such phenomena. The steer-ability of a PDC cutting structure depends greatly on the bit profile, the flatter the profile is, and the more steerable the bits are. Bit steer ability is nonlinear function of the active gauge length and decreases as the active and passive gauge length increases and depends on the applied side force.

Helms *et.al* (1989), discover although PDC bits can outperform conventional roller-cone bits in many applications, they do have limitations because the diamond surfaces are extremely hard, they are inherently brittle. Impact with hard metals can cause major damage to the cutters.

Durrand (2010), founded VTL TESTING the common industry method of conducting accelerated wear or abrasion tests on PDC cutters is to use a log of rock material on a specially instrumented lathe. The Stinger cutter exhibits reduced vertical and drag forces compared to conventional shear cutters when tested on the VTL. It has significantly improved abrasion resistance over extended wet testing on the VTL. Hot Testing by cooling the PDC's during VTL testing allows the cutter to dissipate heat away from the cutting surface to the fluid, essentially prolonging the length of the test prior to burnout and failure. The Stinger cutter shows far higher linear footage to burn out in dry/heat testing compared to conventional PDC. Laboratory testing at Terra Tek showed the Stinger bit to successfully cut hard abrasive rocks with no observable wear and the Initial field testing substantiated the laboratory observed drilling mechanism in hard rock rotary drilling, however poor bit integrity negated the run as a representative wear test.

Akbari *et al.* (2014) tested on the parameters that were controlled. The effect of cutter size for the tested conditions on the frictional response of the cutter is insignificant. Even a slight increase in the chamfer size can decrease cutter aggressiveness significantly. Changing the chamfer size from 0.25 mm to 0.41 mm causes the aggressiveness to reduce by 23% for the 13 mm and by 14% for the 16 mm cutter. For the conditions tested, to maintain the same cut depth, the chamfer size does not affect the cutting force. However, a larger chamfer requires more normal force to cut. In other words, a bit containing cutters with a larger chamfer requires more WOB to maintain the same ROP while producing similar TOB. The friction angle decreases with back rake angle increase in an almost linear manner. Two coefficients of this linear relationship depend on the rock type. On this basis, an empirical correlation was proposed and widely used in this paper. The change in friction angle is explained by a change in the flow regime of the rock ahead of the cutter face. Increased back rake angle causes a portion of the rock to flow from underneath the cutter creating opposing frictional forces.

Heavy set PDC bits can be a detriment to the drilling performance in hard formations. Testing showed a three bladed PDC bit with 19mm cutters out performing an eight bladed bit under identical conditions with less wear. These results were further validated by the test results with 8mm cutters for a four bladed bit against one with eight blades. Cutter overloading is the major limitation to bits with less cutter density. Sinor *et al.* (1998) founded the rate of penetration and torque response with new PDC bits is primarily controlled by the aggressiveness of the cutter.

A fourfold increase in WOB was shown in Carthage limestone for a bit with 7°, 10°, 15° back rake compared to a bit with 40° back rake. For Catoosa shale, the difference was nearly six fold. To improved steerability, a bit design should use less aggressive cutters inside the cone and more aggressive cutters toward the gage. Cutter wear was shown to increase as the cutter size decreases while Bit speed was shown to increase the rate of wear, from basically no wear at 60 to 80 rpm to 20% wear for a bit rotating at 270 rpm through the same formations.

2.3 Literature Findings

After done the critical review randomly taking from 30 journal and articles from various sources, the author found that 36.67% of previous case studies perform experimental and lab test for test criteria for shape, size, formations, and mechanical properties including the loads, stress and torsional but most of the study focusing in the parameters which is the back rake angle and effect of size. The walk angles, steerability using the directional test enable observation of spiraling problems and define minimum requirement.

At least 30% of the journal and articles the author found were on numerical and analytical test where the previous study mostly focusing on the effect or characteristic of wear and the rate of penetration (ROP). Most on the research studies more on the mechanical properties compare to the parameters of the PDC cutter. The numerical and analytical method by using governing equations on wear and other failures of PDC Cutters, deformability, tensile strength, and fracturing to improve cutter performance and, ultimately, to reduce the drilling cost phenomena and mechanisms of wear and other failure modes. The initial numerical tests are investigating the effect of various geologic and drilling parameters.

Only 33.33% of the journal and articles perform on the computational and simulation with focus on forces on the cutter to test on the wear characteristic and the rate of penetration (ROP). The simulations are based on the data of actual values using ANSYS software by using Distinct Element Method. The buildup edge of crushed material modeling provides a good evaluation of back and side rake effect on PDC forces.

CHAPTER 3: METHODOLOGY & PROJECT WORK

3.1 Research Methodology

Research is a method taken in order to gain information regarding the major scope of the project. The sources of the research cover the handbook, e-journal, e-thesis and several trusted link. As the project is a laboratory based, the experimental procedure is being design carefully to ensure the safety as well as to get the required result. This project is done step by step. In general, the step for conducting the project is similar to as mentioned. Figure 3.1 illustrate the flow chart diagram for this project.

Initially, an intensive review is conducted to attain the required information and existing research work based on the academic resources from journals and books. Numerous journals and books were studied to obtain the necessary information on this project especially for analytical model. By following the literature review, the analytical model will be developed to collect the required results. Author will proceed with the simulation modeling using Autodesk Inventor for 3D drawing, which is based on the results of the analytical model. Subsequently, the experiment modeling will be conducted using ANSYS Explicit Dynamic and Fluent for the drilling simulation based on the cutter parameters. After that, the result from the experiment will be analyzed, in which the optimal characteristic of the cutter is obtained.

The Gantt chart and the Key Milestone for the whole project are shown as per attached in **APPENDIX I** and **APPENDIX II** respectively.

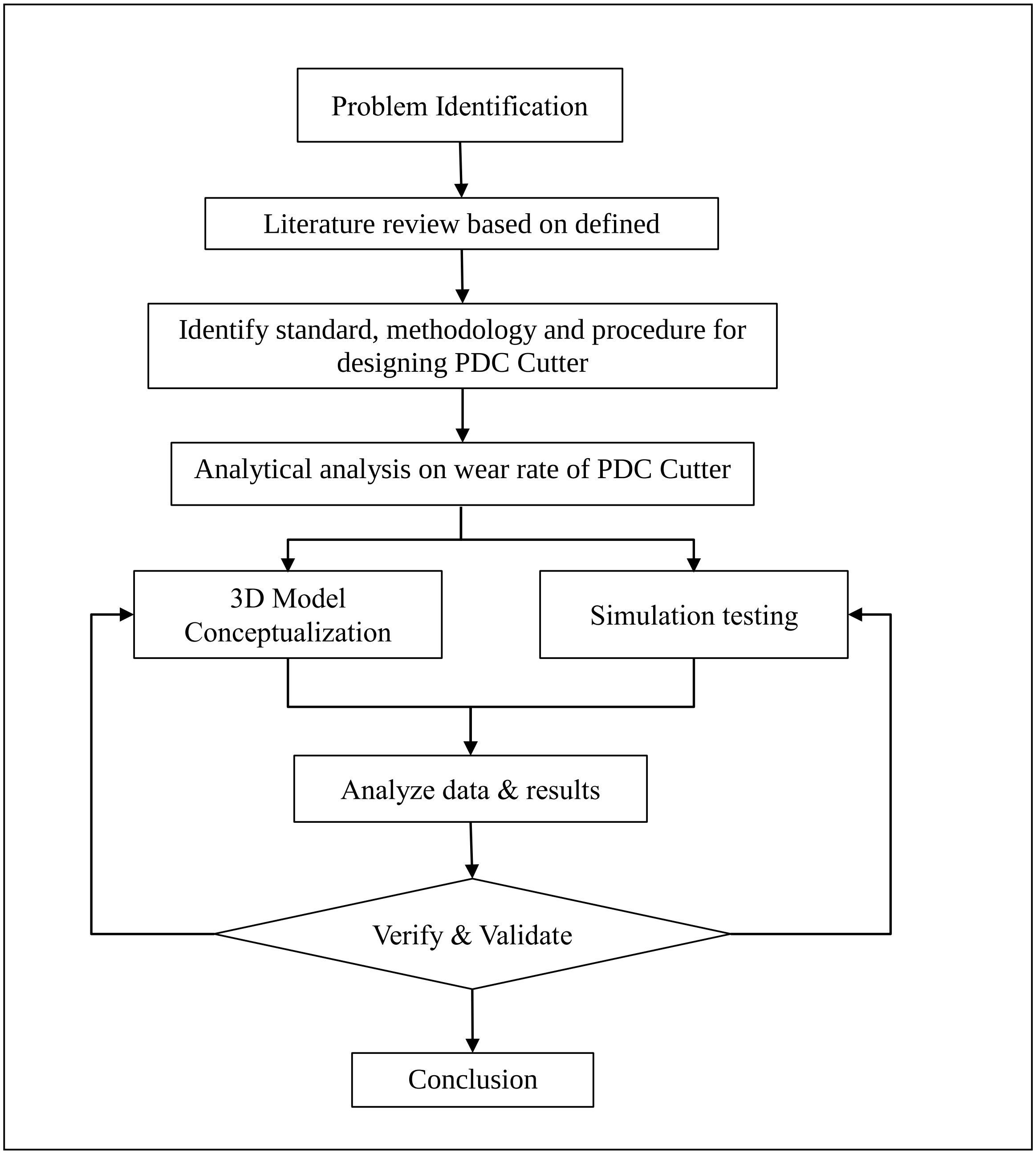


Figure 3.1: General Flow of Research

3.2 Project Work

This chapter shown the project work along the study on PDC drill bits cutter by using some analytical analysis 3D modelling and simulation by using software to determine the optimal characteristic of PDC cutter in hard abrasive formation using certain parameters as a reference.

