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Coiled Tubing Drilling for Mineral Exploration

Low-Torque Drilling Tools

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Abstract

Coiled Tubing Drilling (CTD) is a relatively new part of the mineral exploration industry, one of the most critical aspects of the Australian economy. Improvement in the efficiency of drilling and reduction of drilling time can substantially benefit exploration operations. The current commercially available drill bits used in CTD are ineffective at medium-hard rock formations due to high torque and high weight-on-bit requirements. In addition, the physical dimensions of CTD drill bits are limited in size compared to rotary drilling. This project focuses on creating a novel drill bit design that aims to address critical issues in drilling within medium-hard rock formations for CTD, increase penetration rate, and reduce the overall wear of the bit. Existing drill bits, their optimal operating conditions with types of rock formations have been studied. Vital design parameters have been found and proposed, and the methods to address the issues have been highlighted to provide a final design that attempts to address current weaknesses. Current challenges of drilling in medium-hard formation have been addressed by selecting insert geometry, materials, bearings and overall design features. Those have been validated using FE modelling and optimised for a higher rate of penetration. The novel drill bit design provided a rate of penetration (ROP) three times, compared to other drill bit designs for CTD, increasing the operational efficiency in mineral exploration.

Table of Contents

List of Figures

List of Tables

1. Introduction

For most of the last decade, iron ore and coal have led Australia's annual resource exports (Van Der Merwe et al. 2018). Coal single-handedly accounts for 25% of the resource exports and 14% of total annual exports. In 2018-2019, coal exports generated 3.5% ($67 Billion) of the nominal Australian GDP (Cunningham, Uffelen & Chambers 2019). Resource companies have carried out extensive capital expenditure to increase the resource industry's productivity, focusing on technological enhancements to impact production levels, increase cost-effective return and competitiveness (Jenner et al. 2018; Van Der Merwe et al. 2018).

The success of mineral exploration is measured by demand for its products, operational efficiency and productivity (Darling 2011). One of the primary considerations of efficiency is the drilling equipment such as drill bits and downhole motor (Hossain & Islam 2018). Coiled tubing drilling was initially developed for oil and gas drilling operations (Abbas 2018). However, new development has been focused on mineral exploration. Coiled tubing drilling (CTD) is a continuously developing technology that aims for rapid, safer, and cost-effective drilling operations (Fultz & Pittard 1990; Simmons & Adam 1993). Over the past decades, CTD has expanded to include more complex applications in drilling, which were previously feasible only with rotary drill rigs (Beaton & Seale 2004). The advancement of CT occurred due to enhanced manufacturing technologies and better material science to provide a more reliable technology (Beaton & Seale 2004).

Figure 1 shows rotary drilling (a) and coiled tubing drilling (b). In terms of drilling fluid, coiled tube drilling has the advantage of continuous fluids circulation that helps achieve a more effective rock particle evacuation, cooling and stable borehole, and preventing drilling failures. In comparison, conventional rotary drilling is a more aggressive technique that was mainly deployed before the introduction of coiled tubing (Beaton & Seale 2004). However, rotary drilling leads to an unstable borehole, which results in difficulties while drilling, increased costs, and drilling time. Furthermore, rotary drilling usually requires substantial equipment and energy to operate due to its size than coiled tube drilling (Zhang 2018). Improvement of drilling equipment can greatly benefit CTD by reducing drilling time and overall cost.

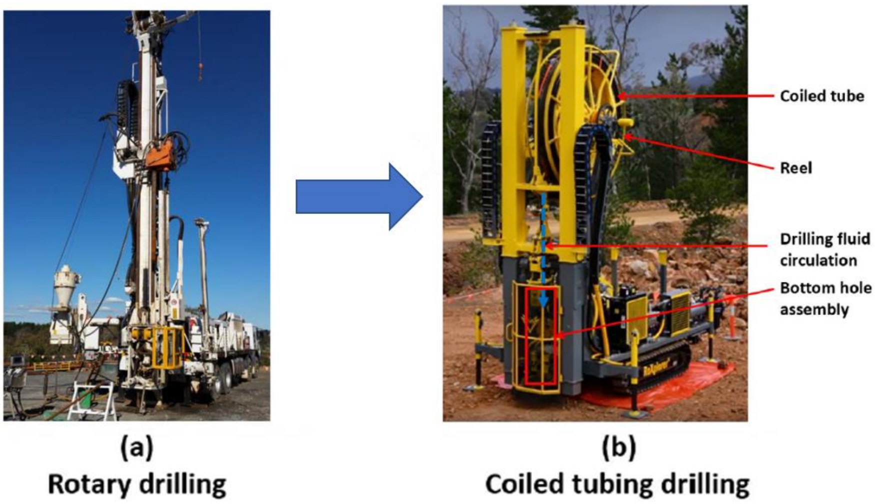


Figure 1: Comparison between (a) rotary and (b) coiled tube drilling rigs used for mineral exploration (Zhang 2018)

The rig consists of a coiled tube made of steel stored in a reel. The workflow and main parts are shown in Figure 2. The reel is equipped with coiled tubing and allows the transfer of torque and weight on bit (WOB) to a drill bit. The bottom hole assembly (BHA) contains the coiled tube, the hydraulic motor and the drill bit to transfer the torque required for drilling. The hydraulic motor provides two modes of rotary and percussive drilling, and there is a continuous passage of drilling fluid to assist in cooling and removing fragmented particles. The motor is powered by fluid pressure by circulating fluid through internal blades that generate rotational motion. Rotational drilling operations require a particular type of drill bit adapted for soft to hard rock formations. In contrast, the percussive operation is used to drill harder rocks to provide a high penetration rate (Zhang 2018). The ROP can vary depending on the overall size of the drilling rig. The average ROP of the RoXplorer mineral exploration drill rig, as shown in Figure 1 (b), is approximately 15 metres per hour (Revolutionary new drill rig 2017).

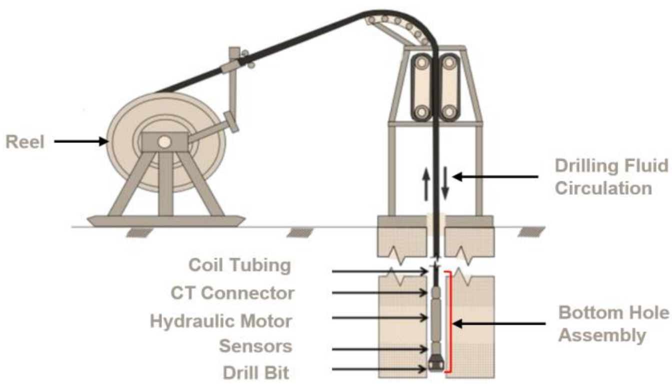


Figure 2: Coil tubing drilling schematics with a bottom hole assembly (adapted from Roufail et al. 2013)

The drill bits shown in Figure 3 represent the five types of commercially available drill bits. Drill bit selection is subject to the soil formation and the types of rock required to drill through (Darling 2011). The types of drill bits are as follows:

(a) Hammer bits are used for very hard formations, where percussive hits are utilised to fracture the formations into smaller pieces.
(b) Roller cone drill bits are often utilised in medium to medium-hard formations due to their effectiveness in crushing rock formations.
(c) Hybrid bits are a combination of polycrystalline diamond compact (PDC) and roller drill bits. It aims to reduce the excessive torque requirements PDC drag bits require while reducing the impact on the bearings of the roller cone drill bit.
(d) PDC drag bits are used to shear harder rock formations at the expense of higher torque.
(e) Drag blade bits are generally used in the initial stages of the drilling operation, where the primary formations consist of soft soil.

