THE ANALYSIS OF PDC CUTTER CHARACTERISTIC IN HARD FORMATION DRILLING RELATING TO WEAR

(BACK & SIDE RAKE ANGLE)

By

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17004

Dissertation submitted in partial fulfilment of

the requirements for

Bachelor of Engineering (Hons)

(Mechanical Engineering)

MAY 2015

Universiti Teknologi PETRONAS

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Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

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Approved by,

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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.

Affan Bin Nasir Gathoth Subroto

ABSTRACT

The project focuses on the optimization of Polycrystalline Diamond Compact (PDC) cutters characteristic features relating to wear for improvement on durability in drilling of hard formation. Case history shows that conventional PDC drill bit failed to complete the section that provides troublesome hard formation. The PDC drill bit's performance dropped and affects the rate of penetration. Therefore, and intensive study in PDC bit design characteristic would help complete the section with high ROP if the design features of PDC drill bit can be optimized. The enhancement of ROP will result in the reduction of the well costs. Design features of PDC bit can be improved with an analysis of important design parameters that can help in improving the ROP. The important design features of PDC bit include the size, shape and number of cutters used, the angle of attack between the cutter and the surface of the exposed formations and cutter orientation which consists of back rake angle and side rake angle. This project focused on back and side rake angle design features to improve PDC bit to resist wear when encounter hard formation drilling process. The drilling operation is simulated under constant applied force and velocity. The theoretical basis of the PDC cutter is studied using the cutter-rock interaction model and Merchant's orthogonal cutting model. A 3D simulation model of rock breaking using a single PDC cutter is done using Ansys based on elastoplastic mechanics and rock mechanics to analyze the stress beneath the cutter. Effect of back and side rake angle of PDC cutter on the rule of cutter wear rate were analyzed by using the wear theory. Result showed that 60 ° back and side rake angled cutter are the best design to minimize the cutter wear rate in hard formation.

ACKNOWLEDGEMENT

An endeavor over a period can be successful only with the advice and support of well-wishers. The author would like to take this opportunity to express his profound gratitude to Universiti Teknologi PETRONAS for providing the platform for the research project to be conducted.

The author also take this opportunity to express a deep sense of gratitude and regards to his supervisor, **AP Dr. Abdul Rahim Othman** for his cordial support, valuable information and exemplary guidance, which help the author in completing the final year project. The blessing, help and guidance given by him time to time shall carry the author a long way in the journey of life on which the author about to embark.

The author would like to thank Almighty, her parents, brother, sisters and friends for their constant encouragement without which this report would not be possible.

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

The developments of drilling technology in oil and gas industry in the past two decades have been very significant. These developments bring the oil and gas industry worldwide to be economically and successfully in utilizing oil and gas fields that engineers maybe not thinking about it before. The successes of drilling projects of oil and gas industry can be predicted on the skill of the drilling engineer who totally understands all the engineering characteristics and apparatus required to drill a usable hole at the lowest expenses (Azar & Samuel, 2007). Whether drilling a vertical hole or a directional hole for the purpose of extracting oil and/or natural gas, several elements are needed to drill the hole successfully and economically.

One of the element is the selection of the suitable drill bit related to the type of formation that going to be drilled. (Bowers et. al, 2004). There are many types of drill bit used to drill whether in soft, medium or hard formation. The most challenging part is when the formation is interbedded with hard stringers, which is known as hard formation. Hard formation consist of hard shale, calcites, mudstones, cherty lime stones and hard and abrasive formations. This formation will easily dull the drill bit when wrong selection of drill bit is used. When this happened, it gives a major impact on the total well cost.

There are two types of drill bit, namely roller cone bit and fixed cutter bit. Each of them have their own advantages and disadvantages. In this project, the wear characteristic of the fixed cutter bit of Polycrystalline Diamond Compact (PDC) cutter will be studied with regards to the several design parameters.

1.2 Problems Statement

PDC cutter have gained popularity in drilling for petroleum due to its long life together with ability to maintain a high rate of penetration (ROP). The shearing action induced by fixed cutters has shown to be more efficient for penetrating rock than the crushing effect of the teeth or inserts on the rolling cones of a roller bit. However, PDC cutter have traditionally had limitations when encountering hard formation, where impact damage, heat damage and abrasive wear of PDC cutters limits the performance (Clayton et al., 2005).

Owing to that, the project will focus on the wear characteristics of PDC cutters in hard formation drilling. Therefore, the 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. Therefore, selecting a proper cutter characteristic for drilling into hard formation is very vital because the selection of parameters may help to prolong the cutter life as well as maximize the rate of penetration (ROP).

1.3 Objective

The objective of this project are:

1. To derive analytical model of the PDC cutter in hard formation drilling.
2. To develop simulation modeling of the PDC cutter in hard formation.
3. To determine the optimal characteristic of PDC cutter in hard formation.

1.4 Scope of Study

The scopes of study that are based on the objectives can be simplified as follows:

1. Mechanical characteristics of the cutter such as size, material type, cutting angle, expose value and parameter on cutting efficiency and their effect to the behavior of hard rock formation will be studied.
2. 3D drawing simulation, Autodesk Inventor/Catia V5 will be utilized in the study.
3. A drilling simulation software, ANSYS Explicit Dynamic will be integrated for the analysis of the cutter parameters.

1.5 The Relevancy of the Project

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

1.6 Feasibility of the Project within the Scope and Time Frame

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

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In 1909, when Howard Hughes Sr. introduced the first rotary drill bit, roller cone drill bits have been used for exploration and retrieval of oil and natural gas. Roller cone bits and their counterpart, polycrystalline diamond compact (PDC) bits form two predominate bit types in use today.

Nowadays, the bits still need some improvement based on the type of formation that going to be drilled. Continued improvements to bit technology depend on the wear characteristic of the bits and other factors. The wear characteristic in drilling have been shown to affect the rate of penetration (ROP) and life of bits. To understand the wear characteristic of drill bits, research work related to this project is required and based on the academia resources from journals and books.

2.2 Rotary Drilling System

In rotary drilling rigs, there have two type of drilling rigs which is onshore (land) and offshore (marine) rigs. Their main design features are mobility, flexibility, and maximum depth of operation. Rig components, in general are common to both onshore and offshore rigs. The only major difference is in the utilization of an extension pipe (drilling riser) between rig floor and seabed when drilling in a marine environment.

Modern land rigs are built-in units and are skid mounted so that they can be transported from one drilling site to another. One on location, the various rig components are easily assembled to drill the well. A diagram of system for onshore drilling is pictured in Figure

2.1. The basic components are a power system, a superstructure consists of derrick structure which holds lifting components, a drilling fluid circulatory system, and a rotary system (Baker. R., 1994). The derrick structure is designed such that it can be assembled and disassembled with ease. The function of derrick structure is to carry loads that are suspended in the wellbore and to provide space between the rig floor working area and the crown block, such that a certain length of the drill string can be made.

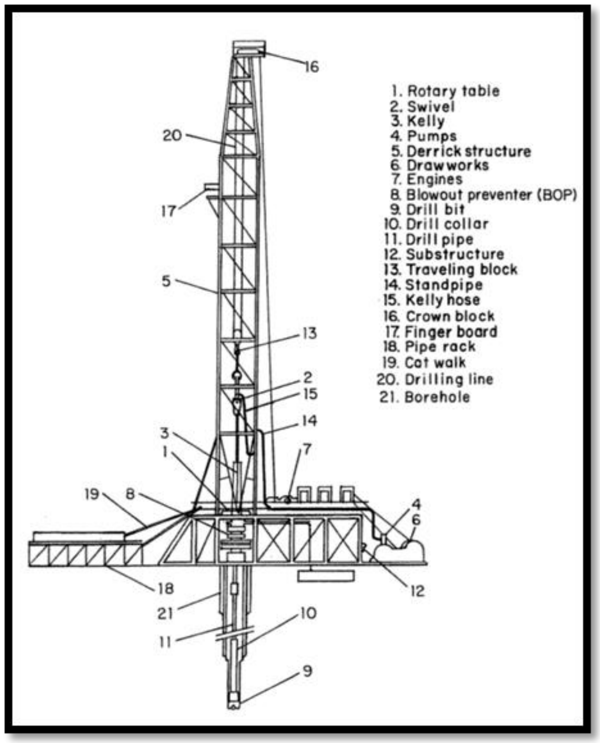


Figure 2.1: A schematic of a typical rig and its components

For power system and lifting components, their names indicate their functions. The power system supplies power to the drill string, lifting components, mud pumps, etc. Amongst other things, the rotary system contains the drill string and the bit at the end of the string. The bit is part of the bottom hole assembly (BHA). The BHA may contain motor, steering equipment, and electronic to supply dynamic and positional data. The circulatory system pumps a drilling fluid, commonly referred to as “mud,” through the center of the drill string and out specially designed nozzles located in the bit. The fluid carries rock cutting up the well between the drill string and borehole wall as well as cools and lubricates the bit.

A rotary system uses the weight of the drill string to apply a downward force to the rock. Heavier section of pipe called drill collar are a part of the BHA and attached at the bottom of the drill string to supply weight on the bit. The hoisting system lifts up the drill string to balance the remaining weight of the drill string. The weight on the bit is difference between the weight of the drill string and the weight held by the hoisting system. This allows the majority of the drill string to remain in tension to prevent buckling. While the force is applied, the drill string and bit are rotated at the surface by the power system.

For offshore, the basic components between onshore and offshore drilling is same. The only different is it was performed from the space above water on structures called platforms. These platform divided into two types which is mobile and fixed type. The selection of a particular rig carrier depends on the operations to be performed and the water depth of the location where such operation are to be conducted.

2.3 Drill Bit

There have two major type of drill bits now widely used in extracting oil and natural gas. Roller cone bit and fixed cutter bit. A roller cone bit comprises of one, two or three cones having teeth sticking out of them, while a fixed cutter bit has no moving part and can drill a very long hole sections when a proper drilling conditions are given.

A roller cone bit divided into two other type which is Tungsten Carbide Insert (TCI) bit and milled tooth bit. TCI bit is one of the hardest materials and it capable for drilling hardest and most abrasive formation while for milled tooth bit. It best in softer formation and less expensive than other type of bit.

Figure 2.2: Several type of PDC drill bit

In figure 2.2, there have three categories of fixed cutter. Polycrystalline Diamond Compact (PDC) bit, Natural Diamond bit and Impregnated bit. PDC drill bit have tungsten carbide cutter topped with hard cap of diamond composite material. The diamond cap are made by heating and compressing artificial diamond grid with tungsten carbide in other metallic binders. It come in a variety of design that can be used for an extensive range of drilling requirement as shown at figure 2.2 and it much more expensive than roller cone bit but generally can penetrate faster and last longer that roller cone bit. For Natural Diamond bit, it have industrial grade diamond, set in the butt surface to create an abrasive cutting face. Their primarily used in hard or highly abrasive formations that would be more damaging to others bit type. They are not effective in softer formation because of their smoother surface. Lastly, impregnated bit where their PDC cutters are protruding straight out of bit body, while regular PDC bit have cutter bonded to the outside in angle to the cutting face. Impregnated design increases cutter ability in the lateral cutting angle keeps cutter sharp as their wear. This design good used in formation with intermittent layer of soft and hard rock because they can effectively

2.4 Mechanism of Drill Bit

Roller cone bit works used the teeth to gouge through rock while fixed cutter work by shearing and scraping through rock. Every mechanism are based on the hardness of the formation for which it will be used. The main considerations in the design the cutting actions is the height and spacing of teeth or inserts.

Soft formation bits require deep penetration into the rock so the teeth are long, thin and widely spaced to prevent bit balling. Bit balling occurs when soft formations are drilled and the soft material accumulates on the surface of the bit preventing the teeth from penetrating the rock. The long teeth take up space, so the bearing size must be reduced. This is acceptable since the loading should not be excessive in soft formations.

For moderately hard formation, bits are required to withstand heavier loads so tooth height is decreased, and tooth width increased. Such bits rely on scraping/gouging action with only limited penetration. The spacing of teeth must still be sufficient to allow good cleaning.

Hard formation bits rely on a chipping action and not on tooth penetration to drill, so the teeth are short and stubbier than those used for softer formations. The teeth must be strong enough to withstand the crushing/chipping action and sufficient numbers of teeth should be used to reduce the unit load. Spacing of teeth is less critical since ROP is reduced and the cuttings tend to be smaller.

2.5 Type of Formation

The formation usually consists of sedimentary rocks where the majority of petroleum was found in this rock. 98% of hydrocarbon production in sedimentary rocks comes from sandstone and limestones. Sedimentary rocks are formed through physical, chemical or biological processes and is classified under clastics and carbonate. Clastics rocks are defined as those created by physical sedimentation which include conglomerates, sandstones, siltstones, claystones and shale. Clastics are classed by grain size, from conglomerates to sandstones to siltstones to claystones (in order of decreasing grain size). Shale are non-reservoir rocks, fine-grained and composed of clay minerals. Shale provides seals that prevent the migration of hydrocarbon and generate traps.). There were three types of formation that drilling process will encounter. Every types of formation consists different type of rocks.

Firstly for soft formation, it consist of unconsolidated sands and clays. These can be drilled with a relatively low WOB (between 3000-5000 lbs/in of bit diameter) and high RPM (125-250 RPM). Large flow rates should be used to clean the hole effectively since the ROP is expected to be high. Excessive flow rates however may cause washouts. Flow rates of 500-800 gpm are recommended. As with all bit types, local experience plays a large part in deciding the operating parameters.

For medium formation, it formation may include shales, gypsum, shaley lime, sand and siltstone. Generally a low WOB is sufficient (3000-6000 lbs/in of bit diameter). High rotary speeds can be used in shales but chalk requires a slower rate (100-150 RPM). Soft sandstones can also be drilled within these parameters. Again high flow-rates are recommended for hole cleaning.

Lastly, the hard formations may include limestone, anhydrite, hard sandstone with quartic streaks and dolomite. These are rocks of high compressive strength and contain abrasive material. High WOB may be required (e.g. between 6000-10000 lbs/in of bit diameter. In general slower rotary speeds are used (40-100 RPM) to help the grinding/crushing action. Very hard layers of quartzite or chert are best drilled with insert or diamond bits using higher RPM and less WOB. Flow rates are generally not critical in such formations. According to Bowers (2004), type of formation is a major factor in selecting the suitable drill bit that going to be drilled. A more detailed description of formation types and suitable bits is given in Table 2.1.

FORMATION	BIT TYPE	CUTTING STRUCTURE	OFFSET PIN ANGLE	BEARING SIZE CONE THICKNESS
SOFT Unconsolidated formations, l ow compressive strength e.g. slays, shales	5-5-7 5-3-7 5-4-7	maximum extension of tooth shaped inserts, widely spaced	pin angle designed to give scraping and crushing action	small bearings and thin cone shell to accommodate long inserts
MEDIUM Softer segments of hard formations e.g. lime, sandy shale	6-1-7 6-2-7	wedge shaped inserts with reduced extension	pin angle reduced to give more crushing action, with some gouging effect	thicker shell to give more protection
HARD Rocks of higher compressive strength e.g. dolomite, chert	7-3-7 7-4-7	wedge shaped inserts closely spaced	offset reduced to give more crushing/grinding effect, very little scraping	thicker shell, larger bearings

Table 2.1: Description of formation types and suitable bits

2.6 PDC Drill Bit

The polycrystalline diamond compact (PDC) consists of a layer of bonded diamond particles backed up by a thicker layer of a tungsten carbide (Gouda al., 2011). The use of the PDC bits has come to a direct impact for an efficient drilling encounters in oil and gas industry. Therefore, the highest profits could be obtained by using the PDC bit while keeping the PDC cutter in good conditions when drilling any type of formation.

The introduction of polycrystalline diamond compact (PDC) cutter in 1973 has aided the evolution of the first drill bit that used synthetic diamonds as cutting elements. The evolution process of this drill bit has developed so that these days a huge amount of footage is drilled with PDC bits.

Figure 2.3 shows the details components of PDC bit. The main part of PDC bit is divided into two parts, consisting of body and blade. The body includes sub-components of waterway, apex and nozzle. The drilling fluid comes out of the nozzle to clean the drill bit while cooling the drill bit as heat is generated at the interface between the cutter and the rock due to the friction (Crouse & Chia, 1985). Next, the other part is blade, involving the cutters and its area, which are further divided into three sections of nose, shoulder and gauge. Each of the main parts of the bit has a number of features. For effective drilling, different technological parameters shall be applied for different rock types.

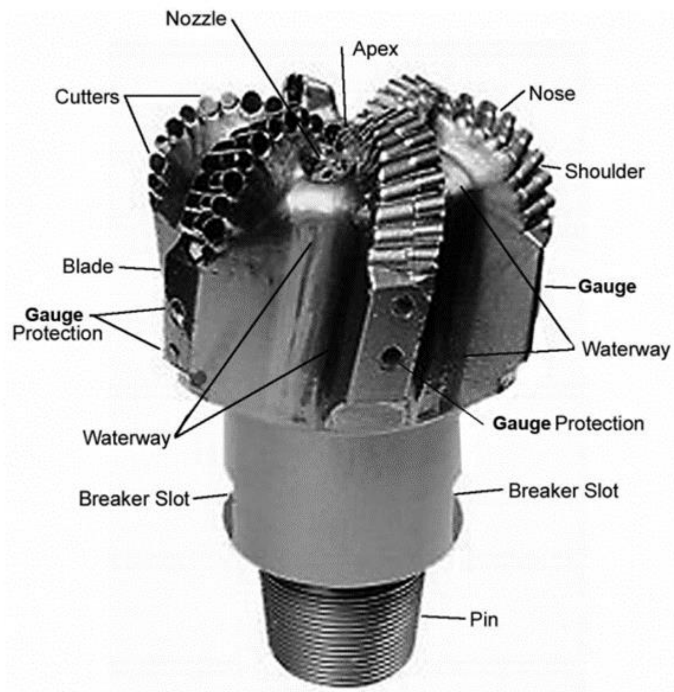


Figure 2.3: PDC bit components

On the blade area, the cutters of PDC bit are mounted on a bit body. Figure 2.4 shows there are two types of bit body used for PDC bits. One of these is an entirely steel body and the other is a steel shell with a Tungsten Carbide matrix surface on the body of the shell. The cutters on a steel body bit are manufactured as studs as shown at Figure 2.5. These are interference fitted into a receptacle on the bit body. Tungsten carbide button inserts can also be set into the gauge of the bit to provide gauge protection. The stud can be set with a fixed back rake and/or side rake.