3.4.1 Analytical Analysis Related Formulae & Calculations

The single cutter analytical model with 0° back rake angel as shown in Figure 3.2 is used to study the cutter-rock interaction. The cylinder represents the PDC cutter and the rectangle represents the granite formation. F_N and F_H is the normal force and the horizontal force applied on the cutter in the drilling process respectively. Depth of cut is set to be half of the cutter diameter. The cutter is moving at a constant velocity.

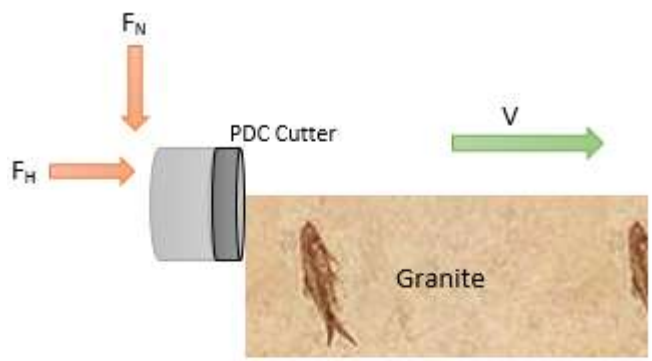


Figure 3.2: Single Cutter Model

The horizontal cutting force of the cutter with a given the normal force can be predicted if the back rake angle of the cutter and the rock coefficient of friction are known. The static balance of forces acting externally on a single PDC cutter during cutter-rock interaction is used to develop an analytical model. F_H is the 3D analytical model that predicts the horizontal cutting force if the normal force and coefficient of friction is known by considering the effect of back rake and side rake angles. If the side rake angle, $\beta = 0^\circ$.

The magnitude of the von Mises stress depends on the contact geometry, the mechanical properties of the materials, the friction and the externally applied forces. This large value of this coefficient indicates that one system parameter, the von Mises stress in the stressed volume, is dominant in the wear process and will determine the wear.

The cutter design parameters studied are back rake angle and size of cutter. The back rake angles selected are 0°, 10°, 20°, 30°and 40° as shown in Table 3.1 and the size of cutter selected are 7mm, 10mm, 13mm, 16mm and 19mm as show in Table 3.2 below.

Table 3.1: Selected Cutter Back Rake Angle

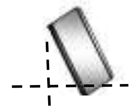
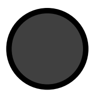
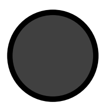
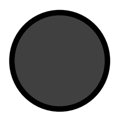
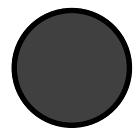
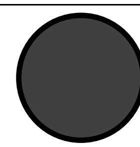
Back Rake Angle, °				
0°	10°	20°	30°	40°
				

Table 3.2: Selected Cutter Size

Size of Cutter (mm)				
 7mm	 10mm	 13mm	 16mm	 19mm

The project continue by listing down the related formulae during the cutter contacting the formation. By using the formulae and calculating by using sample or random value which within the range of the tolerance the analytical/numerical analysis is done.

In order to calculate the horizontal force for both selected back rake angle and size of cutter, Equation 3.1 is used as shown below.

$$F_H = F_N \left[\frac{1 - \ \mu \ \tan\alpha}{\tan\alpha + \mu}\right] \qquad \text{Equation 3.1}$$

Where F_N is the normal force, μ is the coefficient of friction taken as 0.45 and α is the back rake angle.

The axial stress and shear stress can be defined as shown in Equation 3.2 and Equation 3.3 respectively below.

$$\sigma = \frac{F_N}{A_N} \qquad \text{Equation 3.2}$$

$$\tau = \frac{F_H}{A_S} \qquad \text{Equation 3.3}$$

Where A_N is the normal contact area and A_S is the shear contact area.

The values of the parameters are summarize in the Table 3.3 below;

Table 3.3: Cutter Constant Parameter

Parameter	**Value**
Normal Force, F_N	2500 N
Coefficient of Kinetic Friction, μ	0.45
Shape of the Cutter	Flat
Surface Area of Cutting Face, A	5.0106×10^{-4} m^2

After the value of combined stress is gained for each selected back rake angle and size of cutter by adding the value of axial stress and shear stress, the wear rate can be compute. To find the value of the wear rate, Equation 3.4 below is used.

$$\mathrm{W} = \mathrm{k_2} \mathrm{V} \bar{\sigma}^{\frac{1}{\mathrm{bn'}}} \qquad \text{Equation 3.4}$$

Where k_2 is an arbitrary wear constant and V is the volume of deformed material taken as constant. V, is approximately equal to $\pi a^2 d$. For simplicity $\mathrm{k_2} \times \mathrm{V}$ was taken as 1.5×10^{-11} and b and $\mathrm{n'}$ is the cyclic strain-hardening coefficient which is taken to be 0.5 and 0.31 respectively. Typical value of $\frac{1}{\mathrm{bn'}}$ are approximately around 6.45. $\bar{\sigma}$ is the von Mises Stress.

3.4.2 3D Modelling of Cutter

Modelling of cutter using Autodesk Inventor are performed before the simulation are done by using 1:1 scale of cutter dimensions. The two cutter design parameters studied are back rake angle and size of cutter. Figure 3.3 below show the example of 3D modelling for 0° back rake angle and 13mm size. The modeling will be export into .stp format in order to import geometry in ANSYS Explicit Dynamic later.

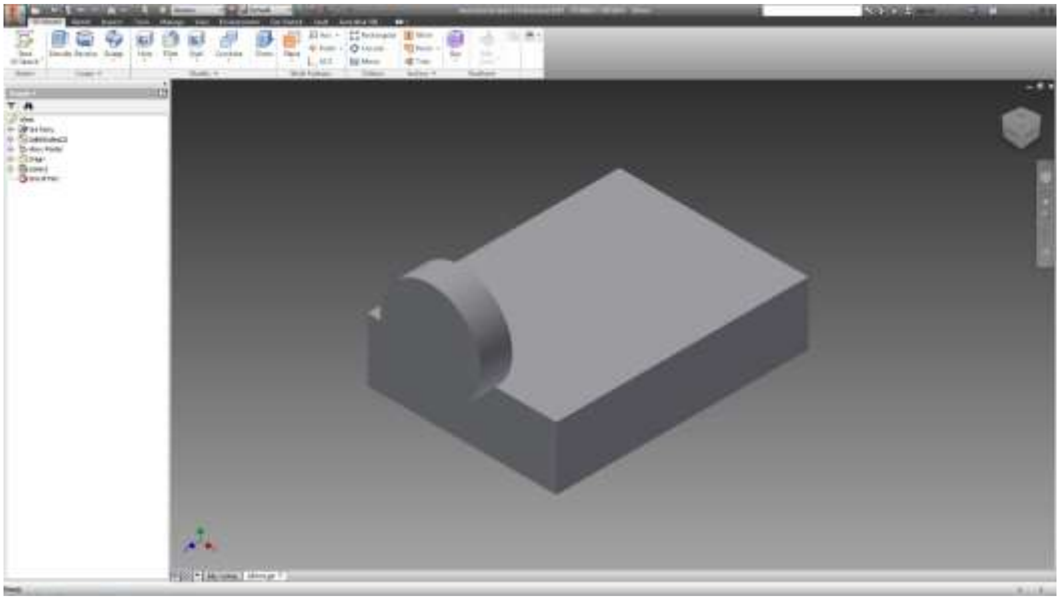


Figure 3.3: 3D Modelling using Autodesk Inventor

3.4.3 PDC Cutter Simulation

After done the modelling the cutter using Autodesk Inventor and exported, the saved file are import to ANSYS Dynamic Explicit to run simulation. The engineering data inserted by following the previous case study values as reference. All the parameters are followed accordingly.

PDC cutter technology is the most important factor affecting the durability of the bit. The theoretical basis of the PDC cutter is studied using the general analytical model. A 3D simulation model of rock breaking using a single PDC cutter is established. The 3D model is generated using Autodesk Inventor software and the model of the single cutter test is run using ANSYS Explicit Dynamic software to analyze the stresses beneath the cutter. The designs of PDC cutter on the rule of cutter wear rate are analyzed by using the wear theory to determine the best design.