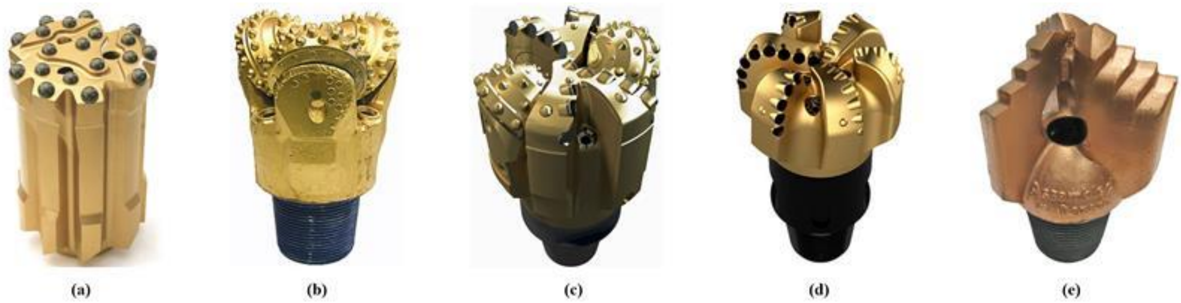


Figure 3: The types of drill bits (a) Hammer bit (Top Hammer Tools With Heat Resistance | Sandvik n.d), (b) Roller cone bit (Customized Tricone Drill Bit, Rock Drill Bit Underbalanced Drilling Conditions Using 2019), (c) Hybrid bit (Hsieh 2015), (d) PDC bit (GenesisTM - Drill bit by Baker Hughes | DirectIndustry 2021, (e) Drag bit (Amcana Drag Bits 2021)

As shown in Figure 4, components of both the Polycrystalline Diamond Compact (PDC) and the roller cone drill bits are different. A roller cone drill bit consists of the main bit body, rotary cutters and bearings. The roller cone bit has a more technically demanding design due to the rollers and bearing assemblies requiring additional design considerations for optimal roller interaction. In contrast, a conventional PDC bit has blades and PDC cutters (Andrés 2013). Detailed descriptions of the types of drill bits used in CTD are further discussed in Section 3.1 Drill Bit Types and Use Cases.

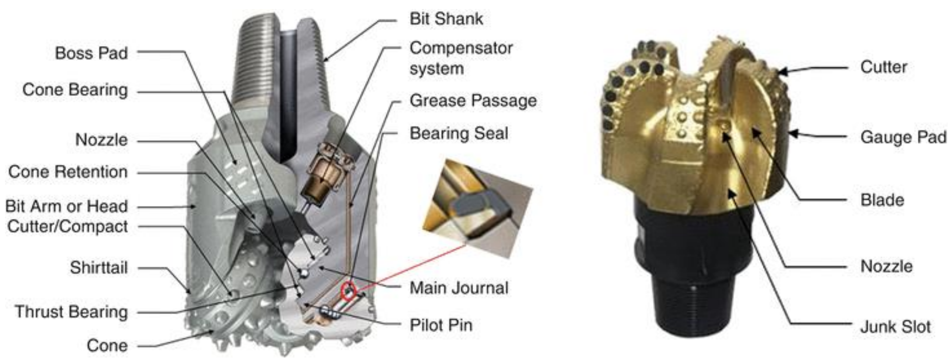


Figure 4: Components of roller cone bit (left) and PDC bit (right) (Andrés 2013)

In coiled tube drilling, the main challenge is the loss of productivity which is often due to teeth, bearing and wear in drag PDC inserts. Additionally, roller-cone bits have a significant bearing predicament. Various elements influence the bit's performance, such as the bearing's operational life and the teeth. The wear of the tooth accelerates when rotary speed is applied, consequently increasing the bearing's revolutions speed, which leads to potential bearing failure. In addition, tooth wear negatively influences the rate of penetration (ROP) and the drilling efficiency (Abbas 2018). During extensive investigations, it has been found that the most common impairment modes are breaking, flatting, cutting, cracking, and spalling (Barzegar, Gharehdash & Osanloo 2014; Gokhale 2010). In addition, it has been found that damage on drill bit parts appears due to mechanical and rock properties (Barzegar, Gharehdash & Osanloo 2014).

Drilling bit wear and replacements are the most significant contributors to mineral exploration costs (Capik & Yilmaz 2021). That leads to increase energy consumption, bearing failure, excessive fatigue, erosion, and abrasion (Beste, Coronel & Jacobson 2006). Unfortunately, commercially available bit designs cannot provide adequate, cost-effective performance due to the constant impact of the bit with hard rock and penetration through various rock formation types.

The overall aim of this work is to design a novel drill bit for CTD. This is achieved by finite element analysis (FEA) using a software package and continuous design improvements to satisfy the drill bit's ability and to withstand medium-hard rock formation drilling. Materials and bearings for the conceptual design were selected through literature review and catalogues, respectively. As shown in Table 1, leading manufacturers and their products form a basis for the initial concept generation and understanding of industrial drill bit designs.

Table 1: Summary of major drill bit manufacturers by types

Manufacturer	Drill bit type
Sandvik	roller, hammer
Baker and Hughes	roller, hybrid
Schlumberger	roller, drag, hammer
Epiroc	roller, hammer

2. Background

Choosing the most suitable drilling methods depends on the hole diameter, hole depth, and formation characteristics to be drilled in mineral exploration. The selection of incorrect drill bits can have a significant cost impact on the operations because bit reselling is difficult (Gokhale 2010). Figure 5 describes the various formations' hardness and the more suitable drill bit types for soft to extremely hard formation indicated by the different shading in the cells. For example, a rotary with tricone bit or down the hole (DTH) has ranges suitable for a given hole diameter. In extremely hard formations, its optimal diameter range is between 225-275 mm. In medium hard formations, it is best to have reduced diameters of 180-225 mm. DTH and top hammer (TH) both refer to hammer drill bit types. However, this research proposal dealt only with DTH due to its relevance to underground mineral exploration.

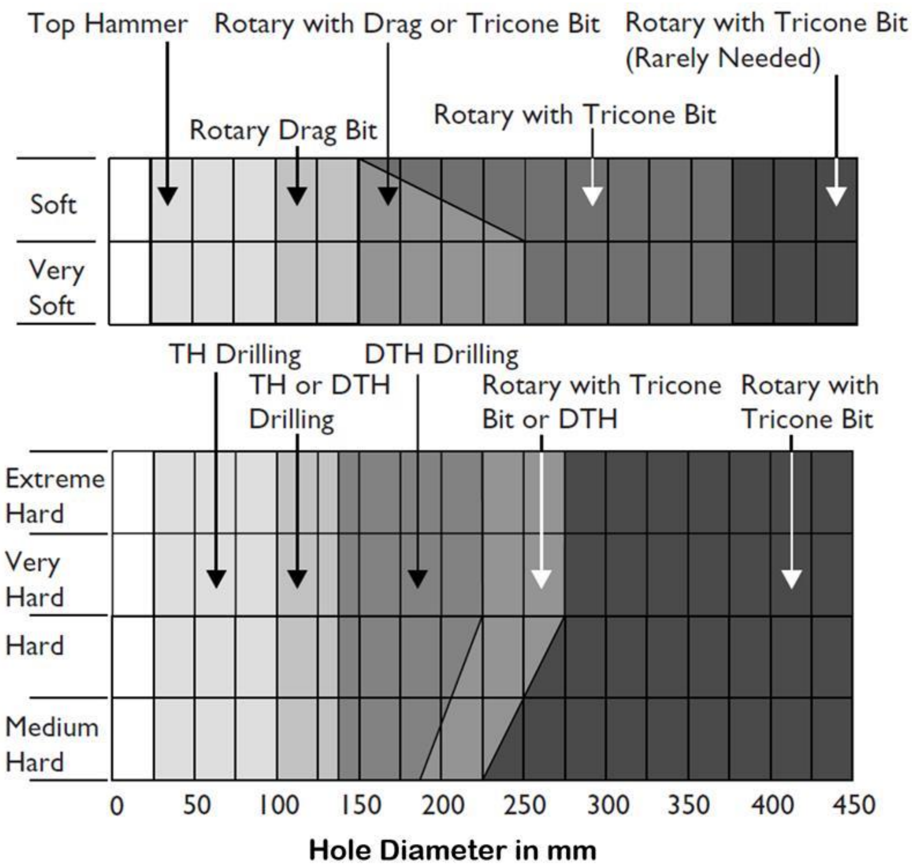


Figure 5: Selection of drill bit type according to the formation (Gokhale 2010)

Figure 6 shows the schematic difference between rotary and percussive drilling. Rotary drilling requires a high weight on bit (feed force) downward on the coil tube. For this reason, the drill bit becomes heavy, which further increases their penetration rates and decreases the drilling operation time. In addition, rotary drilling requires high torque to increase its efficiency in rock breaking. On the other hand, percussive drilling does not require high feed forces on the bit nor high torque, but its main feature is percussive blows that improve rock fracturability.