(a) (b)

Figure 2.4: (a) Steel-body bit; and (b) Matric-body bit (Source from Halliburton Drill Bits and Services)

An advantage of using a stud is that it may be removed and replaced if the cutter is damaged and the body of the bit is not damaged. The use of a stud also eliminates the need for a braze between the bit body and the cutter.

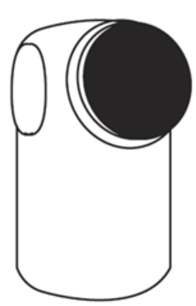


Figure 2.5: PDC stud cutter

Field experience with the steel body bit indicates that face erosion is a problem, but this has been overcome to some extent by application of a hard facing compound. Steel body bits also tend to suffer from broken cutters as a result of limited impact resistance as shown at figure 2.6. This limited impact resistance is because there is no support to the stud cutter.

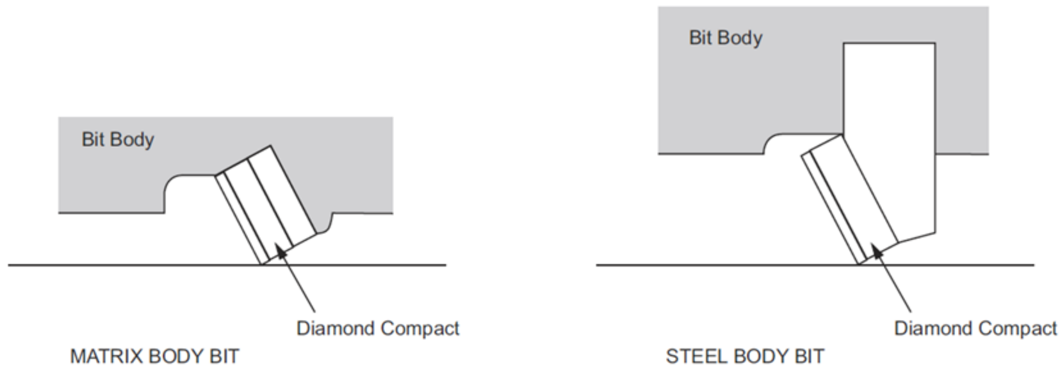


Figure 2.6: Setting of the cutter

For matrix body bits, it use the cylindrical cutter (Figure 2.7) that is brazed into a pocket after the bit body has been furnace by conventional diamond bit techniques. The advantage of this type of bit is that it is both erosion and abrasion resistant and the matrix pocket provides impact resistance for the cutter. Matrix body bits have an economic disadvantage because the raw materials used in their manufacture are more expensive.

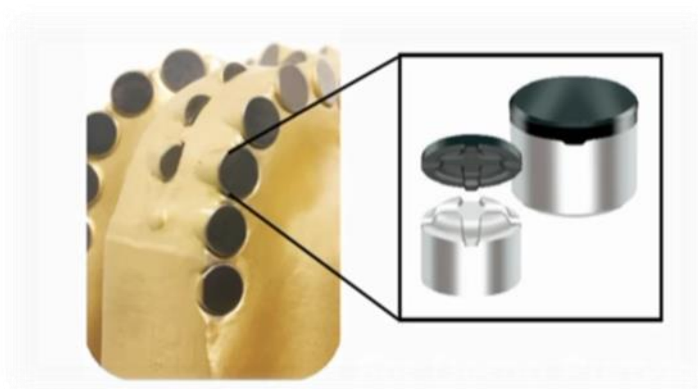


Figure 2.7: PDC cylindrical cutter

Currently, the PDC bits are still evolving and through development, several design will affect bit performance. But now, they perform best in soft, firm and medium-hard non-abrasive formation (Bourgoyne et al., 1986). Good results of utilizing these bits have been accomplished in sandstone, siltstone and shale although bit balling is a serious problem in soft formations. Nonetheless, a rapid cutter abrasion and breakage are a serious problem in hard abrasive formations.

2.7 Design Parameter of PDC Drill Bit

Many factors effects the wear characteristics for PDC bit. Cutter density is one of them. The cutter density is the number of cutters per unit area on the face of the bit. The cutter density can be increased or decreased to control the amount of load per cutter. This must however be balanced against the size of the cutters. If a high density is used the cutters must be small enough to allow efficient cleaning of the face of the bit.

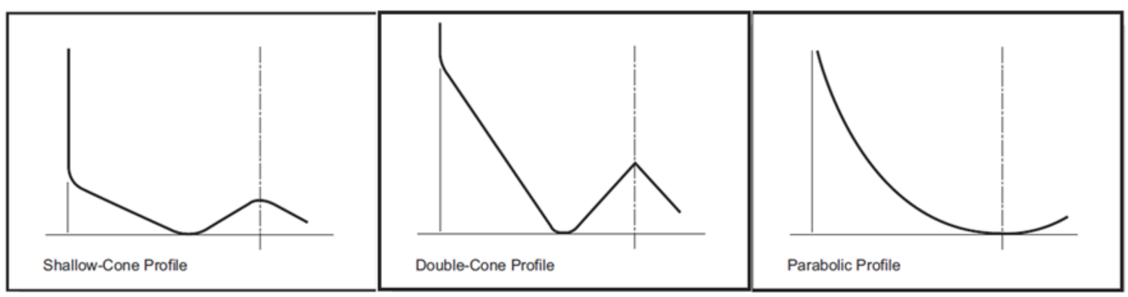


Figure 2.8: PDC bit shallow-cone, double-cone and parabolic profile

Bit profile also contribute in effect of wear characteristic for PDC bit. There are three basic types of PDC crown profile as shown at figure 2.8. Flat or shallow cone, tapered or double cone and parabolic. There are variations on these themes but most bits can be classified into these categories. The flat or shallow cone profile evenly distributes the WOB among each of the cutters on the bit. Two disadvantages of this profile are limited rotational stability and uneven wear. Rocking can occur at high RPM, because of the flat profile. This can cause high instantaneous loading, high temperatures and loss of cooling to the PDC cutters. The taper or double cone profile allows increased distribution of the cutters toward the O.D. of the bit and therefore greater rotational and directional stability and even wear is achieved. The parabolic profile provides a smooth loading over the bit profile and the largest surface contact area. This bit profile therefore provides even greater rotational and directional stability and even wear. This profile is typically used for motor or turbine drilling.

In addition, cutter rake also is important design parameter. The PDC cutters can be set at various rake angles. These rake angles include back rake and side rake. The back rake angle determines the size of cutting that is produced. The smaller the rake angle the larger the cutting and the greater the ROP for a given WOB. The smaller the rake angle, however, the more vulnerable the cutter is to breakage should hard formations be encountered. Conversely the larger the rake angle the smaller the cutting but the greater resistance to cutter damage. Back rake also assists cleaning as it urges the cuttings to curl away from the bit body thereby assisting efficient cleaning of the bit face. Side rake is used to direct the formation cuttings towards the flank of the bit and into the annulus.

According to Hareland (2009), the cutter penetrates the rock based on the point load on each cutter originated from the applied weight on the bit (WOB). Figure 2.9 shows the PDC cutter and parameter acting on it where the cutter is titled with an angle, ϕ, with respect to the rock. The angle, ϕ, is the back rack of the cutter. The best setting for back rake angle are either at 0° or at 25° but the effect of back rack angle become less significant as the depth of cut decreases.

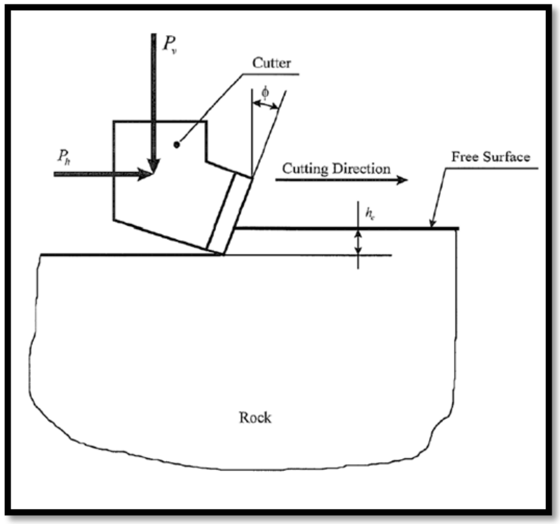


Figure 2.9: PDC cutter and parameter acting on it

However, even when the depth of cut is less than 0.02 inch, there is still a noticeable effect by the rake angle, especially at 0°. This implies that the back rake angle of a PDC cutter become more important at a larger depth of cut.

Another factor is cutter exposure. Cutter exposure is the amount by which the cutter protrude from the bit body. It is important to ensure that the exposure is high enough to allow good cleaning of the bit face but not so high as to reduce the mechanical strength of the cutter. High exposure of the cutter provides more space between the bit body and the formation face, whilst low exposure provides good backup and therefore support to the cutters.

Kerr (1988) mentioned that some of the technological advancement that have been tested are the PDC cutter. According to him, a large diameter of PDC cutter can provide an increase in exposure which features a higher point loading. Larger cutters have a high amount of usable diamond volume compared to smaller cutters, thus increase the bit's durability (Taylor et al., 1998). Case history shows that certain formations are believed to respond more positively to width of cut than depth of cut. For that case, larger cutters that cover a wider sideways area will be efficient.

2.8 Wear Characteristic of PDC bit

In wear characteristic for PDC bit, there were two major category that caused the wear effect to PDC bit which is abrasive wear and result of impact loading of the cutters. Abrasive wear indicated steady-state wear that is normally associated with the development of uniform wear flats on the PDC cutter and the degradation in rate of penetration over the bit life. It is a function of the operating cutting parameters applied to the bit and individual cutters, cutter temperature, cutter velocity, formation properties, and cutter properties. For result of impact loading of the cutters, wear may be caused by dynamic loading of the bit during bit whirl (backwards vibration) or from drilling through nonhomogeneous formations. Cutter wear from impact loading is typified by chipped, broken, and lost cutters. Dynamic loading of the cutters can be caused by abrupt changes in the surface drill string control, forces induced by cutter/rock interaction, or from drill string dynamics. Due to the lack of optimizing the drilling cutting parameter, minor chipping of the diamond table along the cutter edge occurred at PDC bits as shown at figure 2.10.

Figure 2.10: Minor chipping of the diamond table along the cutter edge.

The cause of chipped cutters is from vibration and type of formation change when doing drilling process. In figure 2.11, it shows there have many others type of wear for PDC cutters while in table 2.2 explanations and cause of the wear characteristic is stated.

BT	broken teeth/cutters
BU	balled up
CR	cored
CT	chipped teeth/cutters
ER	erosion
HC	heat checking
JD	junk damage
LN	lost nozzle
LT	lost teeth/cutters
NO	no major/other dull characteristics
PN	plugged nozzle/flow passage
RO	ringout
WO	washed out
WT	worn teeth/cutters

Figure 2.11: PDC wear characteristics

Table 2.2: Explanations and cause of PDC wear characteristic

Wear Characteristic	Explanations	Cause
BT – Broken Teeth/Cutters	A cutter that is broken flush or nearly flush to the diamond table and carbide substrate.	Operating parameter; vibration; junk damage; high-impact loading, formation too hard for bit; stick-slip.
BU – Balled Up	Obstruction of the junk slot by the cuttings.	Hydraulics; drilling practices; mud properties; reactive formations.
CR - Cored	The loss of effective cutting structure and substantial damage to the matrix originating from the center of the bit. Result in bottomhole pattern forming a peak.	Drilling practices; lost or broken cutter; high WOB; drillout damage; highly abrasive formation; vibration; off-center rotation.

CT – Chipped Teeth/Cutters	Minor chipping of the diamond table along the cutter edge.	Vibration; formation change.
ER - Erosion	Loss of carbide substrate behind the diamond table or loss of bit-body material from fluid action.	High flow rate; high solids content; abrasive sand.
LN – Lost Nozzle	One or more nozzle missing from the bit.	Poor nozzle installation.
LT – Lost Teeth/Cutters	Complete loss of one or more cutters, resulting in an empty pocket.	Erosion; vibration; junk damage.
NO – No Major/Other Dull Characteristics	No major dull characteristics.	-
RO - Ringout	The loss of effective cutting structure and substantial damage to the matrix, originating outside the center of the bit usually in the shoulder area. Bottomhole pattern forms a ring.	Drilling practices; lost or broken cutter; drillout damage; highly abrasive formation; vibration.
WT – Worn Teeth/Cutters	Less cutter projection as a result of even wear.	Normal drilling in a stable mode. Wear in abrasive formations.

2.9 Optimizing Drilling Performance

Optimizing drilling performance is frequently understood as maximizing penetration rate. However, this is not always the case as in some applications; drilling performance will be optimized by maximizing run length and reducing the number of trips. In these applications, an example of which is hard formations, the goal is to protect the cutting structure so it may be necessary to compromise penetration rate for run length.

For effective drilling, different technological parameters can be applied for different rock types. According to Taylor et al., (1998), in order to minimize the cutter damage when entering and leaving hard stringers, the shape of the PDC bit profile can be redesigned. Figure 2.12 shows that, recently there are several crown shapes of PDC bit profile and this provides important design features of PDC bit. The crown shape of bit should be designed within a similar plane or concave conical. Zhu et al. (2012) mentioned that under certain circumstance, the lateral side of bit is very sharp, which is advantageous to deflect without affecting the axial cutting. However, the crown shape could not be designed to the convex conical, because of the lateral cut capacity is very low and it will disturb the lateral cutting rock.

Figure 2.12: Several crown shape of PDC bit profile

Other important design features of PDC bit include the size, shape and number of cutters used and the angle of attack between the cutter and the surface of the exposed formations. Cutter orientation is defined in terms of back rake angle, side rake angle and cutter exposure. Cutter orientation must be properly matched to the hardness of the formation being drilled. Due to the important role that the cutting elements play in the application of the drilling bit, the PDC cutters are treated as a special unit.

According to Kerr (1988), the two current PDC bit-body materials that are being used now, tungsten-carbide matrix and steel. There have not been any definite answer to which of the design is more efficient, but a few characteristics of each have become apparent. Among the differences are those matrixes bits should provide high resistant to wear than those of the steel. However structurally, steel bits are more resilient than matrix bits.

Recently, the development of steel and matrix bit bodies are continuously progressing and their limitations are regularly reduced. Steel bits have been greatly protected with materials that are more resistant to abrasion and erosion than matrix. Concurrently, the structural and wear resisting properties of matrix are swiftly improving. The importance of steel bits is growing relative to matrix bits but both types have their place (Azar et al., 2002).

The challenge when drilling any section is to remain on the well profile at the highest penetration rate possible without causing hole problems (Taylor et al., 1998). A high average rate of penetration is required in hard formation so that the total time for a section can be reduced. Larger cutters usually produce larger cuttings that improve cleaning in soft formation. . Larger cutters have a high amount of usable diamond volume compared to smaller cutters, thus increase the bit’s durability (Taylor et al., 1998). Case history showed that certain formations are assumed to react more positively to width of cut than depth of cut. For that case, larger cutters that cover a wider sideways area will be efficient. On the other hand, smaller cutter provides long bit life in medium-soft to medium hardness formations. In addition, the middle-range cutters respond to a midpoint between the softest and the hardest formations.

Figure 2.13 shows the multiple rows of cutter, which possesses second row of cutters instead of just one on regular PDC bit. It can drill through a variability of lithology without consuming its performances. Multiple cutters offer a stable, low vibration bit for a tool face control. A smaller amount of energy is required thus optimizing the efficiency and stability even at a low rate of penetration. In harder formations drilling, the multiple cutters are used to increase the amount of diamond available to drill without reducing the open face volume of the bit.

Figure 2.13: PDC Multiple Row of Cutters. (Beaton et al. 2008)

2.10 Finite Element Method (Explicit Dynamics)

Finite Element Method (FEM) is a computer model of a material or design that is analyzed to get specific results. It helps a company to verify a proposed design to meet client's specifications subject to manufacturing or construction. This method is utilized by modifying an existing product or structure is to improve or qualify the product for a new service condition. If the model fails, FEM is very useful to help designer to modify back the design to meet the targeted condition. In addition, FEM also helps analyst to predict failure due to unknown stresses by showing problem areas on an object and giving chances for designers to see all of the theoretical stresses within.

The mechanism of finite element method is the solid is discretized into finite elements using an appropriate meshing scheme. Each individual element is the smallest unit in the finite element model and unit stresses and displacements will be defined for each element. A finite element solution will be a new stress field and displacement field after application of a loading on the body. Two different classes of finite element were offered which is implicit and explicit. For the purposes of this analysis, the selected finite element method is explicit.

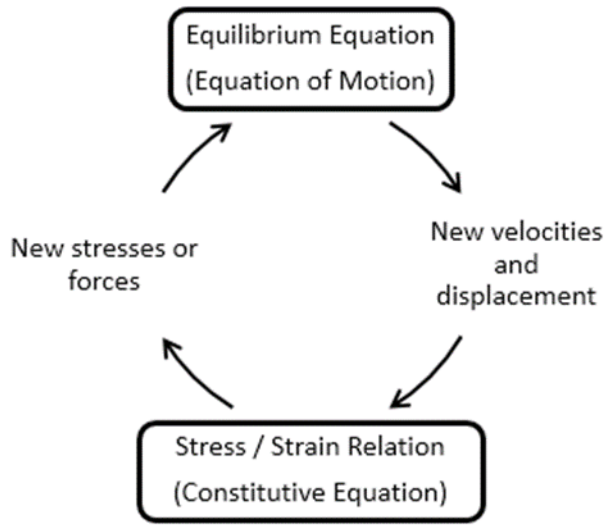


Figure 2.14 Calculation sequence in an explicit FEM method

In explicit solution of finite element method (sometimes called finite difference method), it solves the dynamic equation of motion over each time step, and then the new velocities and displacements give the new strain field. In turn, the new strain field is converted to the new stress field using the constitutive equations, and these give new forces acting on elements that will again be inserted into the dynamic equation of motion. This cycle continues for as many time steps as required as shown in figure 2.14.