The simulation flow show in Figure 3.4 below.

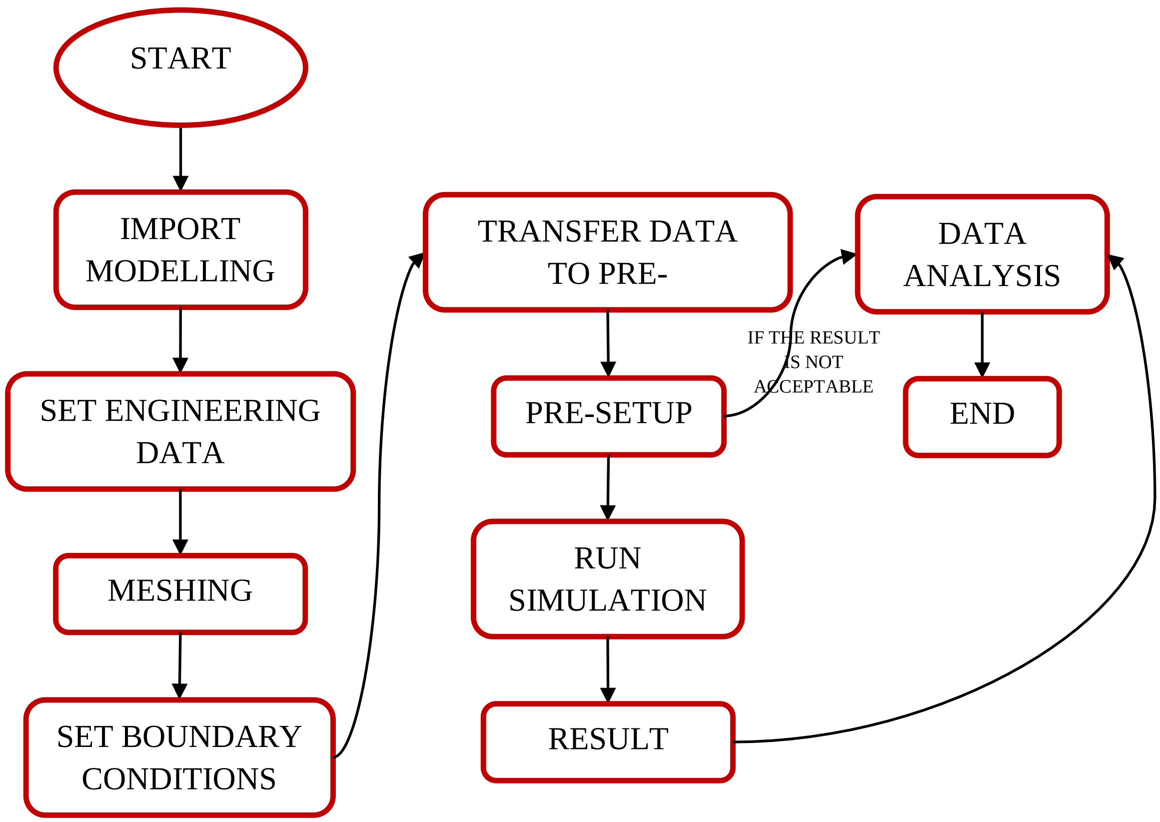


Figure 3.4: Simulation Flow Chart

Explicit Dynamic is probably the not common application in the finite element analysis. In this project, author has decided to use Explicit Dynamic. Explicit Dynamic is use when the problem require advanced analysis tools to accurately predict the effect of design on product to understand such complex phenomena especially when it is too expensive or impossible to perform physical testing. Figure 3.5 below show the project schematic of Explicit Dynamic.

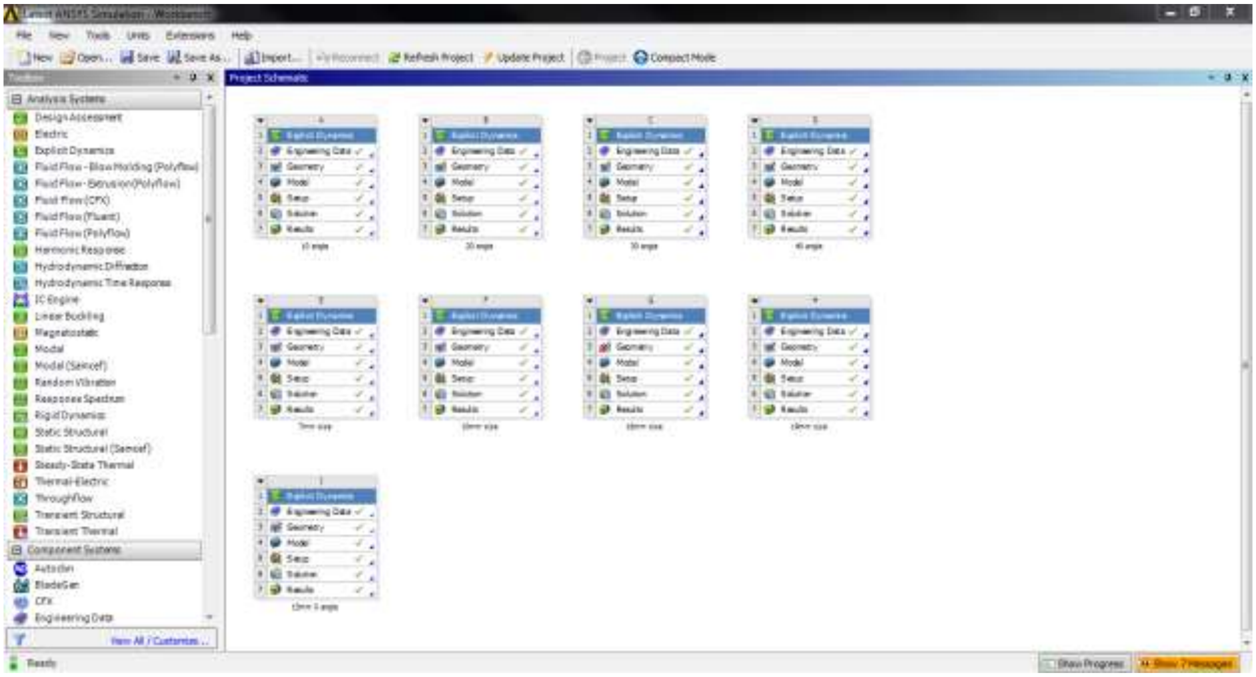


Figure 3.5: Project Schematic of Explicit Dynamic

In running the simulation for both back rake angle and size of cutter the process of the simulation are same but differ in geometry modelling. The model parameters used for both cutter and formation which we inserted in Engineering Data in ANSYS Explicit Dynamic are shown as Table 3.4 and Table 3.5 respectively below.

Table 3.4: Model Parameters of Cutter

	PCD
Material Parameters	***Parameter Values***
Density, ρ (kgm^{-3})	3510
Young’s Modulus, E (GPa)	890
Poisson Ratio	0.07
Shear Modulus, G (GPa)	545
Strength Parameters	***Parameter Values***
A (MPa)	4000
B (MPa)	500
N	0.14
Damage Parameters	***Parameter Values***
D1	0.05
D2	1.873
D3	-2.272

Table 3.5: Model Parameters of Formation

Material Parameters	***Parameter Values***
Unconfined Compressive Strength, UCS (MPa)	300
Density, ρ (kgm^{-3})	26200
Ultimate Tensile Strength, UTS (MPa)	256
Shear Yield Stress, τ_{yield} (MPa)	132
Young's Modulus, E (GPa)	70
Poisson Ratio	0.30
Kinetic Coefficient, μ_k	0.45
Strength Parameters	***Parameter Values***
A (MPa)	0.79
B (MPa)	1.60
n	0.007
Damage Parameters	***Parameter Values***
D1	0.040
D2	1.000
D3	0.040

Meshing is one of the important aspect in engineering simulation. Meshing is an integral part of the computer aided engineering simulation process. The mesh influence the accuracy, convergence and speed of the solution. The meshing setting and pattern for this project was set as shown in Figure 3.6 below.