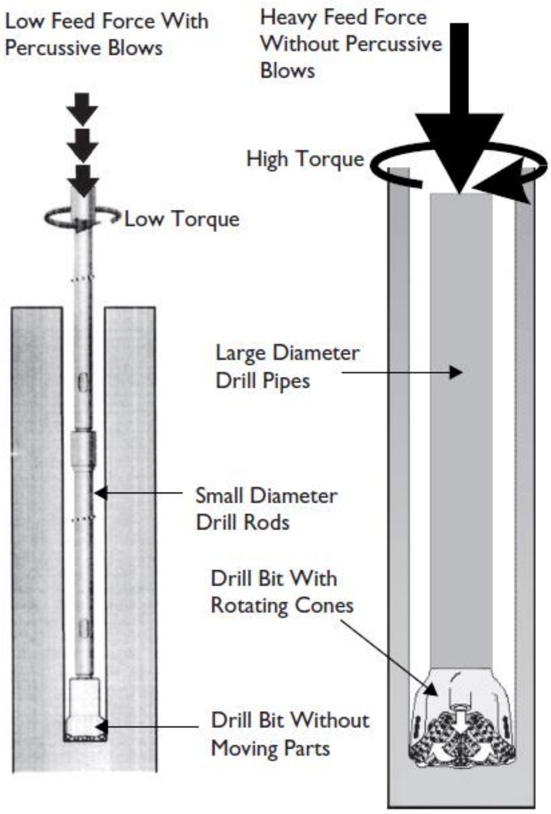


Figure 6: Distinction difference between percussive and rotary drilling techniques (Gokhale 20101)

The energy generated in rotary percussive drilling creates shock waves in the drill string. These shock waves from the drill bit are transmitted to fracture the rock via cutting edges. Consequently, the rock mass develops cracks in the form of rock chips. In comparison, a significant downward force is required to push the rotary bit in the rock mass. Therefore, rock chips and cracks propagate when the weight-on-bit is transmitted through a drill bit's cutting elements. In addition, those heavy vibrations and loads accelerate the end of life of a drill bit by affecting drill bit components such as bearings, inserts, and the drill bit body (Gokhale 2010).

2.1 Rock Classification

Failure and breakage start once a specific tensile stress value is reached in rocks with elastic properties such as clay gouge (Haines et al. 2013). When a rock is pressed by a drill bit downwards with WOB, it experiences compressive stress on the contact surface. At the same time, tension occurs in the opposite direction of the surface (Tingay, Reinecker & Müller 2008). In the case of rocks with high plasticity, there is an increase in the tensile strain even though the axial force does not increase. The tensile strength for rocks is significantly lower than that of compressive strength. Therefore, the rocks are more brittle when the ratio of compressive strength and tensile strength increases. The unconfined compressive strength value is evaluated by rock testing in the laboratory. Table 2 shows the rock classification based on the unconfined compressive strength. Common rocks such as limestone and shale fall within the medium-strong (R2-R3) unconfined compressive strength (UCS) ranges and are points of interest moving forward with this project for designing a novel drill bit. The strength and hardness of particular rock formations are crucial in designing a drill bit and selecting suitable cutting tools and materials to overcome the failure stresses of different rocks (Kolapo 2020). For instance, for FEA, the various material properties of each rock type are essential to evaluate if the cutting tools can withstand the specified hardness of the rock, causing the rock to yield before the drill bit itself (Kolapo 2020).

Table 2: Rock class classification based on UCS, point load and Schmidt hardness with examples (Gokhale 2010)

Class	Uniaxial compressive strength (MPa)	Point load index (MPa)	Schmidt hardness by L-hammer	Method of strength in the field	Examples of rocks in the class
R5- Extremely Strong	>250	>10	50-60	Rock material only chipped under repeated hammer blows	Fresh Basalt, Vhert, Diabase, Gneiss, Granite, Quartzite
R4- Very Strong	100-250	4-10	40-50	Requires many blows of a geological hammer to break intact rock specimens	Amphibolite, Sandstone, Basalt, Gabbro, Gneiss, Granodiorite
R3-Strong	50-100	2-4	30-40	Handheld specimens broken by a single blow of a geological hammer	Limestone, Marble, Phyllite, Sandstone, Schist, Shale
R2- Medium Strong	25-50	1-2	15-30	Firm blow with geological pick indents rock to 5 mm, knife just scrapes surface	Claystone, Coal, Concrete, Schist, Shale, Siltstone
R1-Weak	5-25	-	<15	Knife cuts material but too hard to shape into triaxial specimens	Chalk, Rock salt, Potash
R0 – very weak	1-5	-	-	Material crumbles under firm blows of geological pick, can be scraped with knife	Highly weathered or altered Rock
Extremely weak	0.25-1	-	-	Indented by thumbnail	Clay Gouge

Drill bits and rock formations refer to different measurement methods in terms of strength. Drag bits are selected based on their ability to drill within rock with high UCS, which is the critical component for drillability. In contrast, percussive drill bits are selected based on their ability to drill within rock with high fracture toughness and UCS (Kahraman, Bilgin & Feridunoglu 2003; Xu et al. 2016). Appendix A lists the Vicker's hardness values of specific rock types that correlate with Schmidt hardness displayed in Table 2.

Fracture toughness is defined as the resistance of a materials fracture propagation under applied stress. The critical stress intensity factor KIC is a way to represent the fracture toughness of a material and is measured by $MPa.m^{1/2}$. Vickers hardness indentation is used to derive the fracture toughness. For example, the fracture toughness KIC of glass is 0.7, concrete is 0.3, and medium tensile steel is 180 (Heiniö 1999; Lancaster 2005). From this example, concrete and glass are prone to higher crack propagation than medium tensile steel. On average, shale has a fracture toughness KIC of 0.33, while limestone has a KIC of 0.65 (Chandler et al. 2016). The classification of rocks and their toughness is required to evaluate the mechanical properties of materials and geometrical features necessary for designing a novel drill bit for an enhanced ROP.

3. Literature Review

3.1 Drill Bit Types and Use Cases

The main issues found in drill bits are attributed to the overall drill bits design, the structural material composition of a drill bit, and bearings that are an integral part of the rotary cone drill bits.

3.1.1 Roller Cone Bit

The roller cone bit is one of the most commonly used bits for rotary drilling. There are two types of roller cone bits, tungsten carbide inserts bit and milled tooth bit. Tungsten carbide insert bits provide three to nine times better performance than milled tooth as tungsten carbide is abrasion-resistant material and is significantly harder under identical working conditions (Gokhale 2010). Tricone bits are conventional roller cone drill bits that consist of three rotating cones that rotate along their axis. The rotation and compressive forces of the drill string account for the drilling operation. Tricone bits are employed for drilling a broad range of rocks in soft and extremely hard formations (Abbas 2018). As the rock hardness increases, the weight on the bit increases and higher torque is required.

Figure 7: Tricone roller cone drill bit with three rollers (Rock Drilling Tools 2018)

Figure 8 shows the working principle of the roller cone bit. The tooth of the cones penetrates the rock surface. A low feed force is used to wedge the insert into the rock formation, creating an initial crush zone. As the inserts of the roller cone further advance, initial cracks in the rock are formed. Cracks initiate and start propagating as the tooth penetrates deeper into the rock, resulting in the separation of rock chips (Gokhale 2010; Šporin et al. 2020).