There is one important consideration regarding the validity of the solutions given by explicit methods. Looking into the calculation cycle, when the stress field changes, the strains should change accordingly; but they do not. This suggests that the explicit simulations might not be realistic; however, if the time step chosen for calculation cycles is sufficiently low that the information physically does not have the time to pass from one element to the other, the simulation results would be valid. This minimum time step is called the critical time step and depends on the smallest element size and also the speed of wave propagation inside the material being modeled.

This method can help to reduce manufacturing costs and time rather than making and testing the real component (Szabo, 1991). Explicit Dynamics is one of the features in Finite Element Method. The ANSYS explicit dynamics product suites well in helping user to gain insight into the physics of short duration events for products that undergo highly nonlinear, transient dynamic events. These specialized, accurate and easy-to-use tools have been designed to maximize productivity. With the ANSYS explicit dynamics products, the author can study how a structure response when subjected to severe loadings. Algorithms based on first principles could accurately predict responses, such as large material deformations and failure, and interactions between bodies and fluids with rapidly changing surfaces.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Project Flow Chart

Figure 3.1 below illustrates the flow chart diagram for this project

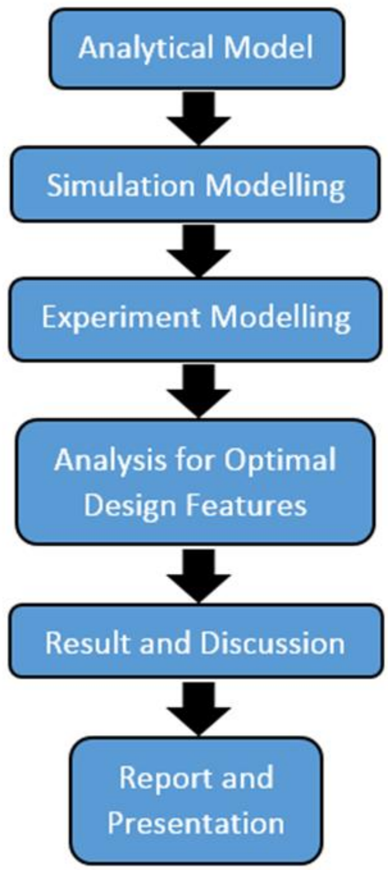


Figure 3.1: Project flow chart

Initially, an intensive review is conducted to attain the required information and existing research work based on the academia resources from journals and books. Numerous journals and books were studied to obtain the necessary information on this project especially for analytical model.

Following the literature review, the analytical model will be developed to collect the required results. Author will proceed with the simulation modelling using Autodesk Inventor/Catia V5 for 3D drawing, which is based on the results of the analytical model. Subsequently, the experiment modelling will be conducted using ANSYS Explicit Dynamic 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.

3.2 Project Activities

3.2.1 Analytical Model

Equation (1) 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 (β = 0), the equation (2) is in the 2D form.

$$\boldsymbol{F_H = F_N \cos\beta \left[\frac{1-\mu\tan\alpha}{\tan\alpha+\mu}\right]} \quad \textbf{(1)}$$

$$\boldsymbol{F_H = F_N \left[\frac{1-\mu\tan\alpha}{\tan\alpha+\mu}\right]} \quad \textbf{(2)}$$

Where F_H is the horizontal force, F_N is normal force, α is the back rake angle and μ is the coefficient of friction.

The effects of stress distribution and failure criteria on loading force variations are being emphasized. The stress on the tool rake face can be obtained using the equation (3) and (4)[6]:

$$\boldsymbol{\sigma} = \frac{\boldsymbol{F_N}}{\boldsymbol{A_N}} \quad \textbf{(3)}$$

where A_N is the normal contact area.

$$\boldsymbol{\tau} = \frac{\boldsymbol{F_H}}{\boldsymbol{A_S}} \quad \textbf{(4)}$$

where A_S is the shear contact area.

The wear rate model is used because it simple, yet effective. The model can be written in equation (5).

$$\mathbf{W} = \mathbf{k_2 V \overline{\sigma}^{\frac{1}{bn'}}} \quad \textbf{(5)}$$

Where the volume of deformed material V is taken as constant compared to the von Mises stress to the power of 6.45 to construct the wear model. The proportionality constant $k_2 \times V$ was taken as 1.5×10^{-11} [1][13].

3.2.2 Simulation Modelling

On simulation modelling using Autodesk inventor 2015, author decided to do modelling of PDC cutter with different back and side rake angle illustrated at Figure 3.2 and Figure 3.3. Where the angle is 0°, 10°, 20°,30°, 40°,50° and 60°.

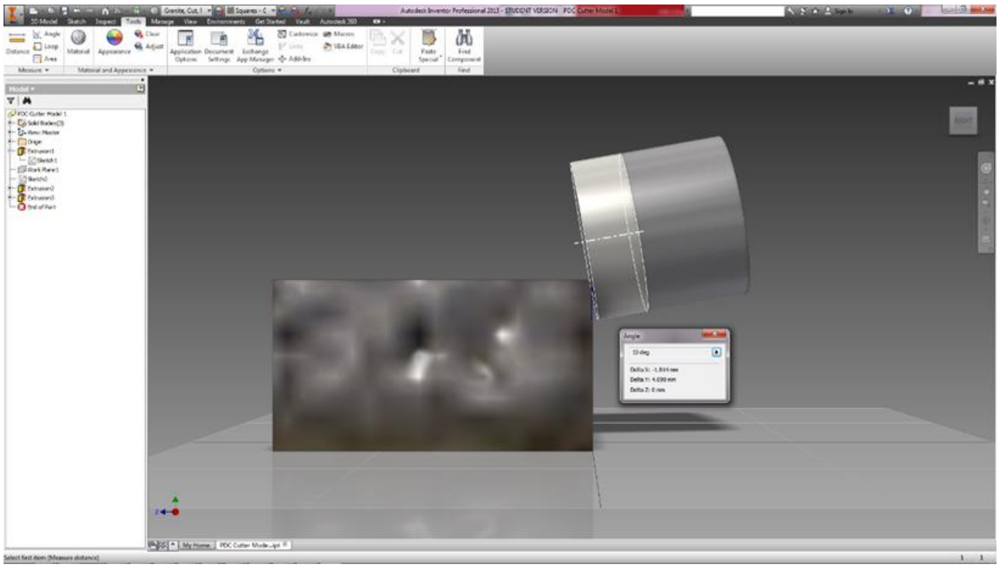


Figure 3.2: Example modelling of PDC Cutter with 10° of back rake angle

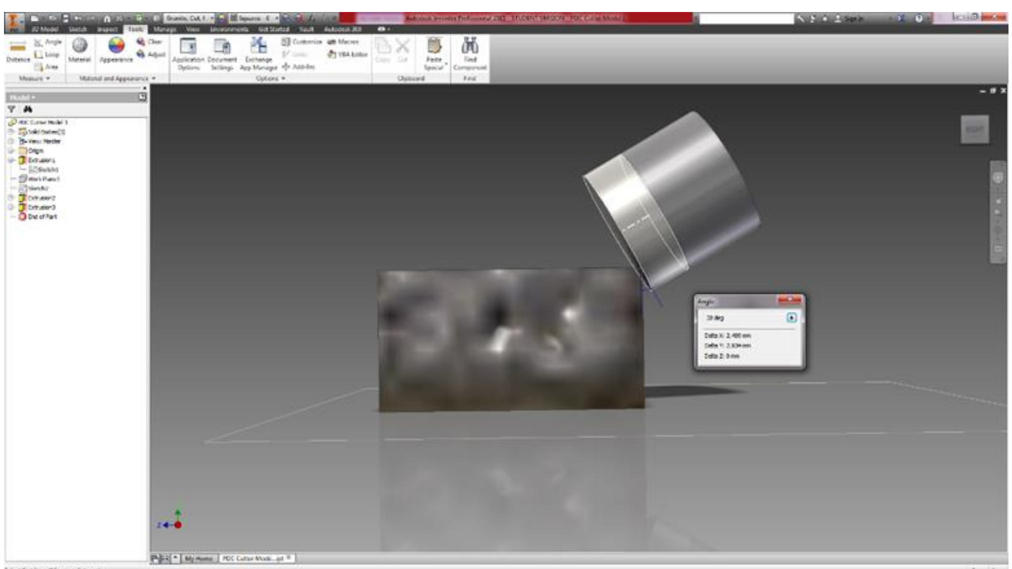


Figure 3.3: Example of modelling of PDC Cutter with 30° of back rake angle

3.2.3 Experiment Modelling

The design of products that need to survive impacts or short-duration high pressure loadings can be greatly improved with the use of ANSYS explicit dynamics solutions. Typical applications used in explicit dynamics are drop tests, impact and penetration. In this project, the author would like to study on the impact of the *PDC* cutter drilling on hard formation. Thus, ANSYS explicit dynamics is the most suitable analysis for this project. Figure 3.4 below shows the optimized PDC cutter with the rock formation in ANSYS explicit dynamic.

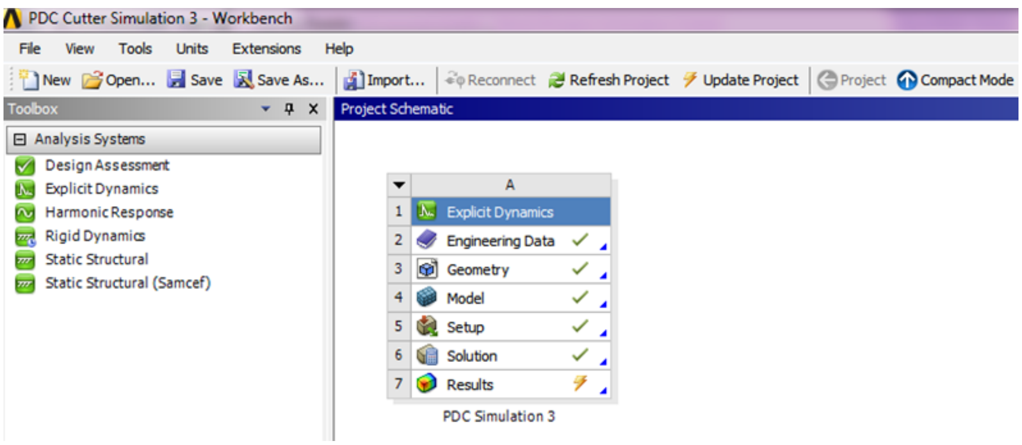


Figure 3.4: Explicit dynamic component analysis

3.2.4 Engineering Data

The properties and material for the component will be used in the analysis is defined in engineering data. Table below shows the material and properties used for the analysis.

Table 3.1: Engineering data of material properties

	Material	Properties
Cutter	Polycrystalline Diamond Compact	Density: 3510 kg m^-3 Young's Modulus:8.9E+11 Pa Possion's Ratio:0.07 Bulk Modulus:3.4496E+11 Pa Shear Modulus:4.1589E+11 Pa
Hard Rock Formation	Granite	Density: 26200 kg m^-3 Young's Modulus: 7E+10 Pa Possion's Ratio:0.3 Bulk Modulus:5.8333E+10 Pa Shear Modulus: 2.6923E+10 Pa

3.2.5 Geometry

The 3D model of PDC cutter and hard rock formation in .stp format are imported into ANSYS Geometry and open in Ansys Workbench for analysis setting as shown at figure 3.5.

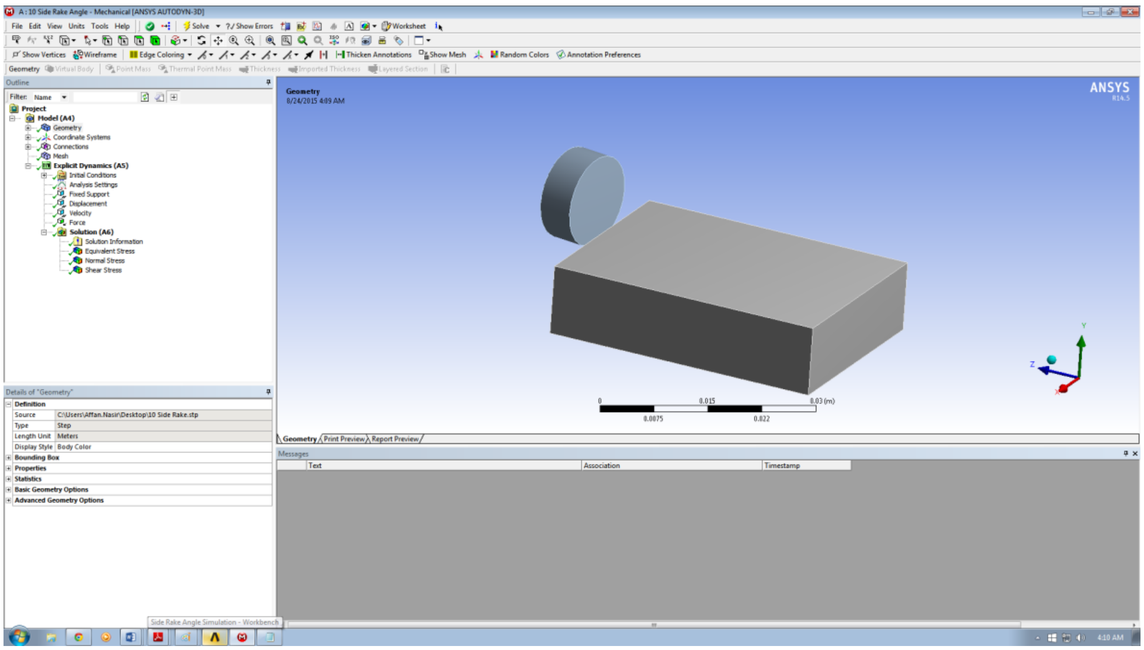


Figure 3.5: Ansys Workbench model interfaces

Material of the geometry, coordinate, connection, meshing properties, initial condition and analysis setting are defined in ANSYS Workbench Mechanical.

3.2.6 Meshing

Meshing is one of the important aspects in engineering simulation. Meshing is an integral part of the computer-aided engineering simulation process. The mesh influences 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.

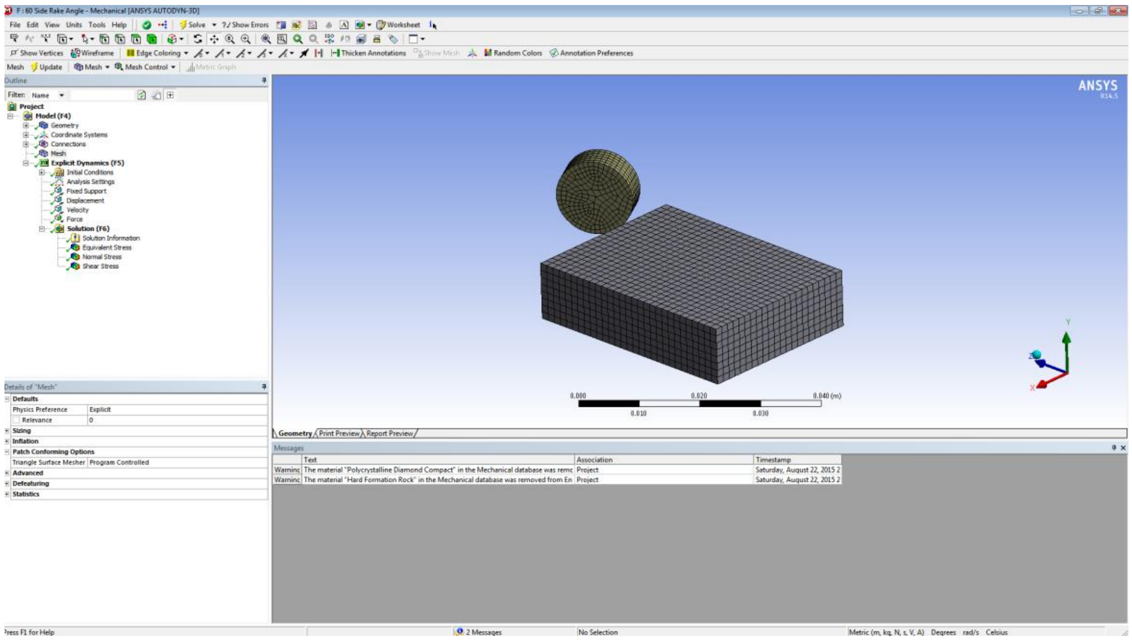
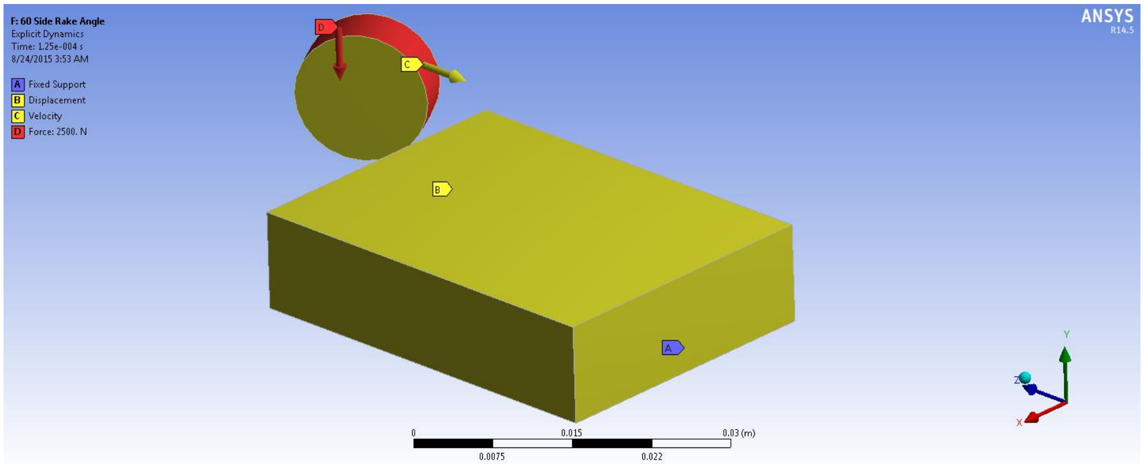