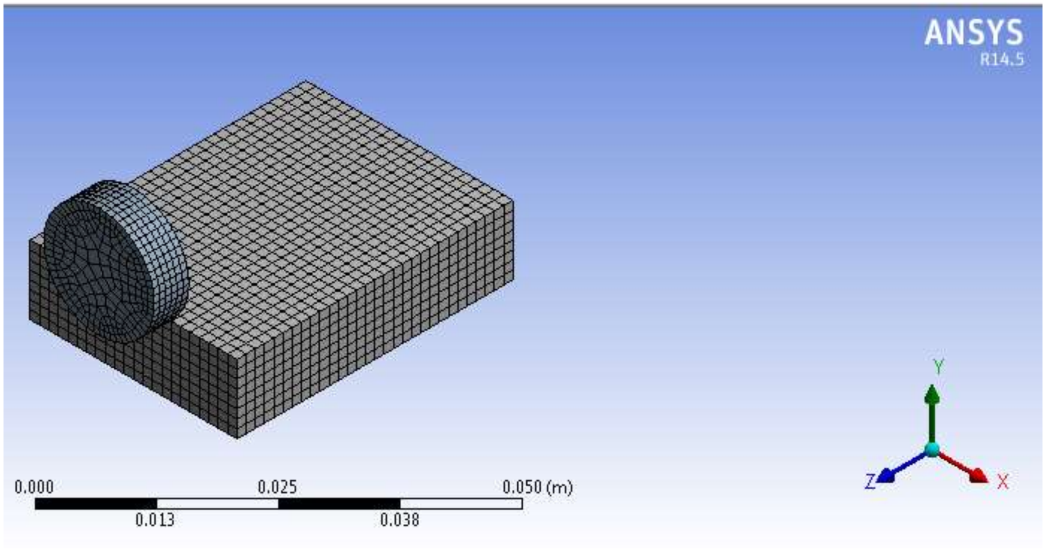


Figure 3.6: Meshing of PDC Cutter and Formation

CHAPTER 4: RESULTS & DISCUSSIONS

The main objective of this research is to derive analytical model of PDC Cutter, to develop simulation modeling the PDC cutter and to determine the optimal characteristic of PDC cutter in hard abrasive formation. To fulfil the main objective, several action must be taken into account which are:

1) To build 3D Modelling with different values of back rake angle and size of cutter
2) To run a simulation test using ANSYS Explicit Dynamic and insert the engineering data that we extract from previous case study.

4.1 Analytical Analysis

This chapter will provide a results and discuss on PDC Single Cutter Analytical Model for Back Rake Angle,α, and Size of Cutter, Analytical Wear (µm^2) and Analytical Wear Rate (µm^2/s) by comparing the stress value.

4.1.1 Back Rake Angle Analytical

The data available for PDC cutter test with various back rake angle is shown in Table 4.1.

Table 4.1: Data available for PDC cutter

Parameter	**Value**
Normal Force, F_N	2500 N
Coefficient of Kinetic Friction, μ	0.45
Shape of the Cutter	Flat
Size of the Cutter	16 mm
Surface Area of Cutting Face, A	5.0106×10^{-6} m^2
Shear Contact Area, A_S	4.258×10^{-6} m^2

To compute the horizontal force Equation 3.1 is used. The calculation will be shown in **APPENDIX III** in details for selected back rake angle analytical.

The relationship between the cutter back rake angles on the horizontal force is calculated and shown in Figure 4.1.

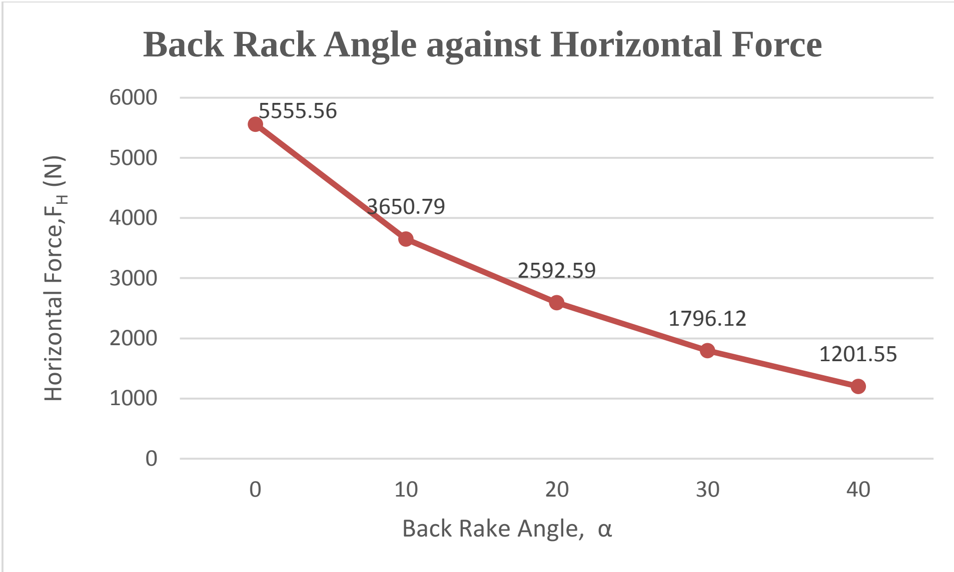


Figure 4.1: Graph of Back Rake Angle against Horizontal Force

Result shows that cutter with higher back rake angle requires less horizontal force applied to cut the formation under a constant normal force. Since the normal force applied on PDC cutter, size of cutter and depth of cut are constant, the axial stress is assumed the same for every cutter.

The shear stress on the cutter faces can be calculated by using the Equation 3.2 by referring to Merchant's Model. Where A_N is the shear contact area, with a value of 6.34 x 10^{-6} m^2. Thus, the axial stress on the cutter is equal to 394.21 MPa.

Therefore, the horizontal force applied on each cutter is used to calculate the analytical shear stress as well as to define the boundary condition of single cutter simulation. By referring to Merchant's model, the shear stress on the cutter faces can be calculated by using the Equation 3.3.

The shear stress and axial stress is totaled up to obtain the combined stress, $\tau + \sigma$, The calculation for combined stress will be shown in **APPENDIX III** in details for selected back rake angle analytical.

The result for the combined stress for different back rake angled cutter is shown in Figure 4.2 below shows the effect of back rake angle on stress by analytical.

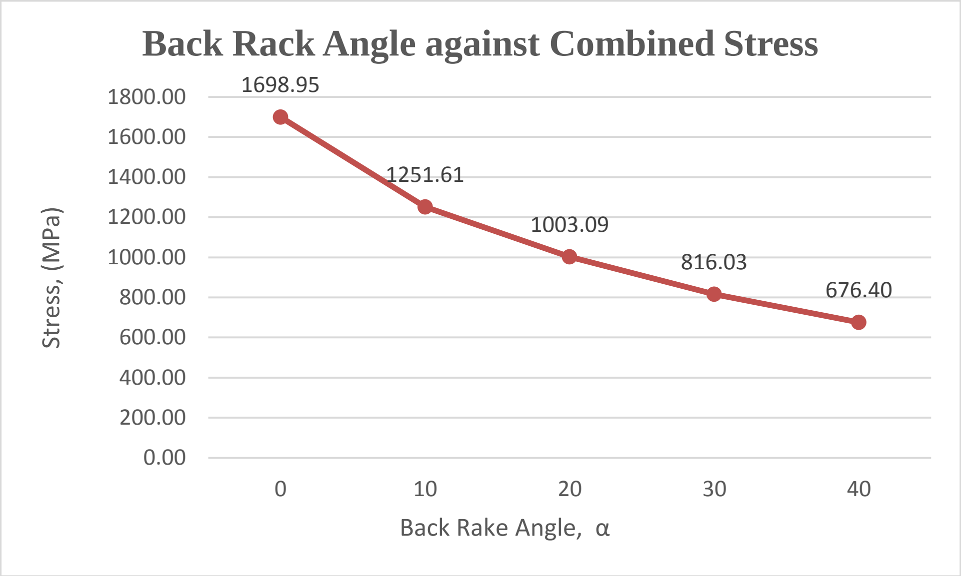


Figure 4.2: Graph of Back Rake Angle against Combined Stress

The result shows that the cutter with higher back rake angle has less stress. This is because the horizontal force applied on the cutter decreases with the increased back rake angle, thus resulting in a lower shear stress. By comparing both Figure 4.1 and 4.2 before, the relationship between shear stress and the horizontal force are gained in the Figure 4.3 below.

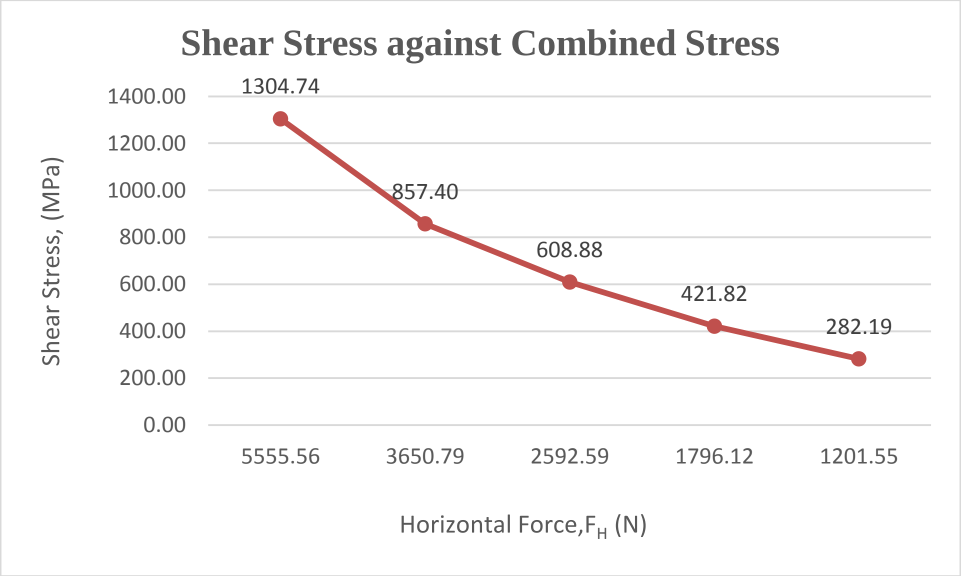


Figure 4.3: Graph of Shear Stress against Horizontal Force

From the graph 4.3 above, horizontal force is directly proportional to shear stress. Therefore, the lower the back rake angle the higher the shear stress gained.