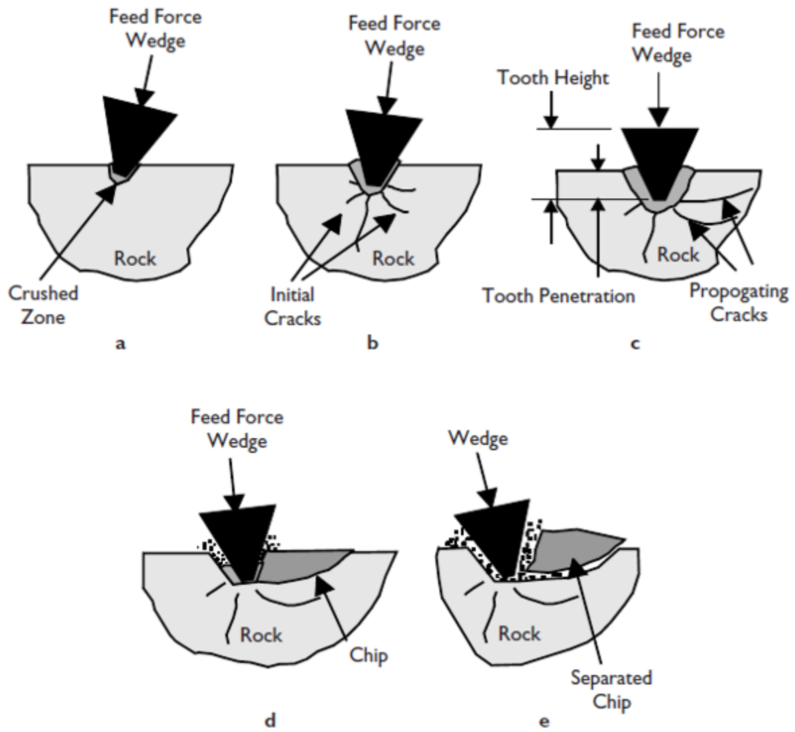


Figure 8: Formation fracture stages of a rotary drill bit insert (Gokhale 2010)

3.1.2 Drag Bit

There are two distinct types of drag bits, as shown in Figure 9. Each bit type is used for different formation hardness. Both types require rotational force to shear and cut through their desired rock formation. Figure 9 (B) shows that conventional drag bits are mainly used on very soft to soft formations. These can range from 1 to 25 MPa, as described in Table 2 (Gokhale 2010). Drag bits are designed to easily shear through soft soil using the three blades to displace soil. While the PDC drag bits displayed in Figure 9 (A) are for medium to hard rock formations as described in Table 2. Drag drill bit types are more efficient in drilling in softer formations due to their ability to generate shearing motion but require a greater torque to overcome the resistance of the rock formations. For this reason, PDC drag bits are more sensitive to WOB (Niu et al. 2019).

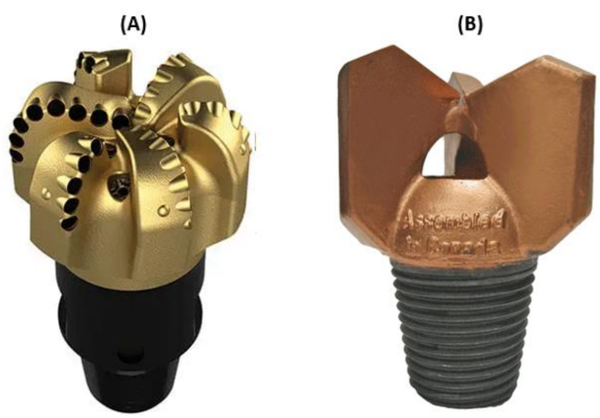


Figure 9: (A) PDC drag bit (GenesisTM - Drill bit by Baker Hughes 2021) and (B) drag bit (Amcana Drag Bits 2021)

PDC drag bit formation fracture shown in Figure 10 illustrates how the PDC contacts the formation producing rock chips. These drag bits require an increasing amount of torque as the rock hardness increases. They become ineffective in very hard rock formations as the necessary amount of torque is required becomes excessive due to resistance of a material to shearing is increasing, resulting in low ROP compared to other drill bit types (Gokhale 2010; Shojaei & Voyiadjis 2017).

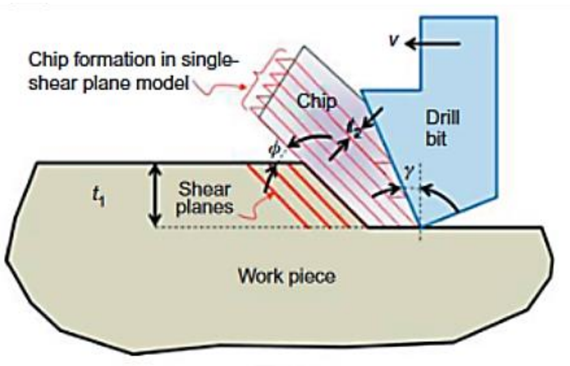


Figure 10: Rock fracture mechanism by PDC drag bit (Shojaei & Voyiadjis 2017)

3.1.3 Hammer Bit

Hammer drill bits are used in CTD as a form of drilling operations in very hard rock formations. The hammer drill bit is struck with high-impact loads resulting in rock degradation, producing small cracks in the rock formations. These cracks resulted from high compressive stress became crushed and chipped (Liu, Li & Chang 2017). As shown in Figure 11, a hammer bit is not effective in rotational drilling as they are designed for downward percussive impacts, unlike rotary roller or drag bits. Therefore, the hammer drill bit type is not effective for drilling in medium-hard rock formations.

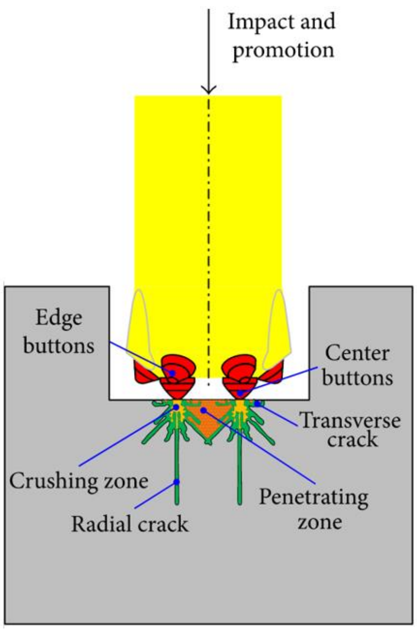


Figure 11: Hammer drill bit fracture mechanism (Liu, Li & Chang 2017)

3.1.4 Hybrid Drill Bit

The hybrid drill bit combines roller cone and PDC drag bits and includes both of their characteristics. During drilling operation, the cutter blades of the PDC drag bit are impelled to rotate along the bit's axis and scrape in contact formation. In addition, during the rotating process, the roller cones propel their teeth on the formation to create a crashing impact and fracture the rock, which increases the rate of penetration and reduces the drilling time (Niu et al. 2019). Hybrid drill bit cones mainly work on the principle of impact excavation. The addition of roller cones is beneficial in reducing the required torque while drilling in medium-hard formations due to the weight on bit distribution (Niu et al. 2019). Figure 12 below illustrates the combination of PDC and roller cone bits, which results in the hybrid drill bit.

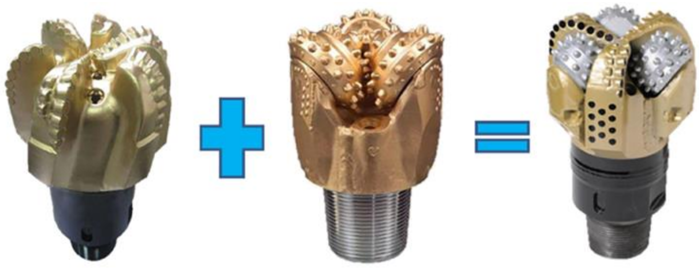


Figure 12: Hybrid drill bit (right), a combination of a PDC (left) and roller cone (centre) drill bits (Niu et al. 2019)

The overhang distance, which is the distance between the highest point of PDC cutters and the inserts of the roller cone, plays a vital role in regulating the torque on bit (TOB). In order to reduce the TOB in medium-hard rock formations, the overhang distance required is between 1 mm and 1.5 mm as the torque is directed to the roller cones rather than the PDC cutters (Niu et al. 2019). The main advantage of the hybrid drill bit is that it combines both the impact action of tricone insert on rock and shearing rotational motion from the PDC units, as shown in Figure 13 below.