Figure 3.6: Meshing geometry

3.2.7 Explicit Dynamics

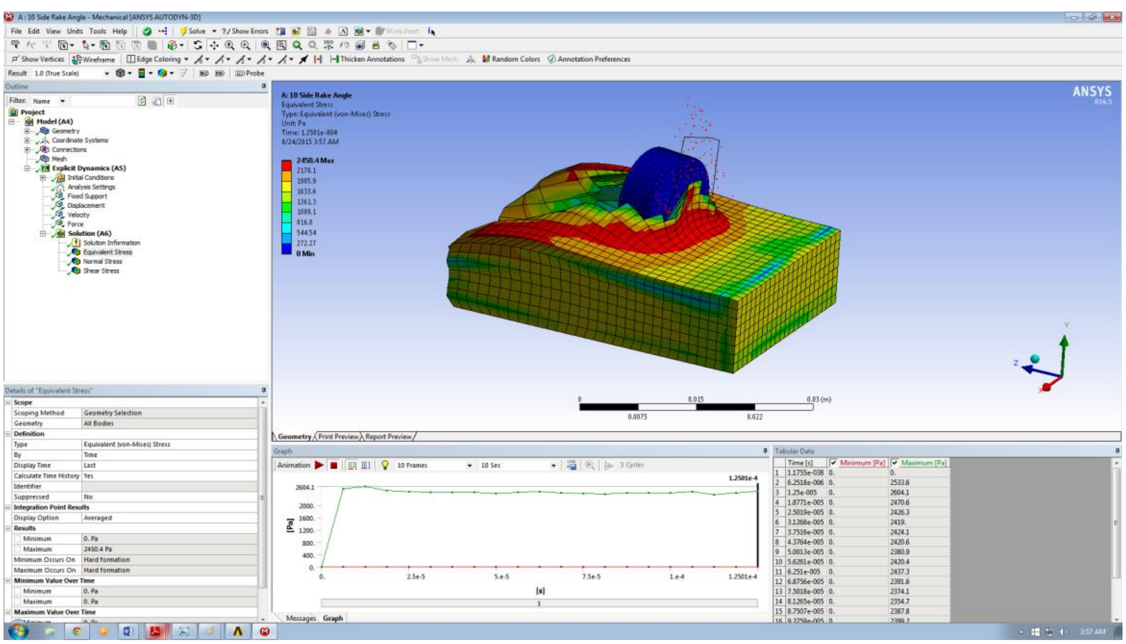
For an Explicit Dynamics system, the Initial Conditions folder includes a Pre- Stress object to control the transfer of data from an implicit static or transient structural analysis to the explicit dynamics analysis. Transferable data include the displacements or the more complete Material State (displacements, velocities, stresses and strains.) while the Analysis Settings include boundary condition and body interaction are defined under explicit dynamics. Velocity of 10 m/s is defined as initial condition. Other parameter such as horizontal and vertical force acting on the PDC cutter.

Fixed support of hard rock formation are inserted under analysis setting in figure 3.7 below.



3.7: Explicit Dynamic analysis setting

After all the settings are defined, the analysis now can be solved. For this project, the type of solution used is “Equivalent stress, shear stress and normal stress” to analyze the impact acting on PDC cutter as shown at figure 3.8 below.



3.8: Impact acting on PDC cutter and hard formation

3.3 Gantt Chart and Key Milestones

Table 3.2 shows the brief Gantt chart and key milestones of the projects for FYP 2. Note that the duration of the final year project includes Semester 1 and Semester 2 of 2015.

Table 3.2 Gantt Chart for FYP 1

No	Task	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Selection of Project Topic	■	■												
2	Literatures Review		■	■	■	■									
3	Submission of Extended Proposal						●								
4	Proposal Defense							■	■						
5	Selection of PDC cutter parameter					■	■	■							
6	3D Drawing Simulation								■	■					
7	Modeling Experiments/ Simulation										■	■	■	■	
8	Submission of Interim Draft Report													●	
9	Submission of Interim Report														●

Legends:

Project activity ■ Key Milestone ●

Table 3.3: Gantt Chart for FYP 2

No	Activites / Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Analytical Model														
2	Simulation Modelling														
3	Experiment Modelling														
4	Submission of Progress Report														
5	Analysis of Optimal Design Features														
6	Result and Discussion														
7	Presentation and Submission of Final Report														

CHAPTER 4

RESULT AND DISCUSSION

4.1 PDC Single Cutter Analytical Model

The single cutter analytical model as shown in figure 4.1 is used to study the cutter-rock interaction. The cylinder represents the PDC cutter and the rectangle represents the hard formation. F_N and F_H is the normal force and the horizontal force applied on the cutter in the drilling process respectively. F_N is the Weight on Bit (WOB) applied on the cutter. Depth of cut is 2mm and the size of cutter is 13 mm. The cutter is moving at a constant velocity of 10 m/s.

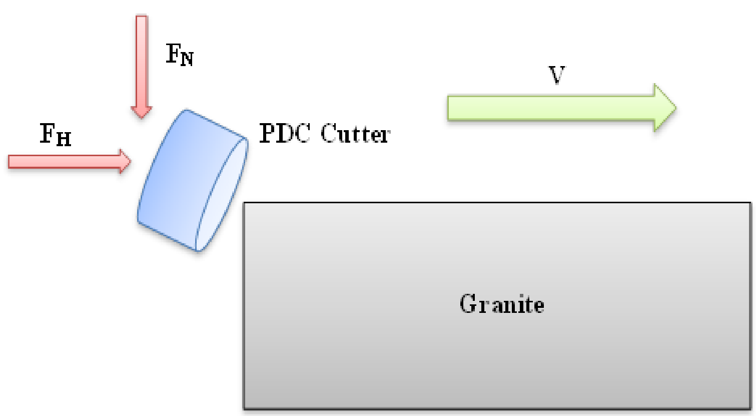


Figure 4.1: Single Cutter Model

4.1.1 Back Rake Angle

The data available for PDC cutter test is shown in Table 4.1.

Table 4.1: PDC cutter parameter (Back Rake Angle)

Parameter	***Value***
Side Rake Angle	0°
Normal Force, F_N	2500 N
Coefficient of Kinetic Friction, μ	0.45
Shape of the Cutter	Flat
Size of the cutter	13 mm
Area of Cutting Face, A_N	1.19781×10^{-4} m^2
Depth of Cut	2 mm

The data for shear contact area A_N with various back rake angle is shown in Table 4.2 and its illustration in Figure 4.2.

Table 4.2: PDC cutter shear contact area, A_N (Back Rake Angle)

Back Rake Angle	***Shear Contact Area, A_S***
0	1.2951×10^{-5} m^2
10	1.3242×10^{-5} m^2
20	1.4171×10^{-5} m^2
30	1.5942×10^{-5} m^2
40	1.9011×10^{-5} m^2

Back Rake Angle	*Shear Contact Area, A_S*
50	2.4401×10^{-5} m^2
60	3.4686×10^{-5} m^2

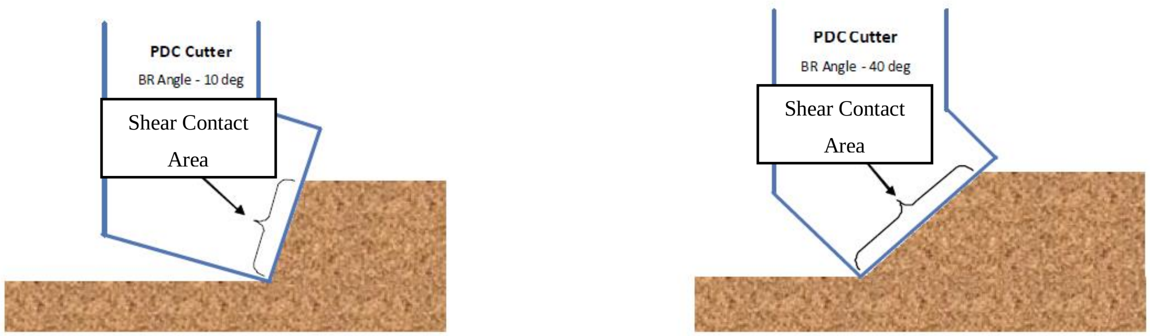


Figure 4.2: Illustration PDC Cutter Shear Contact Area

To compute the horizontal force, the equation (1) is used [12]:

$$\boldsymbol{F_H = F_N \left[\frac{1-\mu\ \tan\alpha}{\tan\alpha+\mu}\right]} \qquad \textbf{(2)}$$

Where F_H is the horizontal force, F_N is the normal force, α is the back rake angle and μ is the coefficient of friction.

The relationship between the cutter back rake angles on the horizontal force is calculated and shown in Figure 4.3.

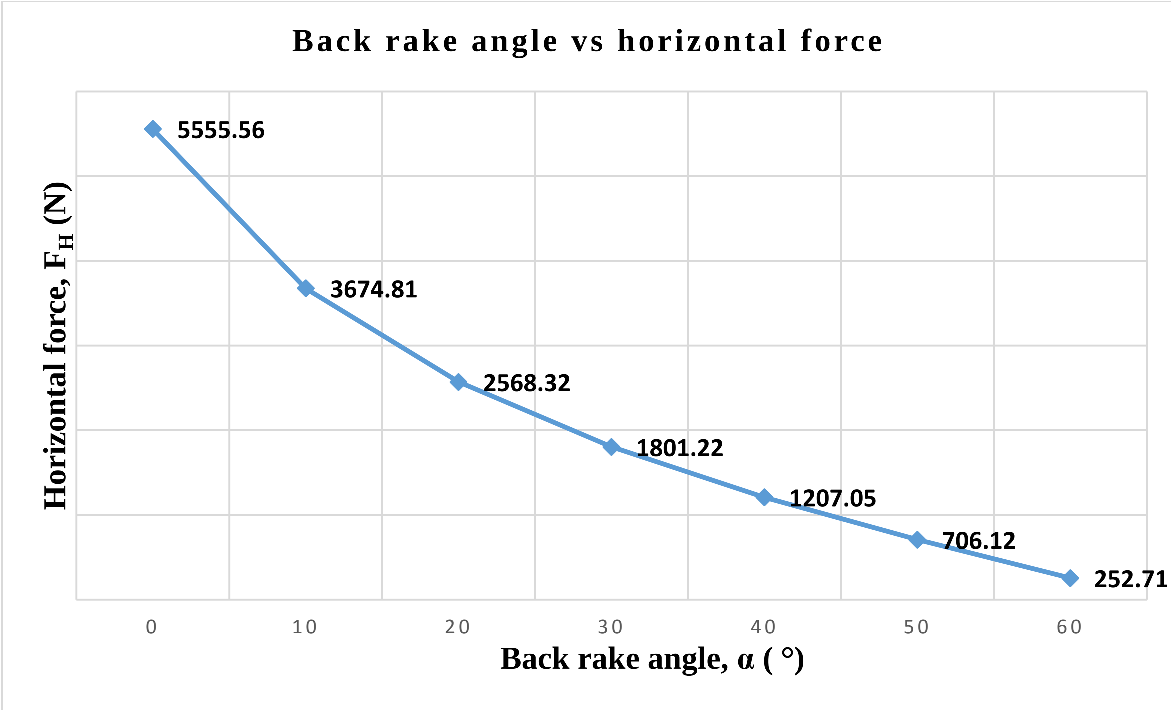


Figure 4.3: Graph of Horizontal Force vs Back Rake Angle

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. By referring to Merchant's model, the axial stress on the cutter faces can be calculated by using the equation (3) [13]:

$$\boldsymbol{\sigma = \frac{F_N}{A_N}} \tag{3}$$

where A_N is the area of cutting face, with a value of 1.19781×10^{-4} m^2. Thus, the axial stress axial stress on the cutter is equal to 20.87 MPa

In drilling, the horizontal force applied is equivalent to the shear force. Thus, 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 (4) [13]:

$$\tau = \frac{F_H}{A_S} \qquad (4)$$

where A_S is the shear contact area.

The shear stress and axial stress is totaled up to obtain the combined stress. The result for the combined stress for different back rake angled cutter is shown in Figure 4.4.

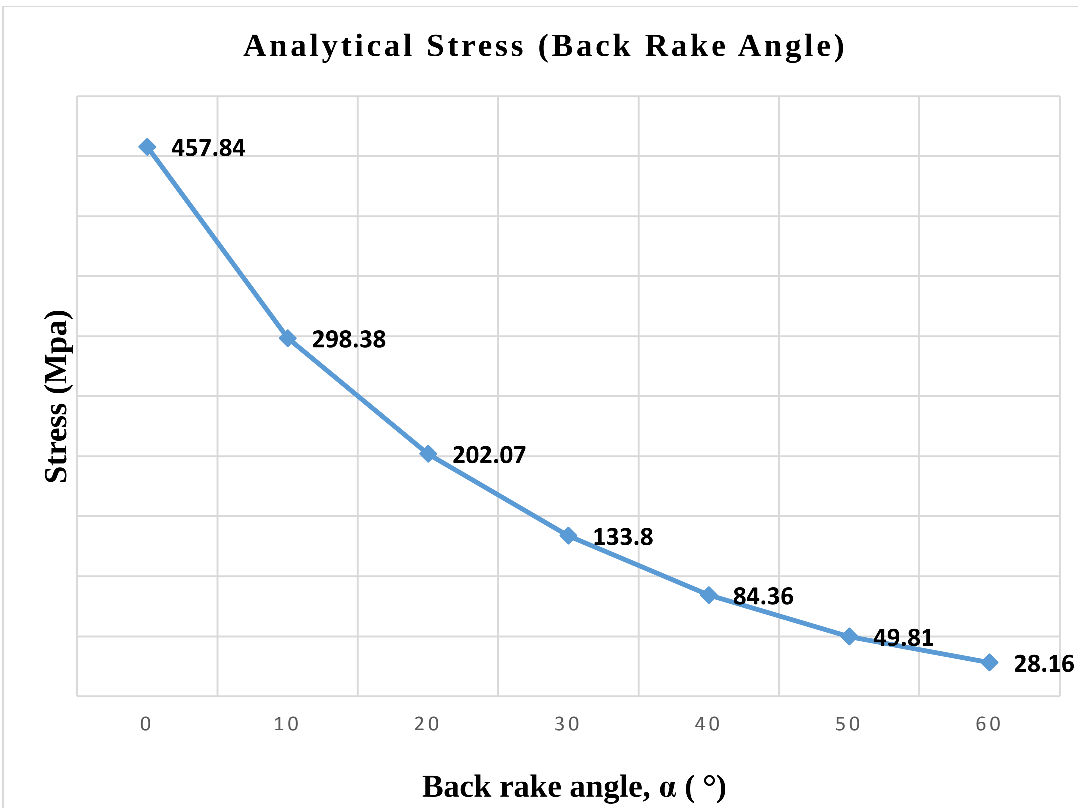


Figure 4.4: Effect of Back Rake Angle on Stress (Analytical)

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. The relationship between shear stress and horizontal force is shown in Figure 4.5.

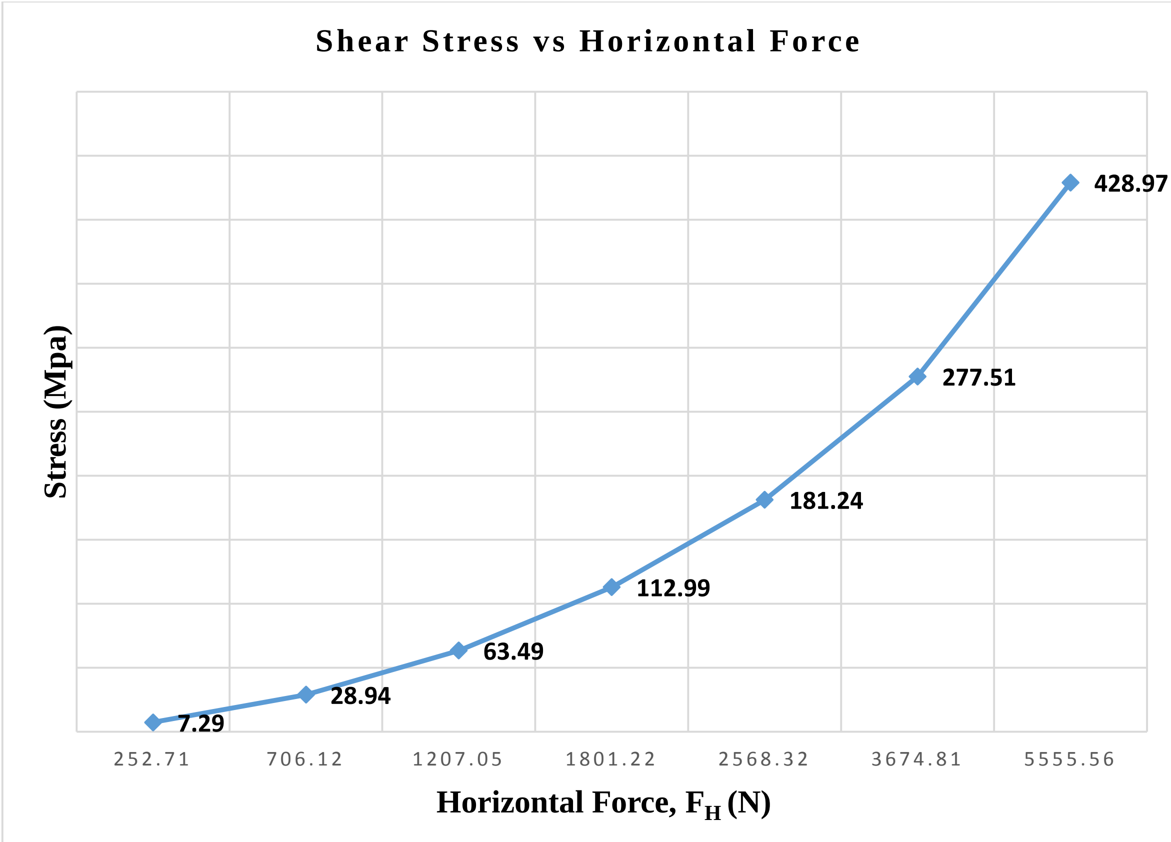


Figure 4.5: Graph of Shear Stress vs Horizontal Force (Back Rake Angle)

According to the Figure 4.5 horizontal force is directly proportional to shear stress. Thus, lower back rake angle results in higher shear stress.