4.1.2 Size of Cutter Analytical

The next analytical models are for different PDC cutter sizes to cut the granite formation with constant back rake angle. Since the cutter back rake angle is constant, thus the applied horizontal force is constant for all sizes of cutter. The shear contact area is taken to be half of the surface area of cutting face as the depth of cut is half of the cutter diameter. The values used for the analytical models are shown in Table 4.2 and Table 4.3 below.

Table 4.2: Constant Parameters for Size of Cutter

Parameter	***Value***
Back Rake Angle, α	0°
Normal Force, F_N	2500 N
Horizontal Force, F_H	5555.56 N
Coefficient of Kinetic Friction, μ	0.45

Table 4.3: Shear Contact Area for Different Size of Cutter

Size of Cutter (mm)	***Shear Contact Area, (m^2)***
7	1.871×10^{-6}
10	2.451×10^{-6}
13	3.032×10^{-6}
16	4.258×10^{-6}
19	4.903×10^{-6}

The axial stress and shear stress for different size of cutter is calculated using Equation 3.2 and Equation 3.3 respectively. The axial stress on the cutter is taken as a constant of 394.21 MPa. The calculation will be shown in **APPENDIX III** in details for selected size of cutter analytical. The combined stress for different size of cutter is shown in Figure 4.4 below.

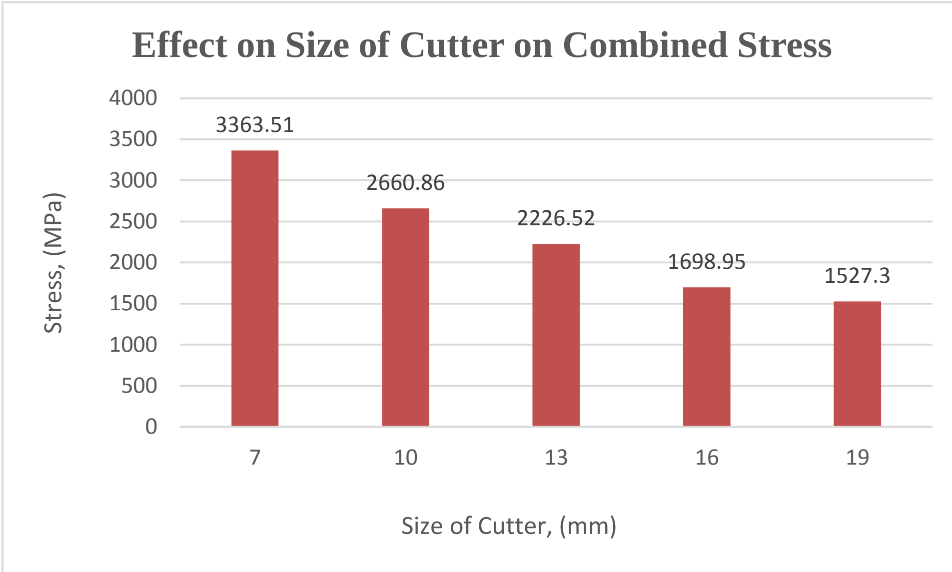


Figure 4.4: Effect on Size of Cutter on Stress

From the chart, we can see that the 19mm size of cutter has the lowest combined stress. This is because shear stress exerted on the cutter decreases respectively with shear contact area.

4.2 PDC Cutter Simulation

The simulation is run by applying the horizontal force and normal force. The horizontal force applied on the cutter is the value obtained from the analytical model. The cutter shears the granite formation at a constant velocity and the simulation period is set to be 60s in order to achieve a constant shearing force. The FEA model of the single cutter test is shown in Figure 4.5.

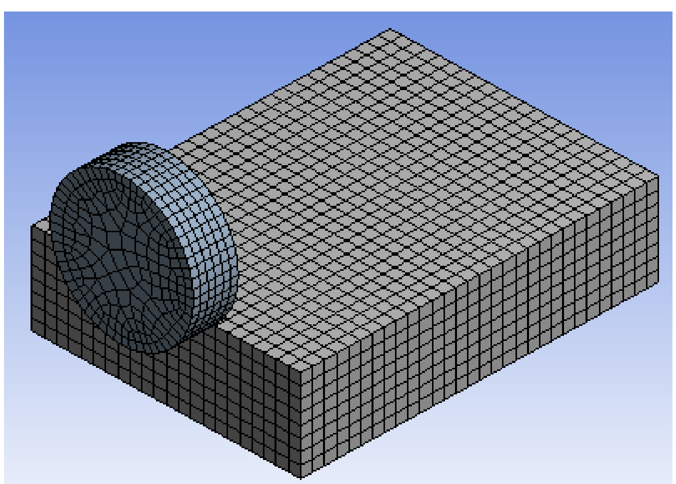


Figure 4.5: FEA Model of Single Cutter

4.2.1 Back Rake Angle Simulation

The stress on the cutter is increasing at the beginning of the simulation. This is because the horizontal force is increased in amplitude and started to reach the applied horizontal force value only after a certain period. In order to ensure the accuracy of the result, the average stress is only taken after a period of 10s. The average von Mises stress induced in each PDC cutter with different back rake angle is shown in Figure 4.6 below.

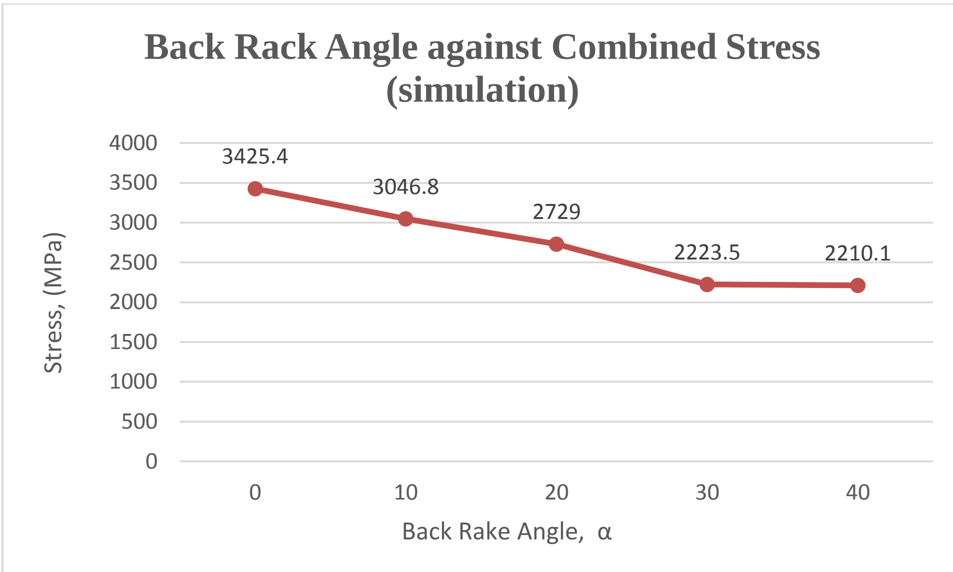


Figure 4.6: Simulated stress for Back Rake Angle

Result shows that higher back rake angle has lower von Mises stress induced in the cutter. This is due to the lower horizontal force applied on the cutter. Cutter with back rake angle of 40° has the lowest horizontal force applied under a constant normal force. Thus, the stress induced in the 40° back rake angled cutter is the lowest. A comparative analysis of the simulation result and analytical result of different back rake angled cutter is shown in Figure 4.7.