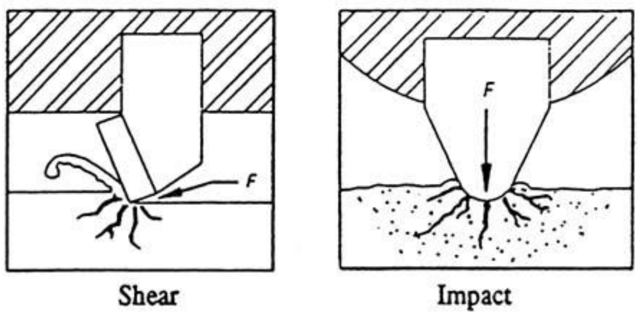


Figure 13: Combined rock fracture mechanism of a hybrid drill bit (Drilling and Excavation Technologies for the Future 1994)

The combination of roller-cones and traditional PDC cutters increases the bit's overall performance compared to their standalone counterparts. The method of rock formation from the scraping action of PDC units and the impact of crushing from the roller cones remained unchanged. The reduced torque on bit (TOB) of hybrid bits has made it exceptional in applications of lower torque requirements. (Niu et al. 2019). A hybrid drill bit's design aims to decrease drilling duration in complex scenarios. The hybrid drill bit's design consists of roller cones and cutters with PDC to provide strength, stability and highly effective shearing. In experiments conducted in the US, the hybrid bits showed incredible results compared to traditional drill bits design such as PDC or roller cones only for withstanding transitions in multiple formations and increased ROP of up to 62%. In another drilling experiment in Brazil, operators drilled 20% deeper and 90% faster (Ma, Chen & Zhao 2016). In addition, hybrid drill bits achieved high durability and reduced cost-per-foot by 36% in an experiment conducted in Eagle Ford (Hsieh 2015). Compared to roller cone-type drill bits, the hybrid has increased ROP and reduced WOB with minimal bit bounce, an unwanted vibration reaction leading to component failures. Compared to PDC, the hybrid drill bit has enhanced stability in various rock formations, reduced stick-slip, and reduced consistent torque requirement (Ma, Chen & Zhao 2016).

In summary, the roller cone drill bit is used in both soft and hard formations. However, it has the lowest ROP when drilling, and it provides only a limited number of operational hours when drilling in hard formations such as limestone and shale. The PDC drag bit has a higher ROP in softer formations. However, due to vibrations when transitioning between formations, the cutting efficiency decreases, and as a result, only a limited penetration depth can be achieved (Kymera Hybrid Drill Bit Technology 2013). The hybrid drill bit has the features of both the PDC drag and the roller cone. Therefore, it can reach a depth almost double than the previous two but slightly lower ROP than the PDC drag bit when drilling in sandstone, limestone, and shale (Kymera Hybrid Drill Bit Technology 2013; Niu et al. 2019). A summary of drilling comparisons within various formations between roller cone, hybrid and PDC drag bit types is shown in Figure 14.

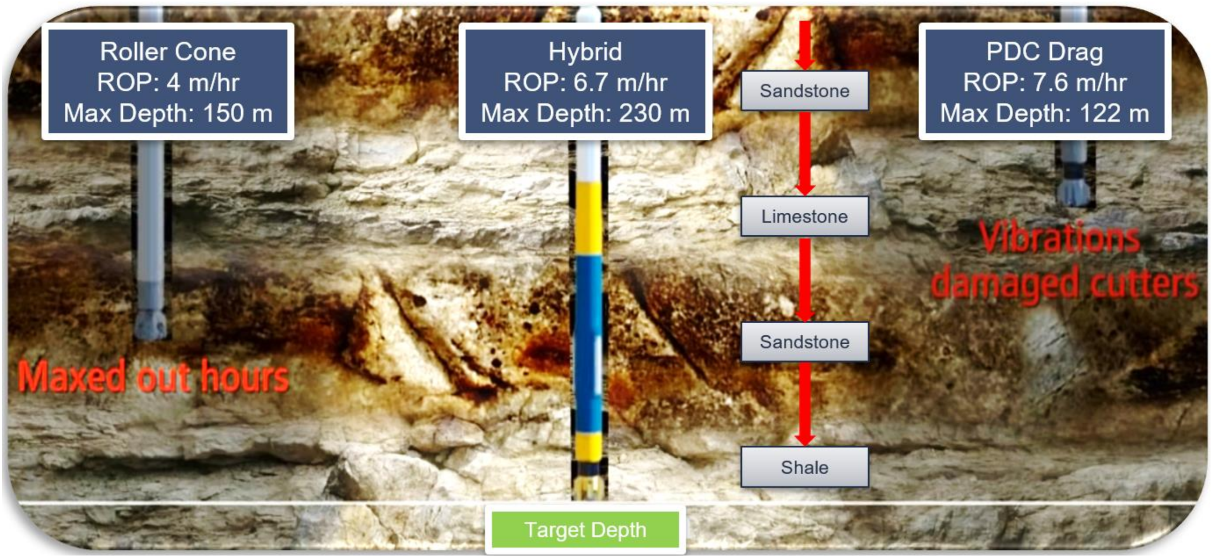


Figure 14: Drilling performance comparison between three drill bit types (adapted from Kymera Hybrid Drill Bit Technology 2013)

3.2 Low Torque Drill Bit Design

Drag and roller-cone drill bits are commonly used in gas well and oil drilling operations (Abbas 2018). Since there is no "one size fits all”, numerous variables must be accounted for to determine a suitable drilling method, variables such as depth and size of the borehole, sampling requirements and geological formations (Gandhi & Sarkar 2016). Numerous studies have attempted to suggest a better conceptual design that can address drilling under different conditions, enhance ROP, and maximise the drill bit life (Gandhi & Sarkar 2016; Karasawa et al. 2002). However, there are many challenges due to highly complicated environmental, geometric and process conditions (Dai et al. 2020).

Tricone roller bits and down-the-hole (DTH) hammer bits commonly utilise drill bit designs in coiled tube drilling (CTD). Fixed-cutter drill bits are widely used for softer formations due to the high torque on bit (TOB) required to operate in hard formations and later swapped to tricone or DTH hammer bits (Franca 2011). Both provide advantages and disadvantages and can significantly vary in size. Current tricone roller bits can drill up to a depth of 10,000 metres in most formations. However, they require high amounts (ranging between 500-25,000 kgs) of WOB, low ROP, and excessive bit wear in hard formations very time-consuming and costly to replace (IADC drilling manual 2000). On the other hand, the percussive drilling method uses DTH hammer bits, which provide lower WOB, higher ROP and can drill through very hard formations. Both types of drill bits address each other's flaws (Franca 2011; Prakash & Mukhopadhyay 2018).

A mono-cone (single cone) bit concept aims to acquire PDC insert drag bits and roller-cone qualities and surpass their deficiencies, with unique advantages demonstrated in slim and deep drill holes. However, significant wear appeared in the roller cutters during experiments, which shortened its service life and reduced the rock fracturing efficiency since only a limited number of cutters could contact against the surface. Also, as the inclination angle increases, the parts' velocities decline, leading to impaired interaction between the PDC cutters and the rock, leading to reduced rock breaking efficiency (Kong et al. 2016). Figure 15 shows two types of single-roller bits. Part (a) illustrates a conventional single-roller bit with worn-down button inserts, while part (b) displays a conceptual single-roller bit with PDC addition to the sphere.