4.1.2 Side Rake Angle

The data available for PDC cutter test is shown in Table 4.3.

Table 4.3: PDC cutter parameter (Side Rake Angle)

Parameter	***Value***
Back Rake Angle	0°
Normal Force, F_N	2500 N
Coefficient of Kinetic Friction, μ	0.45
Shape of the Cutter	Flat
Size of the cutter	13 mm
Area of Cutting Face, A_N	1.19781×10^{-4} m^2
Depth of Cut	2 mm

The data for shear contact area A_N with various side rake angle is shown in Table 4.4.

Table 4.4: PDC cutter shear contact area, A_N (Side Rake Angle)

Side Rake Angle	***Shear Contact Area, A_S***
0	1.2951×10^{-5} m^2
10	1.3126×10^{-5} m^2
20	1.330×10^{-5} m^2
30	1.3475×10^{-5} m^2
40	1.3650×10^{-5} m^2
50	1.3824×10^{-5} m^2

Side Rake Angle	*Shear Contact Area, A_S*
60	$1.81905x10^{-5}$ m^2

To compute the horizontal force, the equation (1) is used:

$$F_H = F_N \cos\beta \left[\frac{1-\mu\tan\alpha}{\tan\alpha+\mu}\right] \quad (1)$$

Where F_H is the horizontal force, F_N is the normal force, α is the back rake angle, β is side rake angle and μ is the coefficient of friction.

The relationship between the cutter side rake angles on the horizontal force is calculated and shown in Figure 4.6.

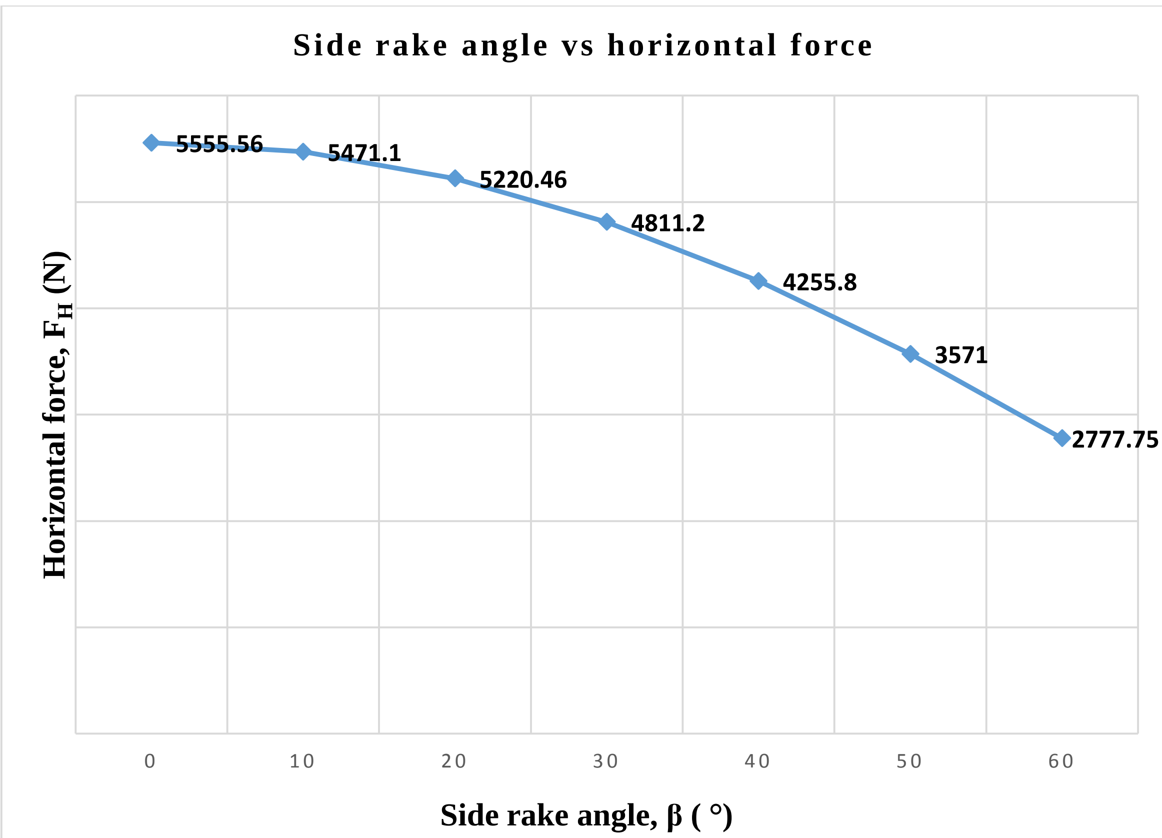


Figure 4.6: Graph of Horizontal Force vs Side Rake Angle

The axial stress and shear stress for different angle of side rake is calculated using equation (3) and (4). The axial stress on the cutter is taken as a constant of 20.87 MPa. The combined stress for different shape of cutter is shown in Figure 4.7.

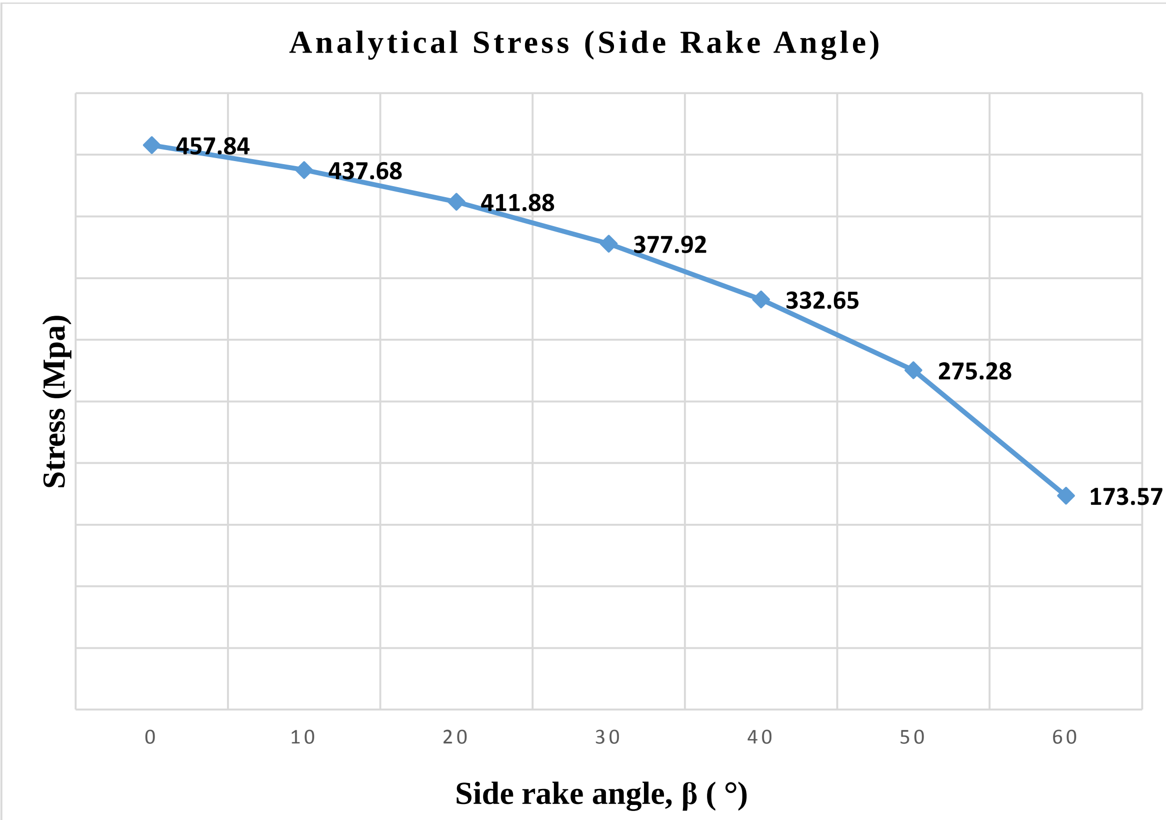


Figure 4.7: Effect of Side Rake Angle on Stress (Analytical)

The result shows that the cutter with higher side rake angle has less stress. This is because the horizontal force applied on the cutter decreases with the increased side rake angle, thus resulting in a lower shear stress. The relationship between shear stress and horizontal force is shown in Figure 4.8.

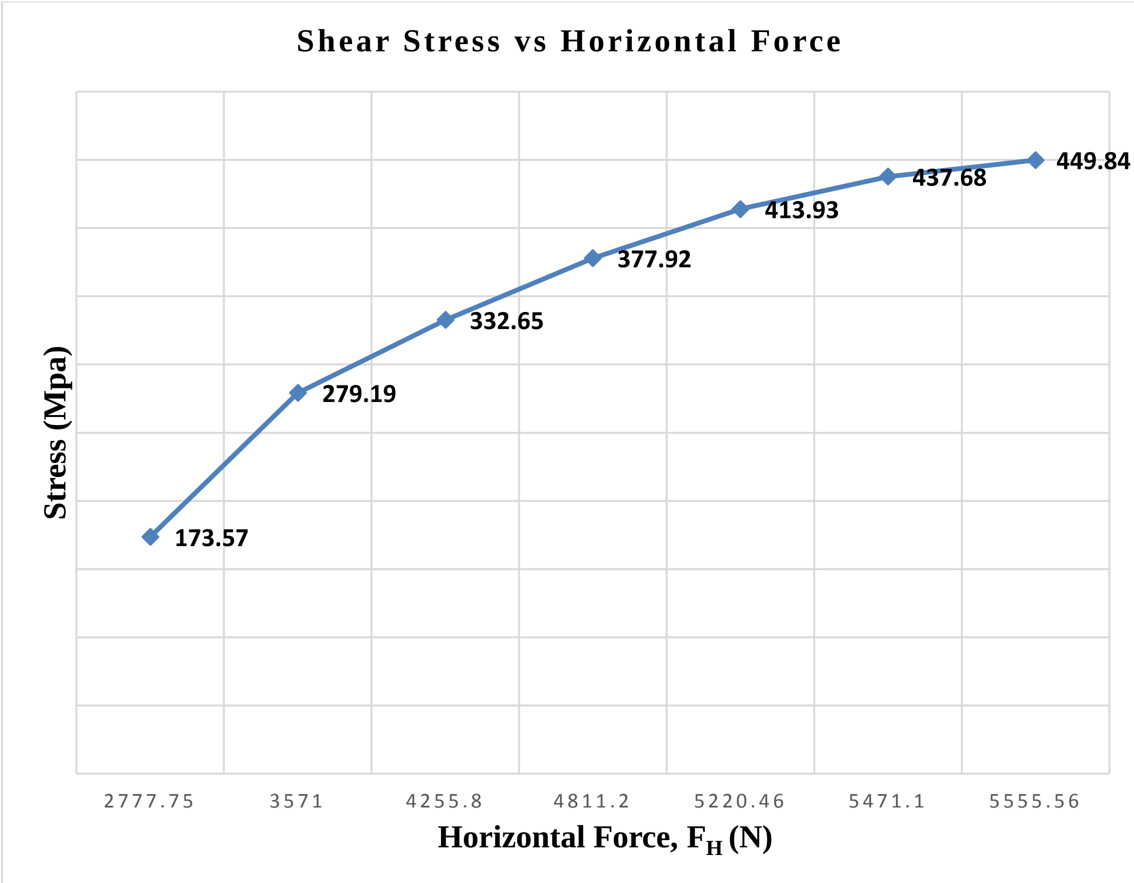


Figure 4.8: Graph of Shear Stress vs. Horizontal Force (Side Rake Angle)

According to the figure, horizontal force is directly proportional to shear stress. Thus, lower side rake angle results in higher shear stress.

4.2 PDC Single 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 hard formation at a constant velocity of 10 m/s and the simulation period is set to be 3s. The FEA model of the single cutter test is shown in Figure 4.9.

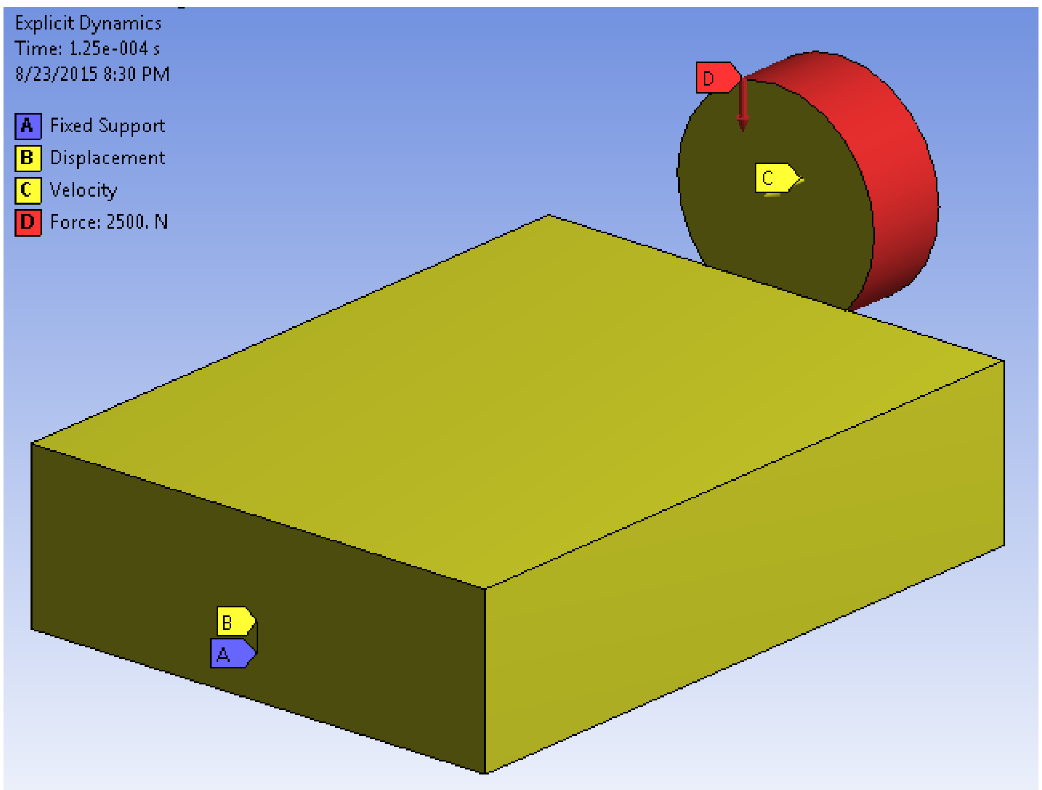


Figure 4.9: FEA model of Single Cutter Test

4.2.1 Back Rake Angle

A graph of stress for different back rake angle is plotted in Figure 4.10.

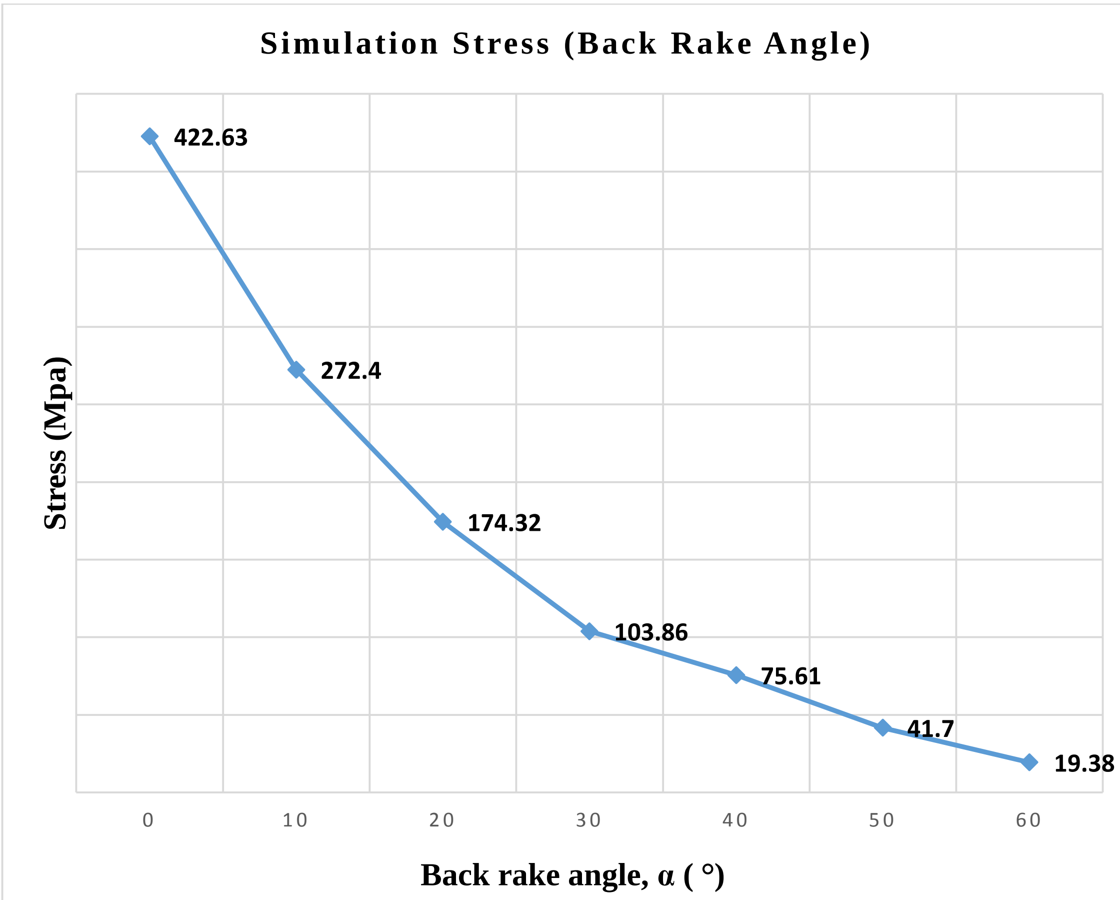


Figure 4.10: Effect of Back Rake Angle on Stress (Simulation)

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 60˚ has the lowest horizontal force applied under a constant normal force. Thus, the stress induced in the 60˚ 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 4.11.