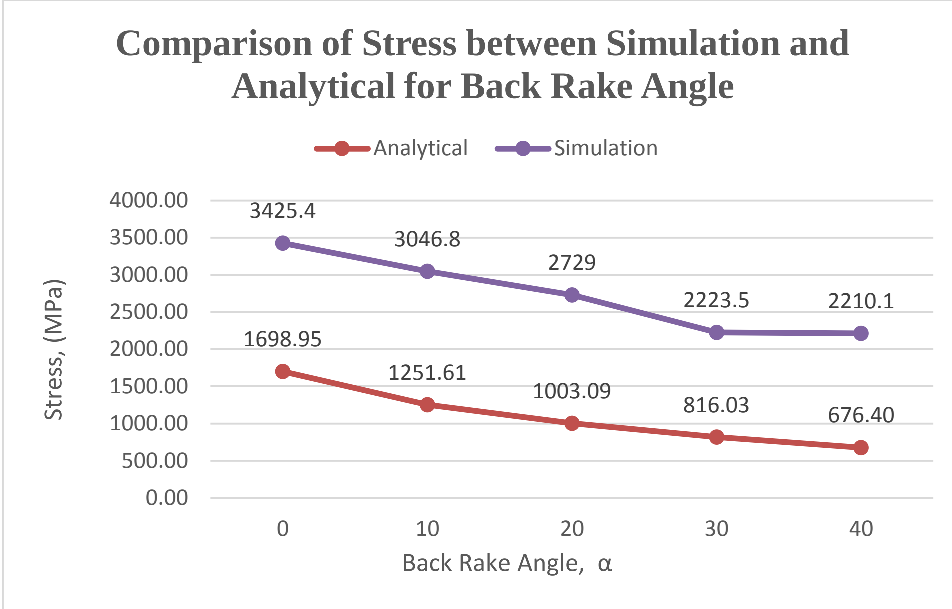


Figure 4.7: Comparative Analysis of Stresses for Different Back Rake Angles

The stress obtained from the simulation is found to be higher than analytical result. The highest percentage of difference for the result is approximately 69.40%. This may be due to the hydrostatic stress exerted on the cutter. Besides, the normal contact area may be smaller which results in a higher normal force. The mesh sizes of the model also influence the result. At the same time, combined with analytical result, with the increase of back rake angle, the stress value decreases, verifying the correctness of the simulation result. PDC cutter with 40˚back rake angle has proved to have the lowest stress values.

4.2.2 Size of Cutter Simulation

The stress induced in the cutter increases at the beginning of the simulation and becomes stable after a period of time. The cutters with larger size require longer time to achieve a consistent stress value. In order to ensure the accuracy of the result, the average stress is calculated once the stress value becomes stable. Figure 4.8 show the average von Mises stress induced in each PDC cutter with different size of cutter.

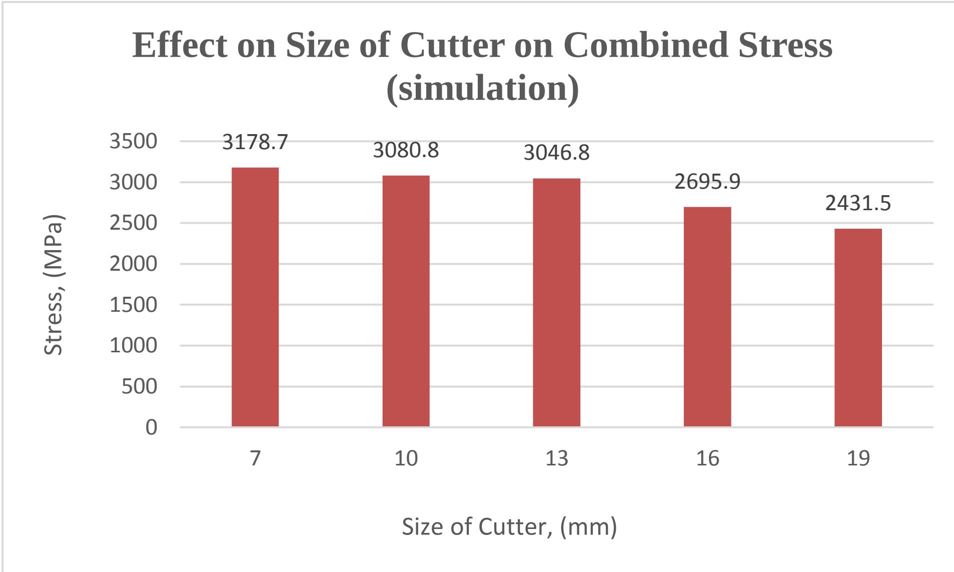


Figure 4.8: Simulated Stress for Different Size of Cutter

Based on the Figure 4.8, we can see that 19mm cutter has the lowest von Mises stress, followed by 16mm, 13mm, 10mm and 7mm cutter. This is because stress is depended on the shear surface area. Increased shear contact area reduces the stress exerted on the cutter. The comparison between analytical stress and simulated stress for different sizes of cutter is shown in Figure 4.9 below.

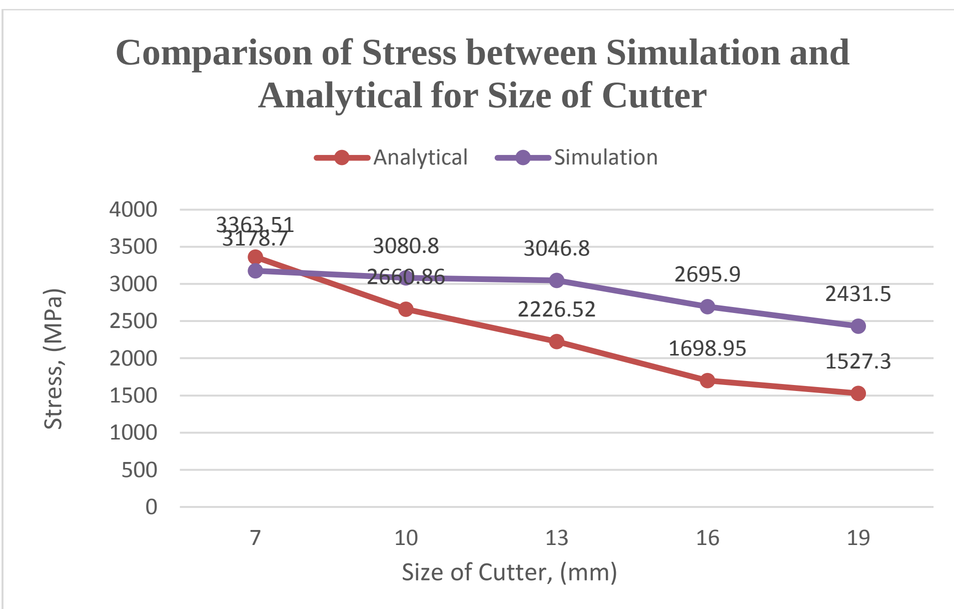


Figure 4.9: Comparative Analysis of Stresses for Different Size of Cutter

The stress obtained from the simulation is generally higher than analytical result. The highest percentage of difference for the result is approximately 37.19%. This is most probably due to and hydrostatic stress induced in the cutter. Besides, the normal contact area may be smaller which results in a higher normal force. Furthermore, the difference in cutter face may result in higher contact force which causes higher stress. The result is also dependent on the mesh sizes of the cutter model. 19mm cutter has the lowest stress value for both analytical and simulation result.

4.3 PDC Cutter Wear Rate

After the analysis of PDC cutter in the process of drilling and the stress distribution is put into the solving theory of cutter wear rate to analyze wear. The wear per sliding distance of the PDC cutter is calculated using the Equation 4.4. The wear rate calculation for both back rake angle analytical and size of cutter analytical will be shown in **APPENDIX IV** in details.

4.3.1 Back Rake Angle Wear Rate

The wear of different back rake angled cutter is calculated. Since the simulation period is 60s, the wear rate of the cutter can be computed by dividing the wear using the time. The wear and wear rate of different back rake angled cutter is tabulated in Table 4.4.

Table 4.4: Wear and Wear Rate of PDC Cutter for Back Rake Angle

Back Rake Angle ,α	***Simulated Wear (μm^2)***	***Analytical Wear (μm^2)***	***Simulated Wear Rate ($\mu m^2/s$)***	***Analytical Wear Rate ($\mu m^2/s$)***
0°	9.4402×10^{5}	1.0251×10^{4}	1.5734×10^{4}	1.7085×10^{2}
10°	4.4349×10^{5}	1.4281×10^{3}	7.3915×10^{3}	2.3802×10^{1}
20°	2.1793×10^{5}	3.4256×10^{2}	3.6321×10^{3}	5.7093
30°	5.8141×10^{4}	9.0489×10^{1}	9.6901×10^{2}	1.5081
40°	5.5918×10^{4}	2.6971×10^{1}	9.3196×10^{2}	4.4952×10^{-1}

A graph of wear rate against back rake angle as shown in Figure 4.10 to analyse the relationship between back rake angle and cutter wear rate.