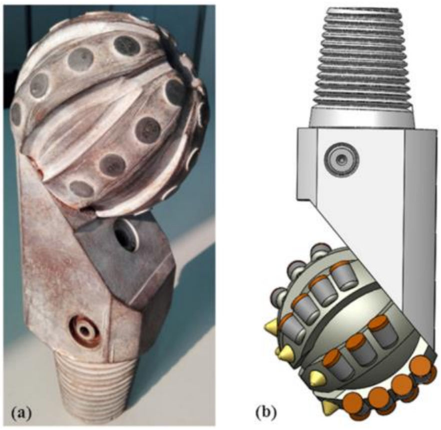


Figure 15: Single-cone drill bit: (a) with roller cone inserts, (b) conceptual PDC inserts (Kong et al. 2016)

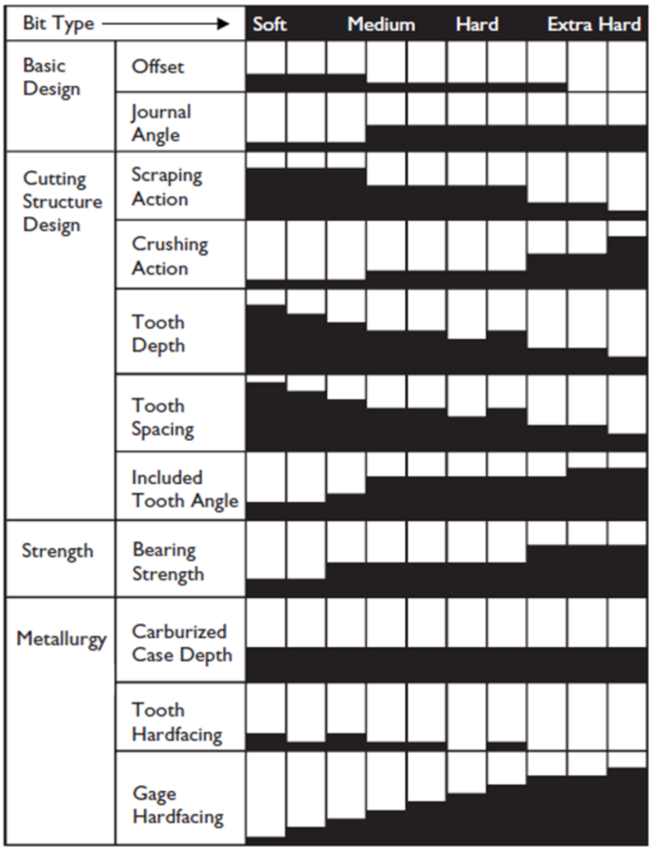
Several studies have been conducted to produce hybrid models of either rotary-cutter or rotary-percussive drill bits. WOB distribution and torque-on-bit (TOB) distribution of a rotary-cutter hybrid design (Dolezal et al. 2011; Niu et al. 2019; Powell et al. 2015). A physical model was made for lab testing to compare against standard tricone and fixed-cutter bits. This study showed that this hybrid model reduced the TOB compared to fixed-cutter bits and increased the ROP than conventional fixed-cutters in hard formations due to the combination of rock-breaking methods (Niu et al. 2019). However, the WOB between the two contact methods can increase variance due to the overhang of the fixed-cutter bits compared to the tricone buttons (Niu et al. 2019). This indicates that the fix-cutter would encounter additional wear over its use in comparison to the tricone buttons.

The PDC roller-cone composite drill bit concept combines two commercially available drill bits (cone-PDC hybrid bit), as shown in Figure 16. This bit combines the PDC properties and the three-cone bits and is mainly used for cutting rock with PDC teeth on a three-cone bit cutting structure. This bit has ROP three to four times more than regular PDC and roller-cone bits, 50 per cent lower torque vibration, and considerably higher operational life in experiments (Huang et al. 2020). This bit has been tested with sandstone, limestone and granite with hardnesses ranging from 50 MPa to greater than 250 MPa (UCS). However, this bit type has a lower rock breaking efficiency, and it is a poor choice for drilling in moderately soft formations such as sandstone (Niu et al. 2019).

Figure 16: Hybrid drill bit: a combination of a roller cone (left) and a PDC (centre) (Eric 2013)

Table 3 outlines the vital design characteristics and their relationship with various formations for different drill bits. The bar graphs denote how design characteristics are influenced by soft, medium, hard, and extra hard formations. For instance, the tooth depth is of higher relevance while working in soft formations, whereas the tooth depth reduces dramatically for extra-hard formations as it poses no benefit. Similarly, the bearing strength is of lower importance when used in soft formation but needs to be increased to work in extra hard formations. Ten columns denote the hardness formation, and the design features are relative and not specified to any scale.

Table 3: Drill bit design features selection according to rock formation hardness (Gokhale 2010)



FEA is an efficient way to anticipate a product's behaviour under real conditions using a computerised method. Particularly, it can evaluate a product in terms of heat, vibrations, fluid flow and interactions with other forces (Kurowski 2018). FEA can be utilised to solve complex problems that would otherwise be very costly to prototype. Evaluate performance and avoid the production of prototypes and save product development time. Although this method can predict a product's behaviour, testing under real-life conditions is essential to evaluate its real performance.

FEA has been used to optimise and redesign existing drill bits for improved efficiency and increased ROP (Abdul-Rani et al. 2014). Other studies have utilised FEA to simulate operational conditions and determine the most likely failure mode (Zhang et al. 2020). The geometrical design of PDC cutters has been studied through FEA simulations for optimal shape and bake rake angle (Liu et al. 2019; Pryhorovska, Chaplinskiy & Kudriavtsev 2015). Numerous studies have been conducted on several PDC cutters through ANSYS explicit dynamics (Dong & Chen 2018; Liu et al. 2019; Pryhorovska, Chaplinskiy & Kudriavtsev 2015). PDC cutter geometry with varying depths of cut was simulated through explicit dynamics. It was concluded that the oscillatory cutting forces regarding different PDC geometry did not affect the required force for each depth of cut (Pryhorovska, Chaplinskiy & Kudriavtsev 2015). FEA can be an efficient method of verifying the feasibility and performance of a novel drill bit design.

3.3 Drill Bit Inserts

A variety of carbide inserts are produced to effectively work on various rock formations, as shown in Figure 17. Taller and more pointed geometry inserts are often utilised for softer formations. It allows for a larger penetration rate due to its increased surface area and the deeper indentations it creates in softer formations. Shorter, more spherical, and conical-shaped inserts are used for harder formations due to larger impact forces often used in hammer bits. Roller cone tungsten carbide inserts are shrink-fitted in the holes of the roller steel body (Gokhale 2010). Other inserts are brazed into pre-machined grooves such a chisel-shaped inserts. During the research, consideration was made to include different types of inserts during the design to improve penetration rate in the novel drill bit in medium-hard formation.

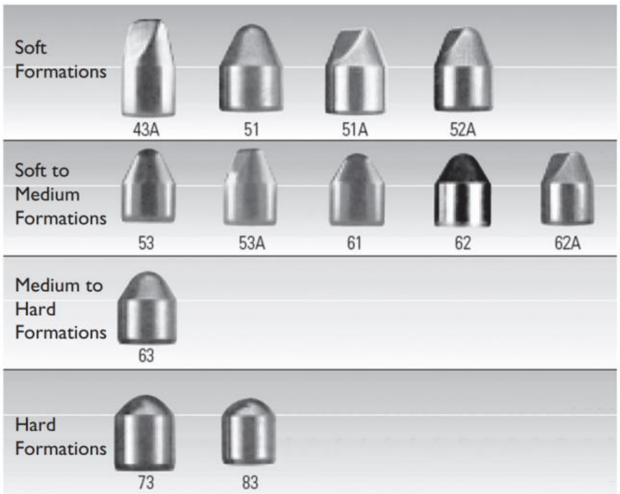


Figure 17: Roller cone insert geometries for various rock formations (Gokhale 2010)

PDC inserts are different to roller cone ones in their shape and purpose. While roller cone inserts are designed to fracture the rock, the PDC inserts add additional shearing operation. PDC inserts are structured differently with a tungsten carbide base and a polycrystalline diamond tip for increased durability. Figure 18 shows a PDC insert. These inserts are made of a tungsten carbide base and a polycrystalline diamond top layer to withstand high stress when interacting with a rock. PDC inserts are usually commercially available with a diameter from 5-19.05 mm, height ranges from 4.5-29 mm (The specifications of PDC cutter for oil drilling bits 2021; PDC Cutter With Size 1308 And 1313 Used For Kymera Hybrid Drill Bits 2021).