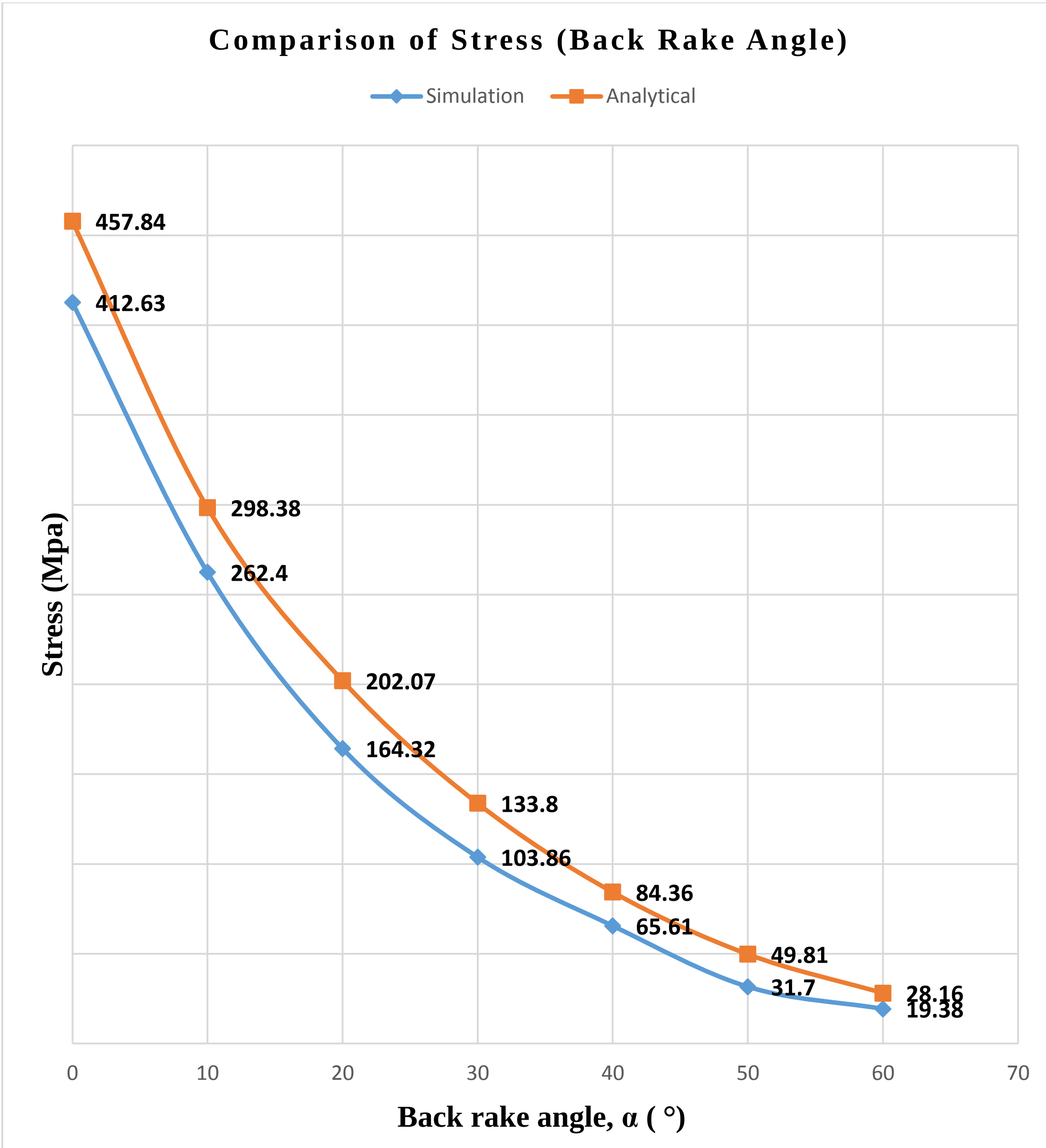


Figure 4.11: Comparative Analysis of Stresses for different Back Rake Angle on Hard Formation

The stress obtained from the simulation is found to be lower than analytical result. The highest percentage of difference for the result is approximately 10.68%. 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. During the simulation, author decided to use medium size of meshing to reduce the simulation time to complete and the mesh sizes of the cutter model will affected the accuracy of 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 60 ° back rake angle has proved to have the lowest stress values.

4.2.2 Side Rake Angle

A graph of stress for different side rake angle is plotted in Figure 4.12.

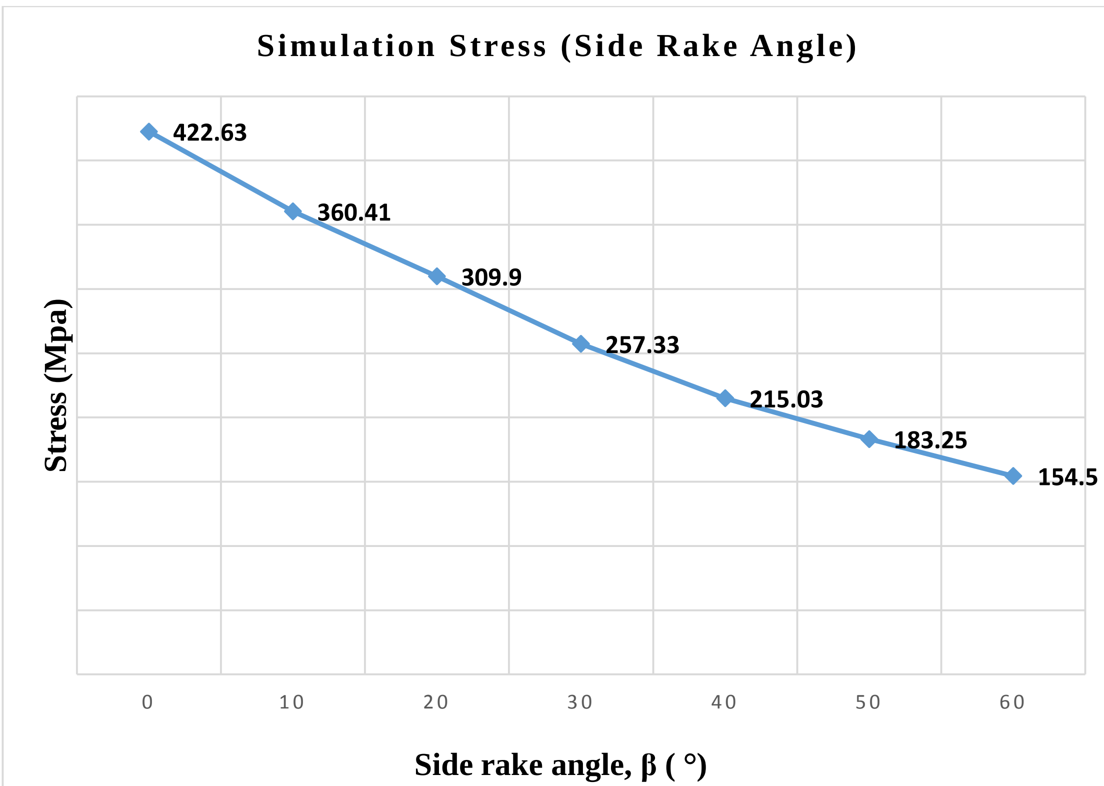


Figure 4.12: Effect of Side Rake Angle on Stress (Simulation)

Result shows that higher side 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 side rake angle of 60 ° has the lowest horizontal force applied under a constant normal force. Thus, the stress induced in the 60 ° 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 4.13.

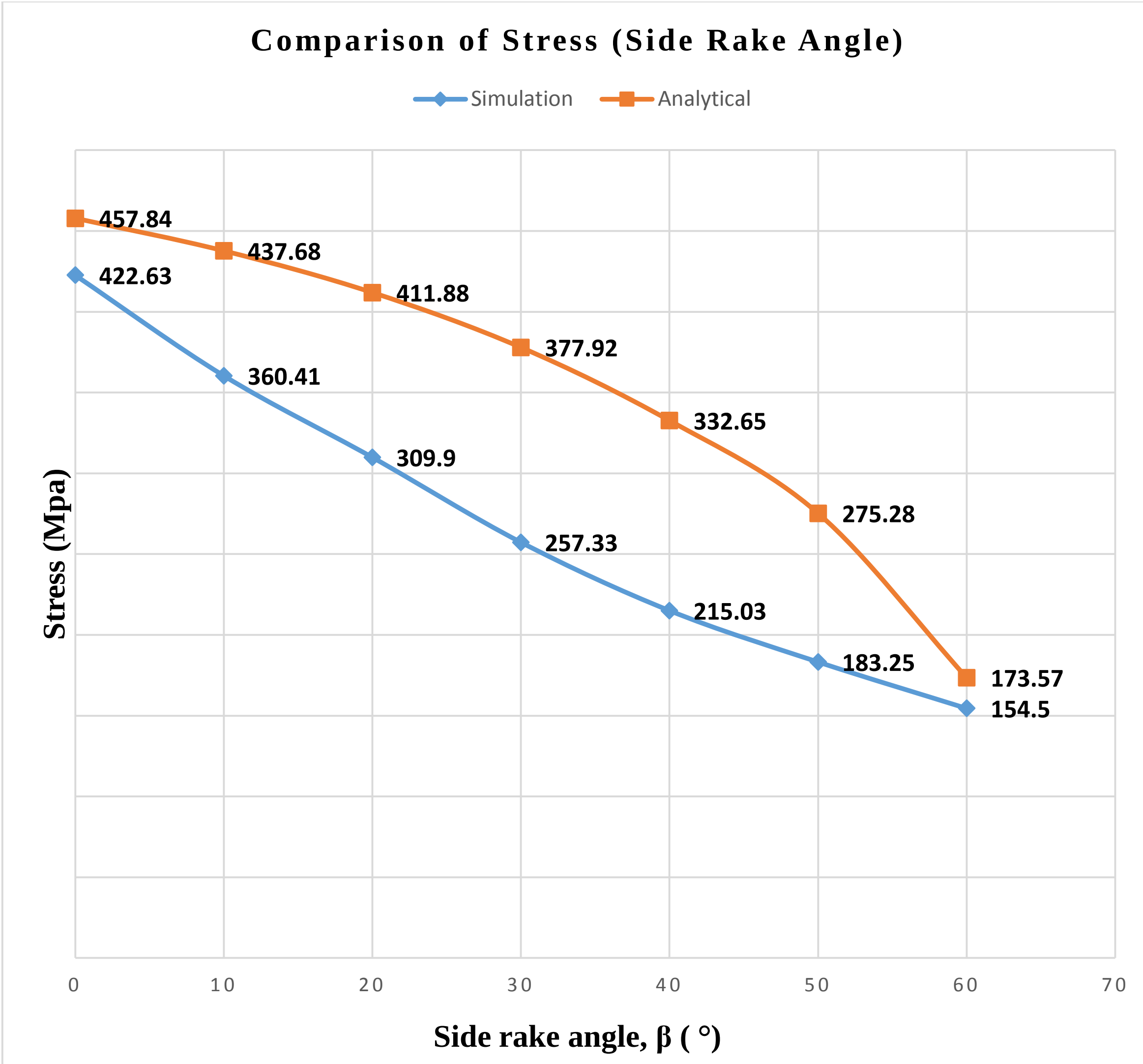


Figure 4.13: Comparative Analysis of Stresses for different Side Rake Angle on Hard formation

The stress obtained from the simulation is generally lower than analytical result. The highest percentage of difference for the result is approximately 31.9%. This is most probably due to and hydrostatic stress induced in the cutter. Besides, the normal contact area may be higher which results in a lower normal force. Furthermore, the inconsistence cutter face may result in lower contact force which causes lower stress. During the simulation, author decided to use medium size of meshing to reduce the simulation time to complete and the mesh sizes of the cutter model will affected the accuracy of the 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) [2].

$$\mathbf{W = k_2 V \bar{\sigma}^{\frac{1}{bn'}}} \quad \textbf{(5)}$$

For simplicity, the volume of deformed material V is taken as constant compared to the von Mises stress to the power of 6.45 to construct the wear model. The proportionality constant $k_2 \times V$ was taken as 1.5 x 10^{-11}[1] [13].

4.3.1 Back Rake Angle (Wear Rate)

The wear of different back rake angled cutter is calculated using equation (4). Since the simulation period is 3s, 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 4.5.

Table 4.5: Wear and Wear Rate of PDC Cutter (Back Rake Angle)

Back Rake Angle, α	**Simulated Wear (μm^2)**	**Analytical Wear (μm^2)**	**Simulated Wear Rate (μm^2/s)**	**Analytical Wear Rate (μm^2/s)**
0˚	2.176	1.113	0.725	0.371
10˚	0.138	0.06	0.106	0.02
20˚	0.011	0.003	0.004	0.01
30˚	0.780x10^{-3}	0.15x10^{-3}	0.026x10^{-3}	0.05x10^{-3}
40˚	0.039x10^{-3}	0.0078x10^{-3}	0.013x10^{-3}	0.003x10^{-3}
50˚	0.0013x10^{-3}	0.072x10^{-6}	0.433x10^{-6}	0.024x10^{-6}
60°	0.033x10^{-6}	0.003x10^{-6}	0.011x10^{-6}	0.001x10^{-6}

A graph of wear rate vs. back rake angle as shown in Figure 4.14 to analyse the relationship between back rake angle and cutter wear rate.

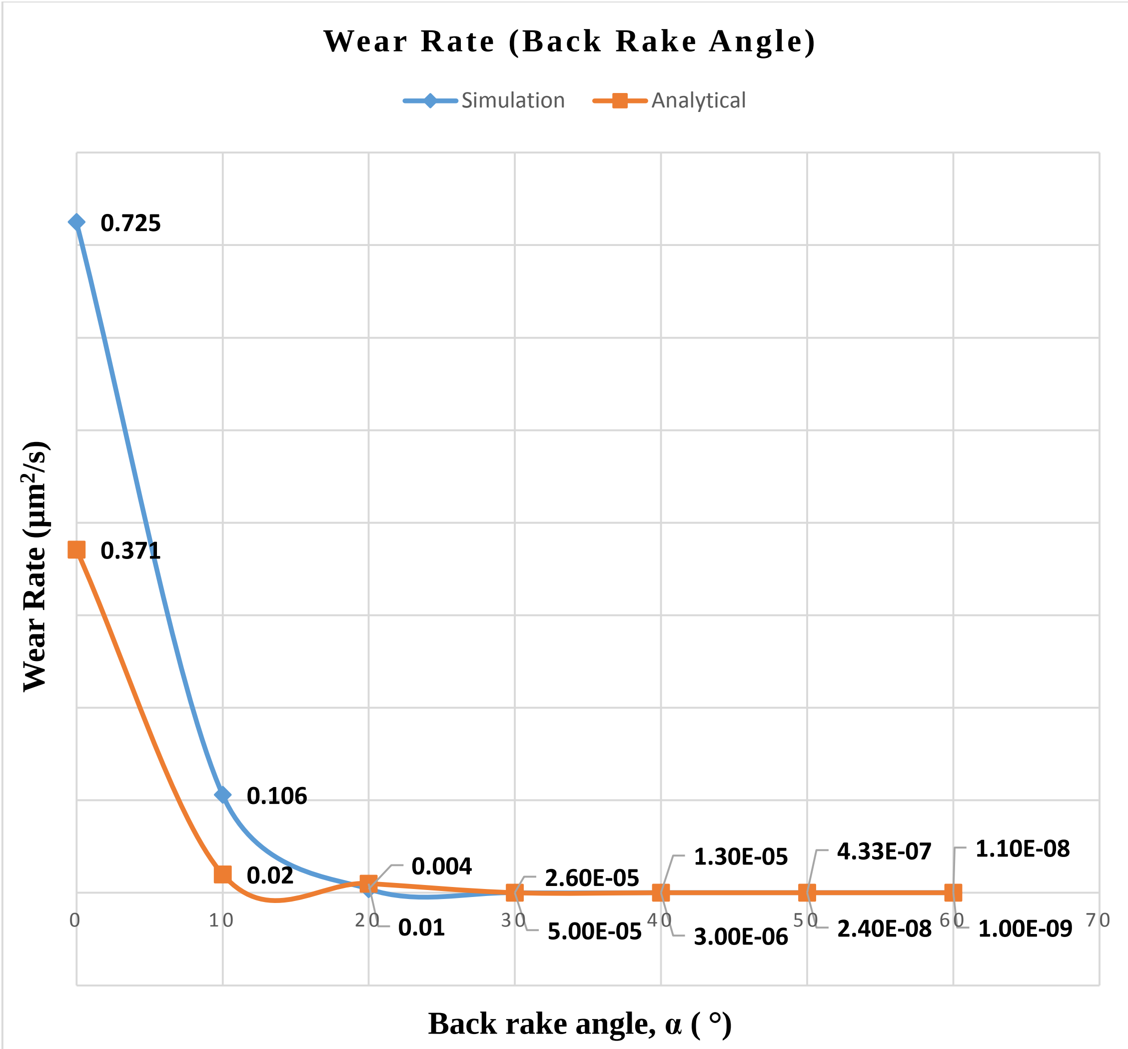


Figure 4.14: Graph of Wear Rate vs. Back Rake Angle

From the Figure 4.14, 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. PDC cutter with 60˚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, 60˚back rake angle with the lowest stress is the best design to reduce wear rate in drilling granite formation. 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.