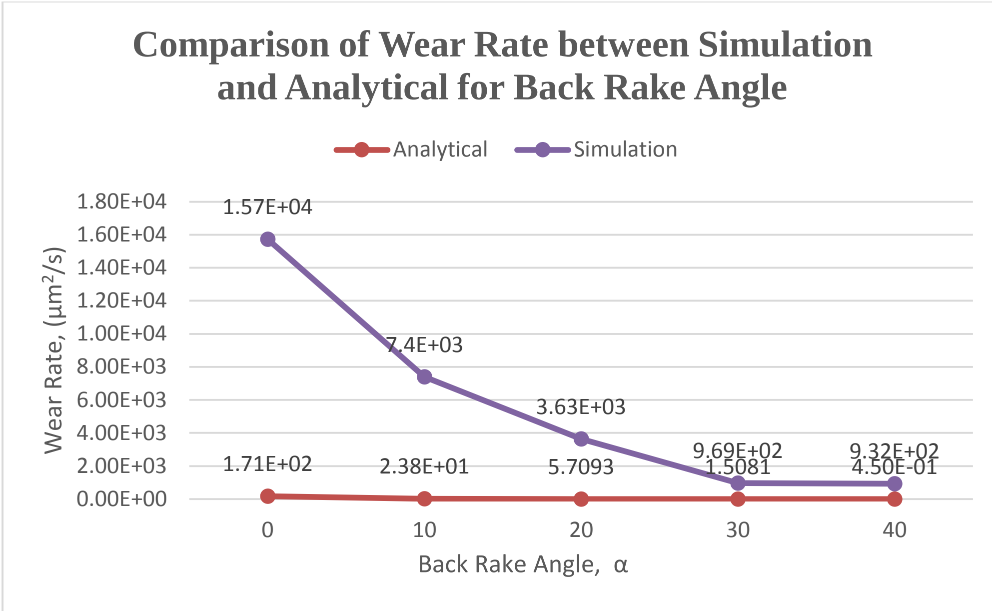


Figure 4.10: Graph of Wear Rate against Back Rake Angle

From Figure 4.10 above we can see that the cutter wear rate decreases as the back rake angle increases, but the decreasing trend is nonlinear. As mentioned, externally applied force affects the magnitude of stress. Keeping the other operational parameters constant, higher cutter back rake angle requires less horizontal force applied to cut the formation at a constant normal force. Thus, PDC cutter with 40˚ back rake angle has the minimum stress value due to the lowest applied horizontal force.

The cutter fails once the von Mises stress induced in the cutter exceeds yield strength of the cutter. Thus, cutter wear rate is affected by the cutter back rake angle. With the increase of the back rake angle of the PDC cutter, the cutter wear rate decreases significantly. Thus, 40˚back rake angle with the lowest stress is the best design to reduce wear rate in drilling. At the same time, combined with analytical result, with the increase of back rake angle, the cutter wear rate is decreased, verifying the simulation result. However, cutter back rake angle higher than 45˚should be avoided in drilling as very large back rake angled tool have less mechanical strength which reduces tool life.

4.3.2 Size of Cutter Wear Rate

The wear of the each cutter with different size is calculated using Equation 4.4. The wear and wear rate of different size of cutter is tabulated in Table 4.5.

Table 4.5: Wear and Wear Rate for Different Cutter Size

Size of Cutter (mm)	***Simulated Wear (μm^2)***	***Analytical Wear (μm^2)***	***Simulated Wear Rate ($\mu m^2/s$)***	***Analytical Wear Rate ($\mu m^2/s$)***
7	5.8291×10^5	8.3928×10^5	9.7152×10^3	1.3988×10^4
10	4.7640×10^5	1.8513×10^5	7.9400×10^3	3.0855×10^3
13	4.4349×10^5	5.8652×10^4	7.3915×10^3	9.7753×10^2
16	2.0143×10^5	1.0251×10^4	3.3572×10^3	1.7085×10^2
19	1.0351×10^5	5.1571×10^3	1.7252×10^3	8.5951×10^1

A chart of wear rate vs size of cutter is plotted as shown in Figure 4.11 to analyze the relationship between size of cutter and cutter wear rate.

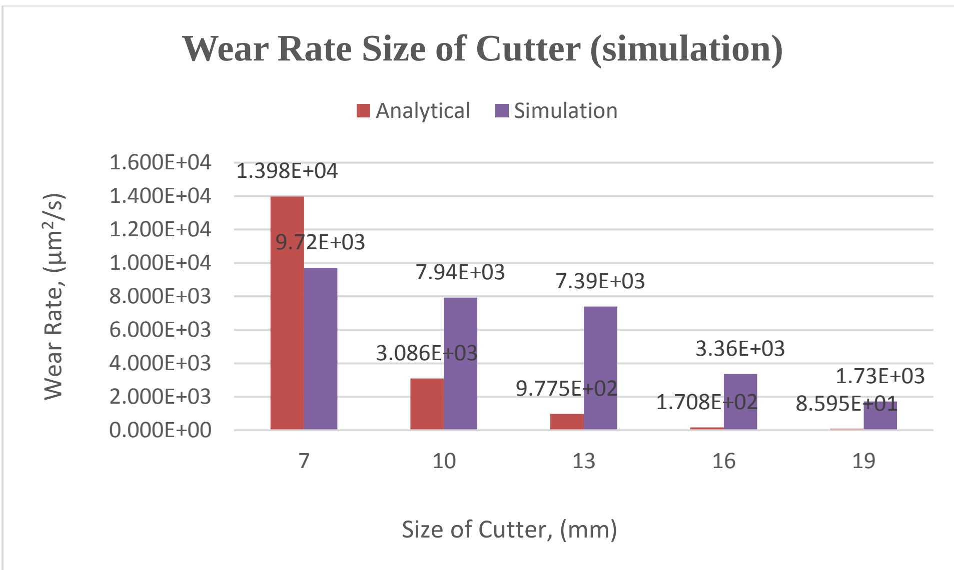


Figure 4.11: Graph of Wear Rate against Size of Cutter

Result shows 19mm cutter has the lowest wear rate of 1.85×10^{-4} $\mu m^2/s$. The size of PDC cutter has a great effect on the cutting area. Different PDC cutter size will have different contact geometry that affects the amount of stress induced under a constant back rake angle. The 19mm cutter with the largest shear contact area have the largest contact geometry compared with other in this simulation resulting in less stress. The cutter will fail once the von Mises stress induced in the cutter exceeds yield strength of the cutter. So, shear contract area of cutter should be maximized to enhance the cutter life.

CHAPTER 5: CONCLUSION & RECCOMENDATION

5.1 Conclusion

This project reported the result of rock cutting tests performed with PDC cutters at various back rake angles and with various sizes. This project has provided a clear review of the literature associated with cutter design of PDC drill bits through this Final Year Project. All the objectives of the project are achieved.

The aim of this study of PDC Drill bit cutter is as stated below:

- To derive analytical model of PDC Cutter in hard abrasive formation drilling.
- To develop simulation modeling the PDC cutter in hard abrasive formation.
- To determine the optimal characteristic of PDC cutter in hard abrasive formation.

To fulfil the main objective, several action must be taken into account which are:

- Perform an analytical for each variables which is back rake angle and size of cutter
- Build 3D Modelling with different values of back rake angle and size of cutter
- Run a simulation test using ANSYS Explicit Dynamic and insert the engineering data that we extract from previous case study.

The objectives are achieved by performing both analytical and simulation which is to derive analytical model of PDC Cutter in hard abrasive formation drilling as well as to determine the optimal characteristic of PDC cutter in hard abrasive formation.

3D modeling of the cutter performed by using Autodesk Inventor. The simulation process are continued by import the modeling to the ANSYS Dynamic Explicit and the engineering data are inserted and continuing on the meshing and simulate for result. Therefore, the objective of develop simulation modeling of PDC cutter in hard abrasive formation are achieved.

As a conclusion, cutter with higher back rake angle requires less horizontal force applied to cut the formation under a constant normal force. The cutter with higher back rake angle also has less stress. This is because the horizontal force applied on the cutter decreases with the increased back rake angle, thus resulting in a lower shear stress. The project prove that horizontal force is directly proportional to shear stress. Therefore, the lower the back rake angle the higher the shear stress gained.

For a different PDC cutter sizes to cut the formation, the back rake angle is take as constant which is 0˚, thus the applied horizontal force is constant for all sizes of cutter. The shear contact area is taken to be half of the surface area of cutting face as the depth of cut is half of the cutter diameter. We can see that the 19mm size of cutter has the lowest combined stress. This is because shear stress exerted on the cutter decreases respectively with shear contact area.

By simulation, the stress on the cutter is increasing at the beginning of the simulation. This is because the horizontal force is increased in amplitude and started to reach the applied horizontal force value only after a certain period. Higher back rake angle has lower von Mises stress induced in the cutter. This is due to the lower horizontal force applied on the cutter. Cutter with back rake angle of 40˚has the lowest horizontal force applied under a constant normal force. Thus, the stress induced in the 40˚back rake angled cutter is the lowest.

The stress obtained from the simulation is found to be higher than analytical result may be due to the hydrostatic stress exerted on the cutter. Besides, the normal contact area may be smaller which results in a higher normal force. The mesh sizes of the model also influence the result. At the same time, combined with analytical result, with the increase of back rake angle, the stress value decreases, verifying the correctness of the simulation result. PDC cutter with 40˚back rake angle has proved to have the lowest stress values.

The stress induced in the cutter increases at the beginning of the simulation and becomes stable after a period of time. The cutters with larger size require longer time to achieve a consistent stress value. In order to ensure the accuracy of the result, the average stress is calculated once the stress value becomes stable. We can see that 19mm cutter has the lowest von Mises stress, followed by 16mm, 13mm, 10mm and 7mm cutter. This is because stress is depended on the shear surface area. Increased shear contact area reduces the stress exerted on the cutter.