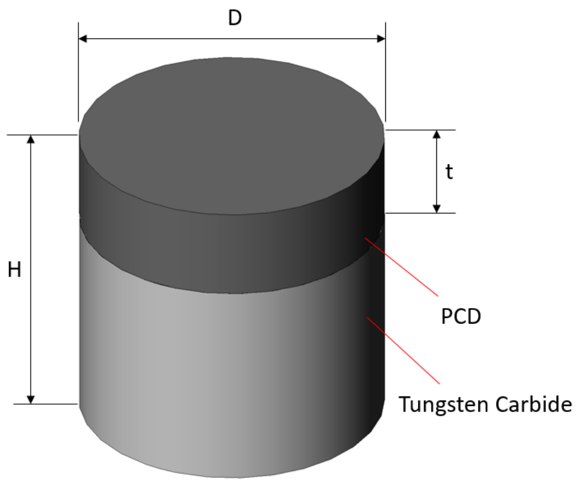


Figure 18: Typical PDC insert structure (adapted from PDC Cutter, Polycrystalline Diamond Compact, PDC Inserts 2021)

Figure 19 illustrates the associated vertical and horizontal force components that act on the PDC insert. Cutting efficiency is defined as the ratio between the unit of rock volume and the maximum force required to remove it. A higher ratio indicates higher cutting efficiency as a force required to remove a unit volume of rock is smaller. (Hareland et al. 2009). The angle ϕ indicates the back-rake angle that can often range from 0°- 25°. A PDC cutter back-rake angle between 0° - 10° degrees is the most efficient cutting efficiency (Hareland et al. 2009). In contrast, Rostamsowlat, Richard & Evans (2018) concluded through an experiment that a back-rake angle between 5°-20° is optimal due to higher cutting efficiency. Cutting efficiency is necessary to evaluate the placement geometry of PDC inserts to achieve an efficient novel drill bit design that is adapted to coiled tubing drilling to utilise an optimised amount of WOB and TOB to drill within various formations.

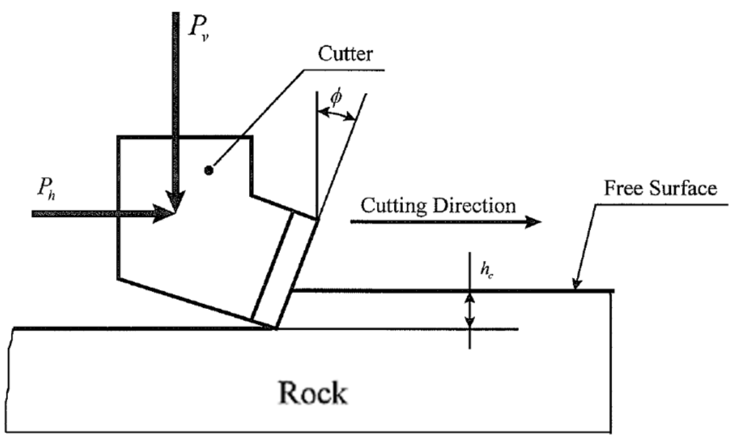
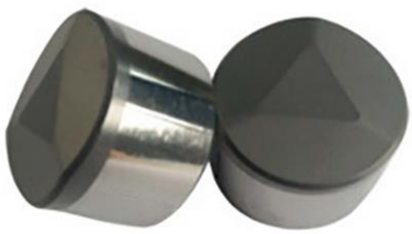


Figure 19: Schematic illustration of a back-rake-angle rock breaking mechanism (adapted from Hareland et al. 2009)

Table 4 below describes the most used PDC inserts types with their main features described.

Table 4: Types of commercially available PDC inserts and their descriptions

Graphic description	Description
 *Scoop (8.5 Matrix VAREL NTS PDC Bit FORCETM Series PDC n.d.)*	The scoop (concave) cutters improve the ROP with a changeable back rake. The concave face gradually achieves greater effective back rake due to the deep shearing action of the cutter. This higher efficiency causes the cutter to achieve higher ROP for identical WOB. A scoop cutter is ideal for drilling horizontally from vertical wellholes (Bellin 2018).
 *Oval (8.5 Matrix VAREL NTS PDC insert FORCETM Series PDC n.d.)*	This oval-shaped cutter allows for a higher depth of cut, increasing the ROP. Its particular geometry enhances stability in harder formations due to the more extended surface area. (PDC Attributes 2021).
 *Fang (8.5 Matrix VAREL NTS PDC insert FORCETM Series PDC n.d.)*	Fang is of a sharp-edged geometry PDC insert. It excels in providing a pre-fracture point with its sharp edge within a rock formation to ease PDC cutter shearing. This geometric shape is often utilised as a secondary row of cutters due to its lower energy requirements and higher ROP. (PDC Attributes 2021).

 *Triforce (8.5 Matrix VAREL NTS PDC Bit FORCETM Series PDC n.d.)*	Triforce (Artimis) PDC bit is designed for an increased ROP. Its edge geometry creates an effective stress point in the rock for fracturing and ploughing. This type of PDC bit is utilised for efficient transition within different hardness of formations and penetrating hard rocks (Bellin 2018; PDC Attributes 2021).
 *Three-ridged (Triple ridged PDC cutter/Triple faced PDC cutter/3D PDC cutter n.d.)*	The Three-ridged Diamond PDC bit has a thicker PDC layer in comparison to conventional PDC cutters. The unique convex cutting surface geometry shears the rock while delivering a crushing action similar to roller cone inserts. The contact stress of the three-ridged bit is 50% less than conventional cutters (Liu et al. 2019).

3.4 Materials of Drill Bits and Inserts

Mono-tungsten carbide and titanium carbide are the mainly used materials to manufacture drill bits, their string, and inserts. The main advantages of tungsten carbides in rock drilling are high hardness, toughness, and wear resistance (Gokhale 2010; Katiyar et al. 2016). Roller cone bits have additional components, thus require different materials for their structure. Table 5 summarises the mechanical properties of mono-tungsten carbide and titanium.

Table 5: Comparing mono-tungsten carbide with titanium (Gokhale 2010)

Carbide formula	Carbide name	Hardness	Crystal structure	Melting point (ºC)	Theoretical density (g/cm^3)	Modulus of elasticity (GPa)	Thermal expansion (mm/m.K)
WC	Mono Tungsten Carbide	2200	Hexagonal	2800	15.63	696	5.2
TiC	Titanium Carbide	3000	Cubic	3100	4.94	451	7.7

The materials described in Table 6 include the desired material properties for each drill bit part and their common materials used to design and manufacture drill bits. For designing a novel drill bit, hardness and modulus of elasticity are important properties of a material to extend a drill bit's life and prevent premature failure while drilling.

Table 6: Materials of drill bit components (Gokhale 2010)

Component name	Desired material properties	Material chosen	Material composition
Cones	Abrasion and Impact Resistance	4817 alloy steel	Fe, C, Si, Mn, Ni, Mo, S, P
Legs and bit body	Weldability, high impact resistance, surface fatigue resistance	8720 alloy steel	Fe, C, Si, Mn, Ni, Cr, Mo, S, P
Roller and Ball Bearings	High strength, impact resistance	S2 tool steel (shock resisting)	Fe, C, Si, Mn, Mo
Journal bushing	Wear resistance	431 stainless steel	Fe, C, Si, Mn, Ni, Cr
Thrust button	Wear resistance	M2 molybdenum high speed tool steel	Fe, C, W, Cr, Mo, Va
Bearing Hard facing	Wear resistance	Chrome cobalt	Co, Cr, C, W, Ni
Tooth Hard facing	Extreme abrasion resistance	Tungsten carbide	W, C, Co

Cemented carbide is a material that is most commonly used for the production of drill bits. It has the best combination of toughness and hardness to withstand mechanical deformations under extreme operating conditions (Beste & Jacobson 2008). New material is developed by modifying and mixing different grades (Beste, Coronel & Jacobson 2006).