4.3.2 Side Rake Angle (Wear Rate)

The wear of the each cutter with different angle of side rake is calculated using equation (4). The wear and wear rate of different side rake angled cutter is tabulated in Table 4.6.

Table 4.6: Wear and Wear Rate of PDC Cutter (Side Rake Angle)

Side Rake Angle, β	**Simulated Wear (µm2)**	**Analytical Wear (µm2)**	**Simulated Wear Rate (µm2/s)**	**Analytical Wear Rate (µm2/s)**
0˚	2.176	1.113	0.725	0.371
10˚	1.627	0.465	0.542	0.155
20˚	1.099	0.175	0.366	0.058
30˚	0.631	0.053	0.210	0.018
40˚	0.277	0.016	0.092	0.0053
50˚	0.082	0.006	0.0273	0.0091
60°	0.004	0.002	0.0013	0.0006

A graph of wear rate vs. side rake angle of cutter is plotted as shown in Figure 4.15 to analyze the relationship between side rake angle of cutter and cutter wear rate.

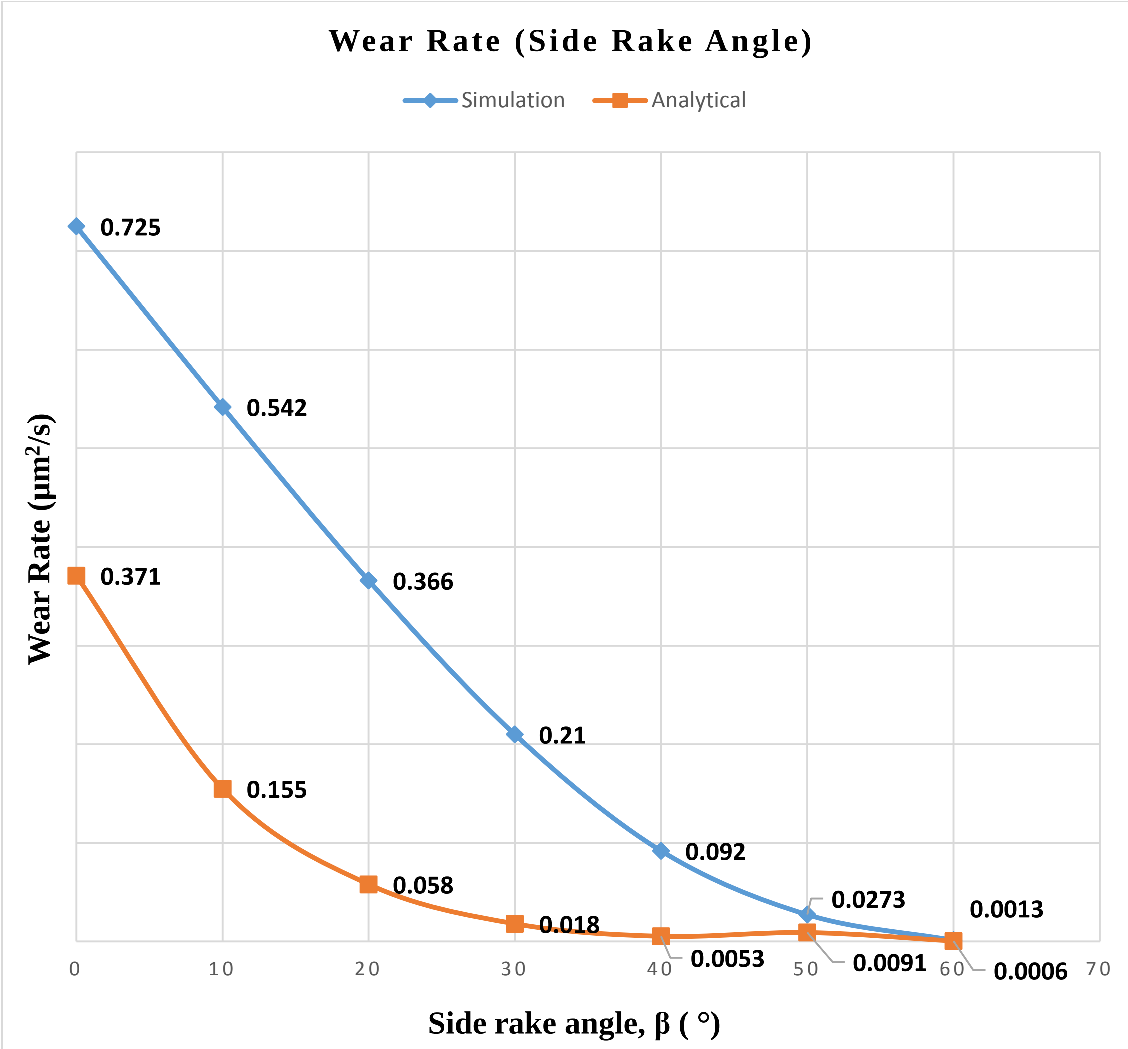


Figure 4.15: Graph of Wear Rate vs. Side Rake Angle

Similar with back rake angle, we can see that the cutter wear rate decreases as the side rake angle increases, but the decreasing trend is nonlinear. PDC cutter with 60° side rake angle has the minimum stress value due to the lowest applied horizontal force. Thus, 60° side rake angle is the best design to reduce wear rate in drilling hard formation. At the same time, combined with analytical result, with the increase of side rake angle, the cutter wear rate is decreased, verifying the simulation result.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

This project reported the result of rock cutting tests performed with PDC cutters at various angle of back and side rake angles. All the objectives of the project are achieved. A single cutter analytical model is used to study the forces and stress in each PDC cutter in removing hard formation. The model combined the cutter-rock interaction model and Merchant's model of orthogonal cutting for analysis. Analytical result indicated that back and side rake angle of cutter have significant effects on stress distribution. Application of the model for simulation test showed that higher horizontal force and larger contact geometry reduce the stress indicated on cutter. Effect of back and side rake angle of PDC cutter on the rule of cutting element wear are analyzed by using the wear theory. Higher back rake angle has less applied horizontal force, thus resulting in lower shear stress and this helps to reduce cutter wear rate. Shear stress indicated in the cutter with larger shear contact area is smaller, thus lowering the cutter wear rate. In a conclusion, 60˚of back and side rake angled cutter are found to be the best design to reduce cutter wear rate in hard formation.

Laboratory test is recommended to be carried out in the future to further verify the result. Universal wear model is used to determine the cutter wear in this project. 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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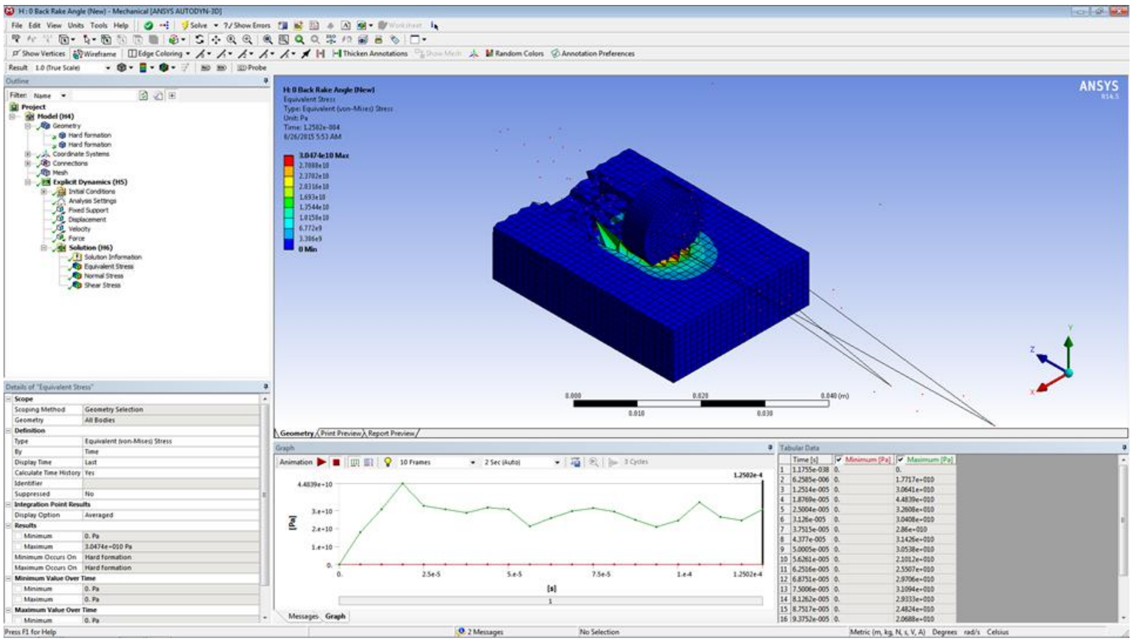
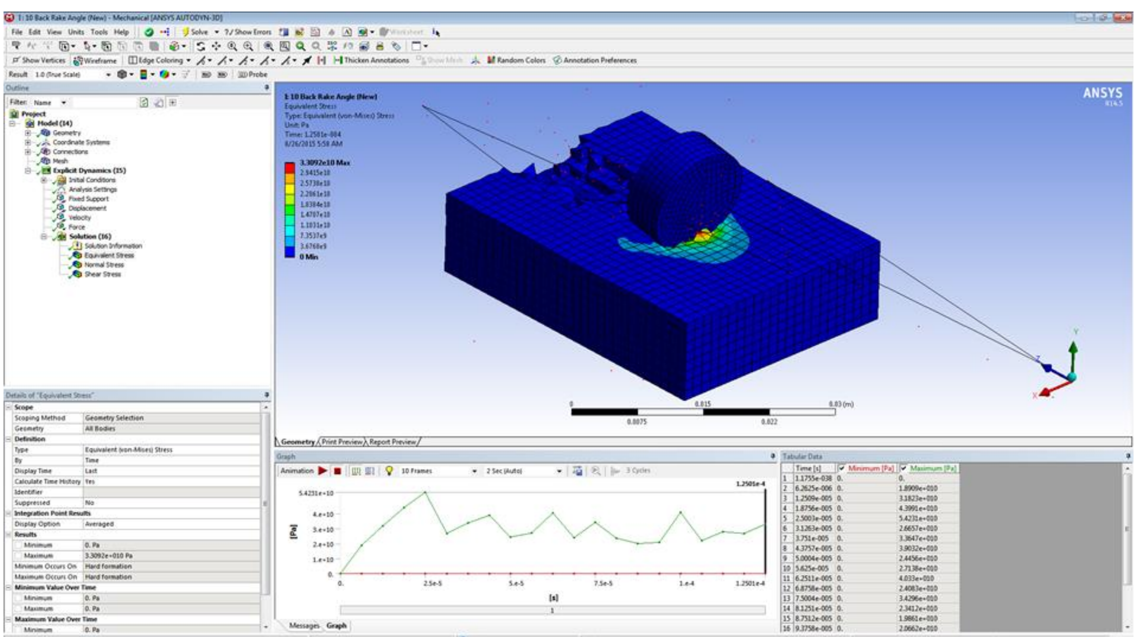
Appendices