The stress obtained from the simulation is generally higher than analytical result most probably due to and hydrostatic stress induced in the cutter. Besides, the normal contact area may be smaller which results in a higher normal force. Furthermore, the difference in cutter face may result in higher contact force which causes higher stress. The result is also dependent on the mesh sizes of the cutter model. 19mm cutter has the lowest stress value for both analytical and simulation result.

The cutter wear rate decreases as the back rake angle increases, but the decreasing trend is nonlinear. With the increase of the back rake angle of the PDC cutter, the cutter wear rate decreases significantly. Thus, 40˚back rake angle with the lowest stress is the best design to reduce wear rate in drilling. However, cutter back rake angle higher than 45˚should be avoided in drilling as very large back rake angled tool have less mechanical strength which reduces tool life. The size of PDC cutter has a great effect on the cutting area. Different PDC cutter size will have different contact geometry that affects the amount of stress induced under a constant back rake angle. The 19mm cutter with the largest shear contact area have the largest contact geometry compared with other in this simulation resulting in less stress. Thus, 19mm cutter has the lowest wear rate.

5.2 Recommendation

It is recommended that the same optimized PDC bit is simulated but including the properties of drilling fluid. The possible output parameter is the wear rate of the bit to analyze the durability of each of the optimized PDC bit. Another recommendation are carrying out laboratory test in the future to verify the results. In order to improve the accuracy of the result, wear model for PDC cutter should be developed based on the field data. Other design parameters should be included to optimize the PDC bit design for hard formation application. Both ROP and bit durability should be analyzed together to optimize PDC bit design for drilling faster and further in hard formation.

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APPENDICES

APPENDIX I

FYP 1 Gantt Chart

No.	Detail/Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	Selection of title																
2	Preliminary Research Work																
3	Submission of Extended Proposal																
4	Proposal Defense																
5	Preparation of data																
6	Submission of Interim Draft Report																
7	Submission of Interim Report																

FYP 2 Gantt Chart

No.	Detail/Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Project Work Continue															
2	Submission of Progress Report															
3	Project Work Continue															
4	Pre-SEDEX															
5	Submission of Draft Final Report															
6	Submission of Dissertation (soft bound)															
7	Submission of Technical Paper															
8	Viva															
9	Submission of Project Dissertation (Hard Bound)															

APPENDIX II

FYP 1 Key Milestone

Week	Activities
1	Topic selection
2	Identify problem statement, objective, and scope of study
3	Literature review, research
4	Research on the size of cutter
5	Research on the back rake angle
6	Submission of Extended Proposal
7	Details research on back rake angle and size of cutter
8	Preliminary research on case study
9	Proposal Defense
10	Research on method to perform analytical and simulation
11	Research on case study
12	Data collections and information gatherings
13	Completing preliminary Interim Draft Report
14	Submission of Interim Report

FYP 2 Key Milestone

Week	Activities
1	Research on the equivalent stress and wear rate of PDC cuter
2	Conduct analytical analysis for PDC cutter back rake angle and size
3	Analyze results obtained
4	Make discussion of the results
5	Perform 3D modelling for all selected angle and size
6	Conduct a simulation for different size of cutter
7	Conduct a simulation for various back rake angle
8	Submission of Progress Report
9	Comparison the effect on wear rate for both analytical and simulation
10	Compiling all the result and construct table and graph
11	Pre-sedex
12	Submission of Draft Report
13	Submission of dissertation and technical paper
14	Viva Presentation
15	Submission of hard bound dissertation

APPENDIX III

Given;

Normal Force, $F_N = 2500N$

Coefficient of Kinetic Friction, $\mu = 0.45$

Surface Area of Cutting Face, A = $5.0106 \times 10^{-6}\ m^2$

Shear Contact Area, $A_S = 4.258 \times 10^{-6}\ m^2$

1) **Horizontal Force of Back Rake Angle**

Horizontal Force

$$F_H = F_N \left[\frac{1 - \mu \tan \alpha}{\tan \alpha + \mu} \right]$$

For 0°

$$F_H = 2500 \left[\frac{1 - 0.45 \tan 0}{\tan 0 + 0.45} \right]$$

$$F_H = 5555.56N$$

Others calculation are simplify in the table below.

Back Rake Angle, °	Horizontal Force, F_H (N)
0	5555.56
10	3650.79
20	2592.59
30	1796.12
40	1201.55

2) Combined Stress for Back Rake Angle

A_N is the shear contact area, with a value of 6.34 x 10^{-6} m^2. Thus, the axial stress, σ on the cutter is equal to 394.21 MPa and take as constant

The shear stress on the cutter faces

$$\tau = \frac{F_H}{A_S}$$

For 0˚

$$\tau = \frac{5555.56N}{4.258\ x10-6}$$

$$\tau = 1304.74\ \text{MPa}$$

$$\text{Combined stress, } \tau + \sigma = 1304.74 + 394.21$$

$$\tau + \sigma = 1698.95\ \text{MPa}$$

Others calculation are simplify in the table below.

Back Rake Angle,˚	Shear Stress, τ (MPa)	Combined Stress, (MPa)
0	1304.74	1698.95
10	857.40	1251.61
20	608.88	1003.09
30	421.82	816.03
40	282.19	676.40

3) Combined Stress for Size of Cutter

Given

Size of Cutter (mm)	***Shear Contact Area (m^2)***
7	1.871x10-6
10	2.451x10-6
13	3.032x10-6
16	4.258x10-6
19	4.903x10-6

For size of cutter the back rake angle are fixed to constant which is 0˚, therefore the horizontal force, $F_H = 5555.56N$. A_N is the shear contact area, with a value of 6.34 x 10^{-6} m^2. Thus, the axial stress, σ on the cutter is equal to 394.21 MPa and take as constant

The shear stress on the cutter faces

$$\tau = \frac{F_H}{A_S}$$

For 16mm,

$$\tau = \frac{5555.56N}{4.258\text{x}10 - 6}$$

$$\tau = 1304.74 \text{ MPa}$$

$$\text{Combined stress, } \tau + \sigma = 1304.74 + 394.21$$

$$\tau + \sigma = 1698.95$$

Others calculation are simplify in the table below.

Size of Cutter (mm)	Shear Stress, τ (MPa)	Combined Stress, (MPa)
7	2969.3	3363.51
10	2266.65	2660.86
13	1832.31	2226.52
16	1304.74	1698.95
19	1133.09	1527.3

APPENDIX IV

Given; $k_2 \times V = 1.5 \times 10^{-11}$ $n' = 0.31$ $b = 0.5$

$b \times n' = 0.155$ Therefore, $\frac{1}{bn'} = 6.45$

The wear rate,

$$W = k_2 V \sigma^{\frac{1}{bn'}}$$

1) Analytical Wear Rate for Back Rake Angle

For 0˚, combined stress = 1698.95MPa

$$W = 1.5 \times 10 - 11\ x\ 1698.95^{6.45}$$

$$W = 1.025e4\ \mu m^2$$

Others calculation are simplify in the table below.

Back Rake Angle,˚	Combined Stress, (MPa)	Analytical Wear (μm^2)	Analytical Wear Rate ($\mu m^2/s$)
0	60.64	1.0251E+04	1.7085E+02
10	41.70	1.4281E+03	2.3802E+01
20	31.17	3.4256E+02	5.7093
30	23.25	9.0489E+01	1.5081
40	17.33	2.6971E+01	4.4952E-01

2) Analytical Wear Rate for Size of Cutter

For 16mm, combined stress = 41.47MPa

$$\mathrm{W} = 1.5 \times 10 \; - 11 \; x \; 1698.95^{6.45}$$

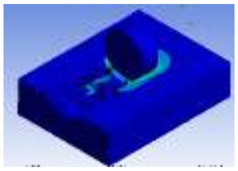
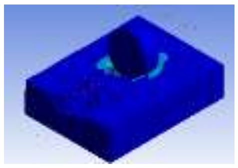
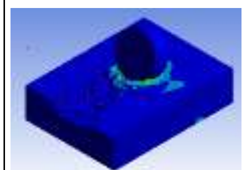
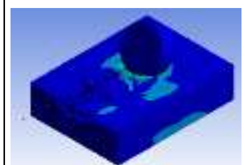
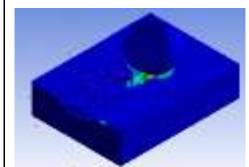
$$\mathrm{W} = 1.025\mathrm{e}4 \; \mu\mu m^2$$

Others calculation are simplify in the table below.

Size of Cutter (mm)	Combined Stress, (MPa)	Analytical Wear (μm^2)	Analytical Wear Rate ($\mu m^2/s$)
7	3363.51	8.3928E+05	1.3988E+04
10	2660.86	1.8513E+05	3.0855E+03
13	2226.52	5.8652E+04	9.7753E+02
16	1698.95	1.0251E+04	1.7085E+02
19	1527.3	5.1571E+03	8.5951E+01

APPENDIX V

Simulation Results on von misses stress

0˚	10˚	20˚	30˚	40˚
				

7mm	10mm	13mm	16mm	19mm