Back rake angle simulation result

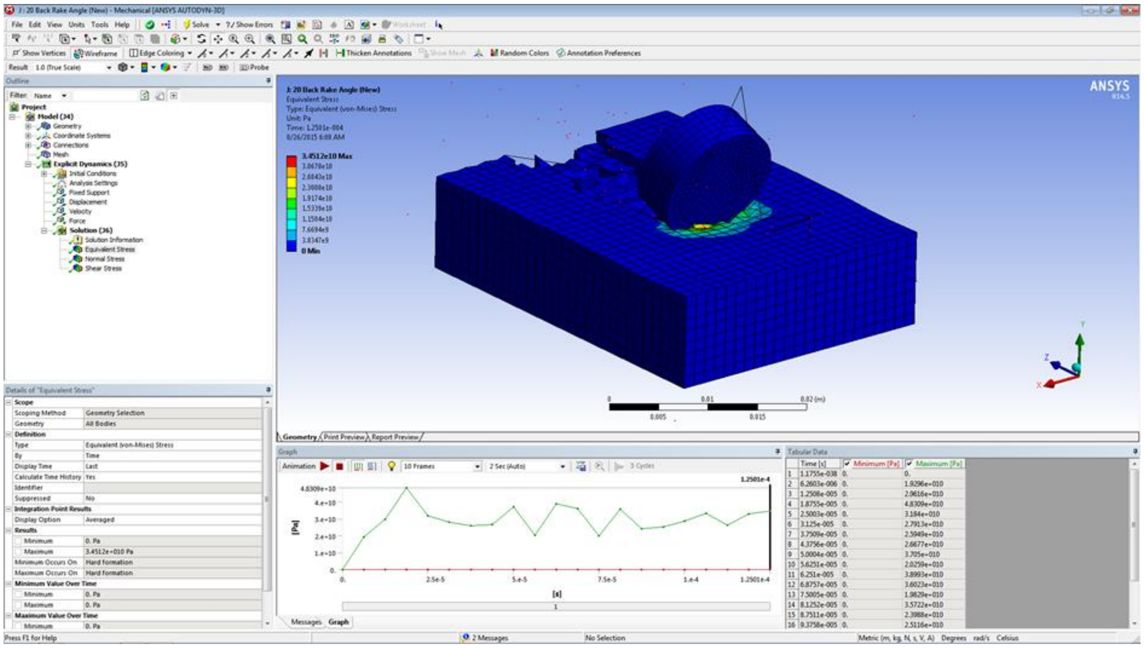
0°



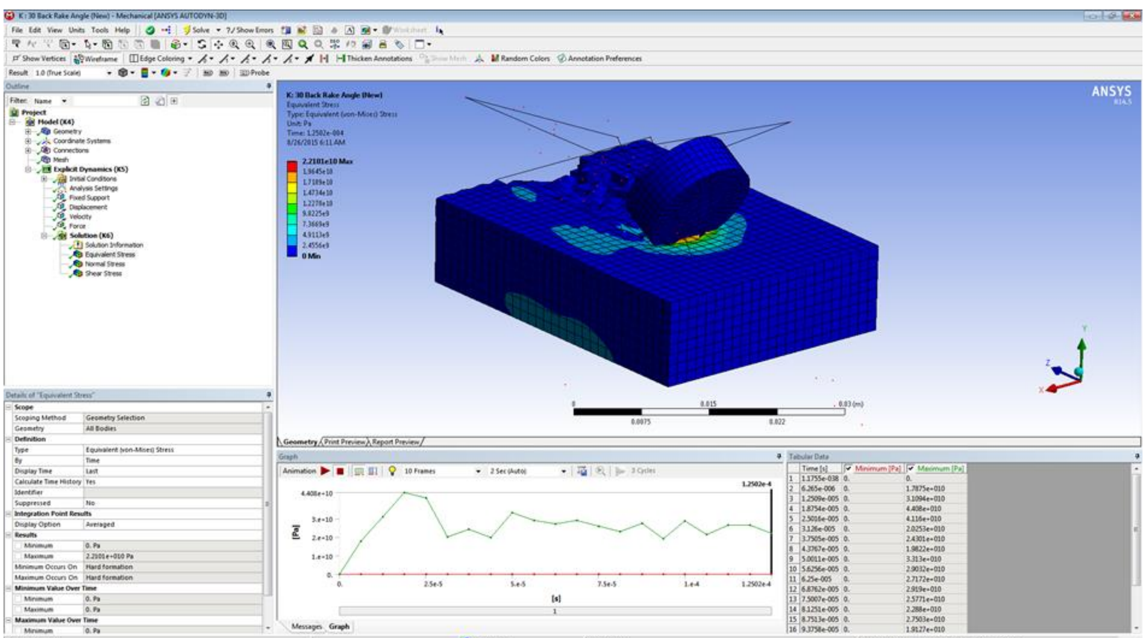
10°



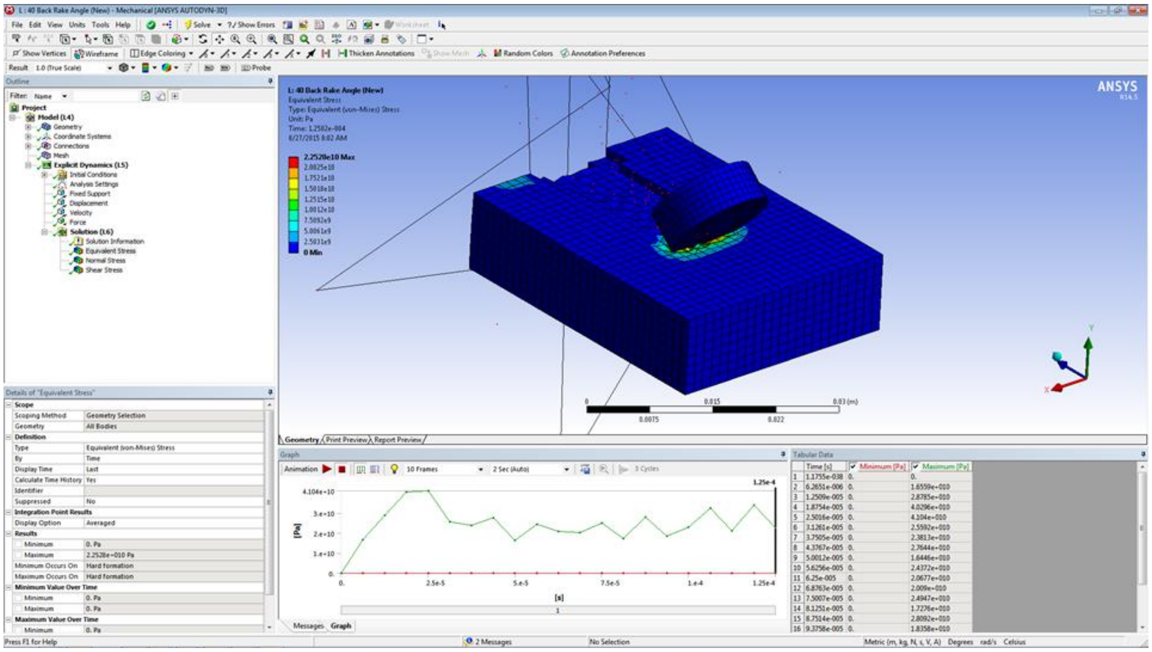
20°



30°



40°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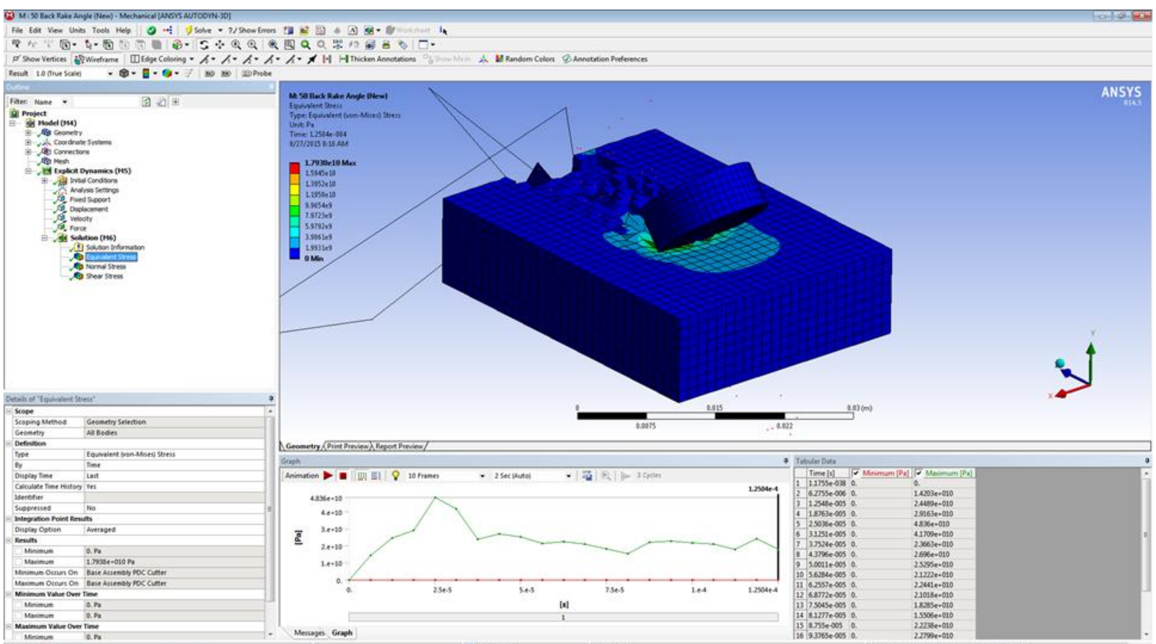
L: 40 Back Rake Angle (New)
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: Pa
ANSYS
Geometry
Print Preview
Report Preview
Graph
Tabular Data

50°


M: 50 Back Rake Angle (New) - Mechanical [ANSYS AUTODYN-3D]
M: 50 Back Rake Angle (New)
Equivalent Stress
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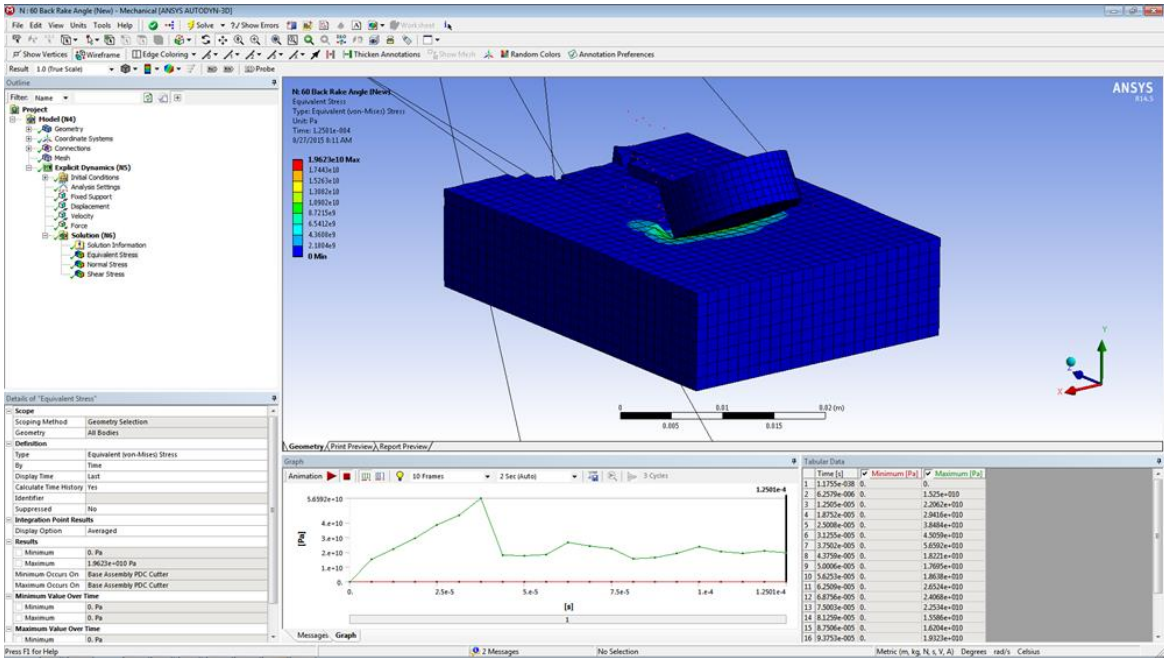
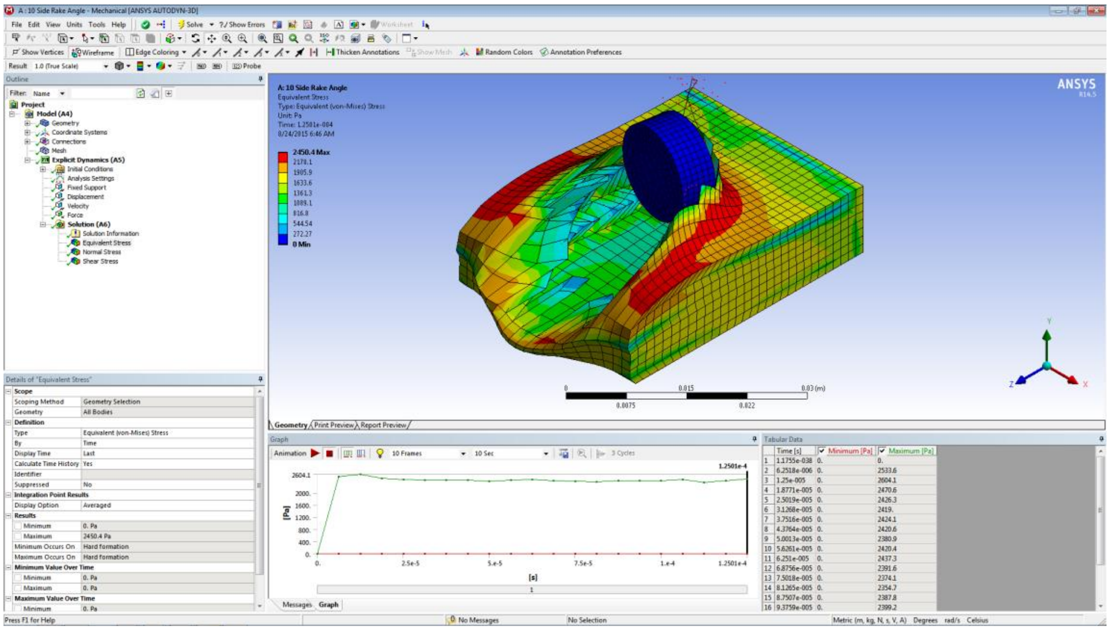
Unit: Pa
ANSYS
Geometry
Print Preview
Report Preview
Graph
Tabular Data

60°

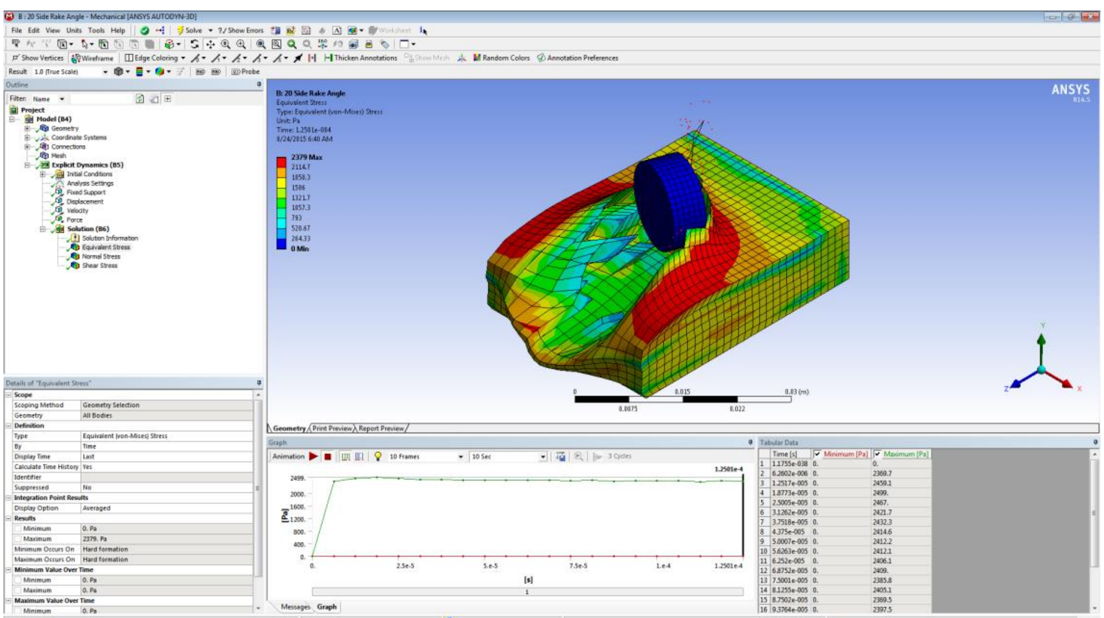

N: 60 Back Rake Angle (New) - Mechanical [ANSYS AUTODYN-3D]
N: 60 Back Rake Angle (New)
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: Pa
Time: 1.2501e-004
1.9623e10 Max
0 Min
ANSYS

Side rake angle simulation result

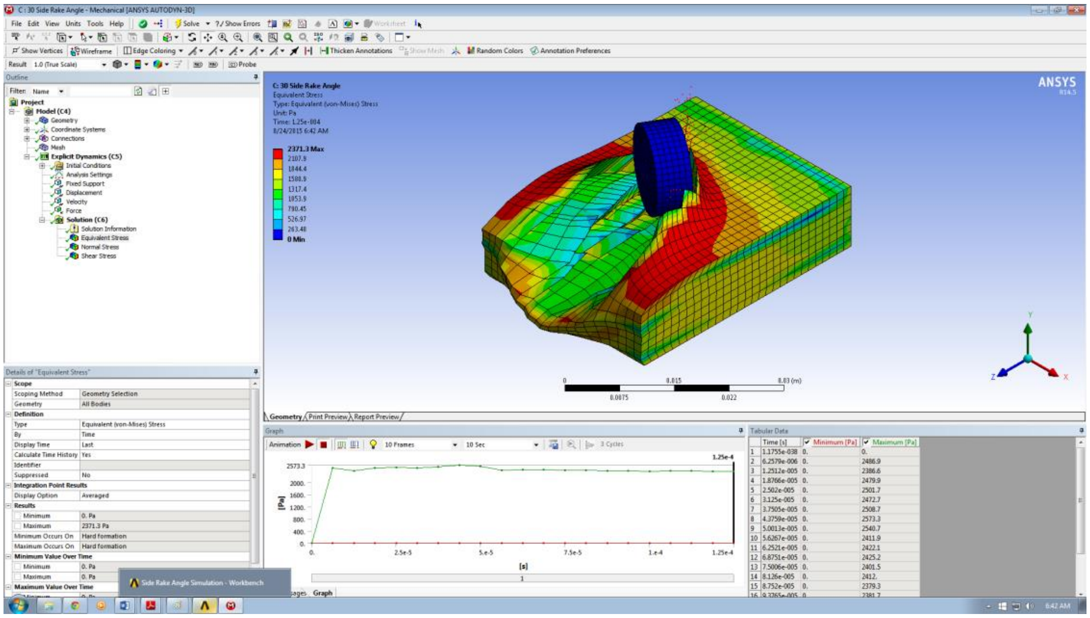
10°



20°



30°


C : 30 Side Rake Angle - Mechanical [ANSYS AUTODYN-3D]
ANSYS
C: 30 Side Rake Angle
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Unit: Pa
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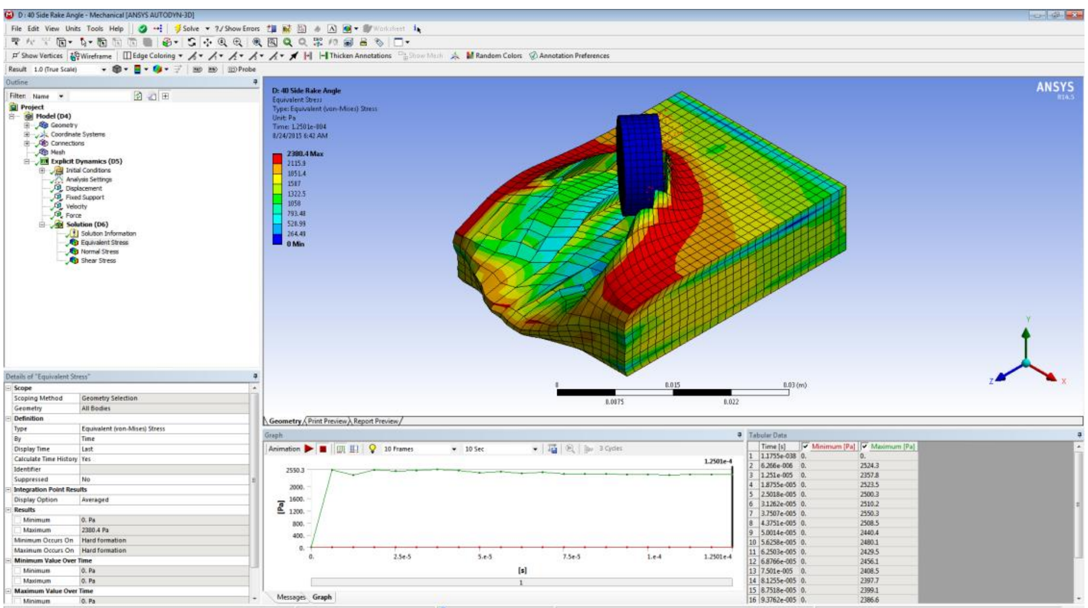
0 Min
Graph
Tabular Data

40°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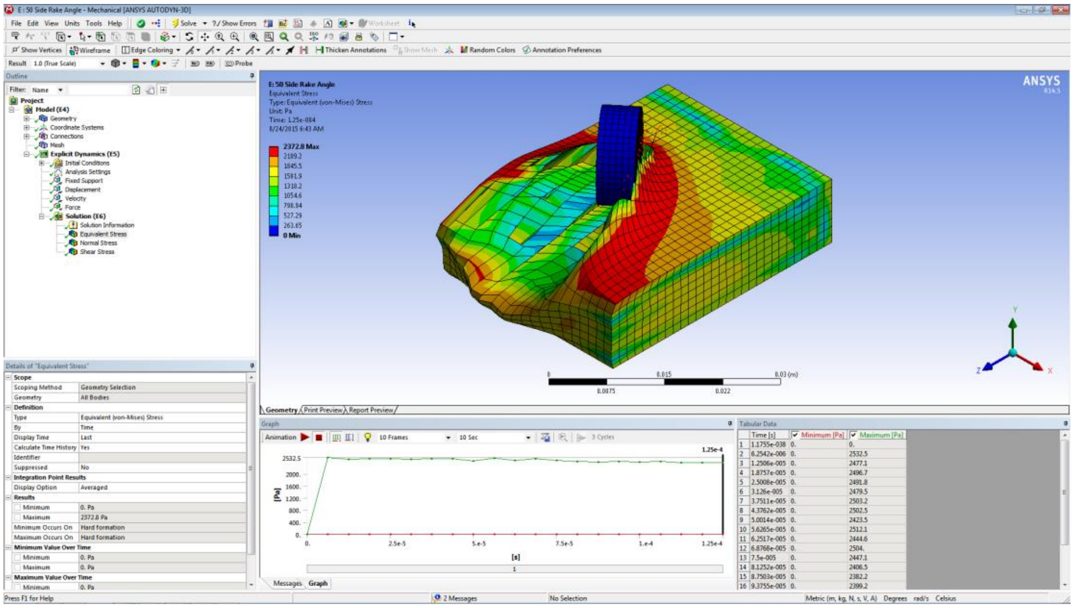
ANSYS
D: 40 Side Rake Angle
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: Pa
2380.4 Max
0 Min
Graph
Tabular Data

50°



60°