Tungsten carbide materials possess excellent wear and hardness resistance (mechanical), chemical, and thermal properties, making them the most common candidate to produce drill bits. The chemical composition, thermal properties, environmental conditions, and geometry of the tungsten carbide determine the drill bit's properties (Prakash & Mukhopadhyay 2018; Tkalich et al. 2017). For instance, the drill bit's wear and abrasion issues can be resolved to an extent by reducing the cobalt and nickel content. If tungsten carbide is composed of very fine particles, it provides improved hardness. If the cobalt and nickel composition is increased, it provides enhanced impact resistance, compressive strength. There are several additives, such as niobium carbide (NbC), nickel (Ni), cobalt (Co), and tantalum carbide (TaC), which can alter the properties to improve softening temperature, shock resistance, and hardness. However, not all the desired properties can be achieved as the chemical composition needs to be changed to achieve different properties (Katiyar et al. 2016).

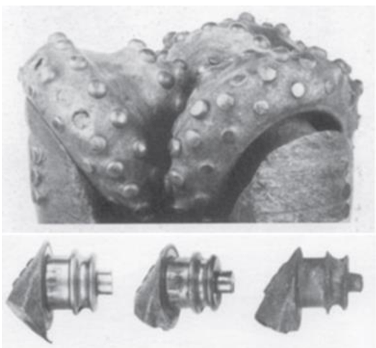
Drill bit body and roller cones are made up of several combinations of alloy steel. For instance, alloy steel 8720 combines carbon, manganese, phosphorous, sulphur, silicon, nickel, chromium and molybdenum. This particular combination has high strength, toughness, impact resistance and works well at high temperatures. For mining applications, alloy steels are generally susceptible to wear, but alloy steel 8720 possess good wear resistance to prolong bit life (Arulmani & Pandey 2014).

3.5 Common Failure Modes

The most common reasons for bit wear involve the deterioration, mainly of the inserts operating in soft-medium abrasive formations, consistent wear on every tooth, shirttail wear due to inclined drilling (Rafezi and Hassani 2021). These phenomena cause the bit to experience heavy side thrust, broken leg, broken inserts, and washed-up teeth, as described in Table 7. Furthermore, as the bits wear, the energy required to drill increases, the ROP decreases, and early replacement of drill bits is needed. These factors increase the operation and maintenance costs and hinder the time taken to execute the drilling process efficiently (Katiyar et al. 2016). To better comprehend a bit's wear, it is suggested to incorporate a dynamometer and a drill bit data acquisition system to provide a more accurate correlation between tool wear and drillability (Dewangan 2019). Also, failure information recorded from such systems can be concealed, incomplete, seasonal, and inhomogeneous. Therefore, it might not accurately contemplate the product's accurate performance when relying on such systems to predict or prevent failure (Prakash & Mukhopadhyay 2018).

Table 7: A summary of common failure modes of drill bits

Failure Mode	Description
 *Heavy wear on shirttail and gage inserts (Drill bit tricone worn 2019)*	As seen in the image, excessive wear can be seen on both the gage inserts and shirttails. Excessive wear on one cone can be attributed to a bent drill bit resulting in uneven distribution of force, thus wears on one side occurs. This failure results in very heavy side thrusts on the bit. This form of failure could also be obtained through the breakage of carbide inserts, which remain in the borehole due to insufficient flushing (Gokhale 2010; Rafezi & Hassani 2021).
 *Broken leg (Rotary Drilling Tools - TRI-CONE BITS OPERATING MANUAL n.d.)*	A broken leg is a typical failure mode for a roller cone drill bit. This type of failure results in the breakage of the part (leg) that holds the cone. This type of failure occurs when the cone gets a direct impact either from dropping or when an excessive WOB is applied. The failure starts with a crack and propagates as stresses are transmitted onto the leg from the cones (Gokhale 2010).

 *Exposed cone-bearing (Gokhale 2010)*	This type of failure is caused when the bit is subjected to bearing failure and all the cones interfere. This causes one of the three cones to be subjected to the full load weight on the bit. In addition, cone bit breaks circumferentially, the cone's inner and nose elements are lost, and the bearings under the cone are exposed (Gokhale 2010).
 *Cracked cone (Rotary Drilling Tools - TRI-CONE BITS OPERATING MANUAL n.d.)*	Similar to a broken leg, this type of failure predicts the breakage of a leg. The crack appears due to excessive load on the cone or when dropped from a height (Barzegar, Gharehdash & Osanloo 2014).
 *Lost cone (Gokhale 2010)*	When this type of failure occurs, it is considered an advanced cone breakage stage as the cone has completely broken circumferentially. The failure of the bearing system leads to losing one of the cones. For example, this failure occurs when one cone is subjected to the full WOB (Gokhale 2010).
 *Bearing failure (Gokhale 2010)*	Bearing failure is the most common failure mode in roller cone drill bits. Bearings are susceptible to high amounts of radial and axial loads (deepening on drill bit size and application). This type of failure is mainly unavoidable since bearings is a sensitive assembly designed to work under specific loads and temperatures between -71°C and 200°C (Gokhale 2010; Noda 1991). Lack of lubrication and bearing seals accelerate the bearing failure, as the amount of grease during drilling decreases over time. When the sealing becomes damaged, it cannot protect the bearing from foreign bodies, and as a result, it causes the bearing to fail (Gokhale 2010; Suto & Takahashi 2011).

 *Broken inserts (Rotary Drilling Tools - TRI-CONE BITS OPERATING MANUAL n.d.)*	The wear distribution of this type of bit is similar to all the cones. The inserts on the gage have been cracked, while inner cones are subjected to minor wear. Broken inserts are usually found when the bit is meant to be used for drilling in soft formations but is utilised in very hard formations. In such a situation, the gage inserts are subjected to very high forces (Gokhale 2010; Rafezi & Hassani 2021).
 *Broken Blade (Drilling Manual 2021)*	Severe impacts on the PDC drill bit can cause the bit blade to fracture and catastrophically fail. This particular failure could occur due to sudden severe change in a rock formation, extreme torque or bit whirl (Drilling Manual 2021).
 *Broken Matrix (Drilling Manual 2021)*	Broken matrix failure occurs when a section of the blade is broken off or is chipped. In this case, the fracture occurs between the top cutter edge and one half of the drill bit height. In some cases, the breakage can occur in other locations distant from the blade itself. This failure mode's leading cause is strong impact, excessive torque on the bit, and foreign objects in the bore hall (Drilling Manual 2021).
 *Ring Out (Drilling Manual 2021)*	This type of failure is characterised by the wear of the ring, which usually occurs at the shoulder or the nose regions. Ring out failure can occur on the entire bit, which leads to massive wear on the gauge. The leading cause for this failure is the loss of the cutting structure (Drilling Manual 2021).

Wear in bits can be mainly classified as chemical, abrasive, adhesive erosive and fatigue (Capik & Yilmaz 2021; Gokhale 2010). The bit's cone's body absorbs the deformations, stress and vibrations during drilling and resists the ambient conditions. During drilling, drill bit inserts must endure the elevated hardness of rocks, friction with the grounds, and resistance to fracture. Materials selection for drilling is restricted to vibrations, temperature, design loads considering resistance to fracture, erosion and abrasion (Benavides-Serrano et al. 2019). Bit body usually wears faster than the inserts, which causes the detachment of inserts, as shown in Table 8. In addition, one detached button increases the forces of dynamic impact on the rest of the buttons. Bit body wear is usually attributed to misuse or manufacturing issues (Capik & Yilmaz 2021).

Table 8: A summary of PDC common failure modes

Failure Mode	Description
 *Worn Cutter/Normal Wear (Drilling Manual 2021)*	When none of the other failure modes affects the cutters and everything works well, PDC experiences even wear flat and normal wear. Generally, the diamond layer is without spalls, cracks, major chips, and worn edges (Drilling Manual 2021). Even though this type of wear is normal, the cause for this type of wear is a combination of thermal and mechanical effects occurring during drilling operations (Tze-Pin et al. 1992).
 *Chipped Cutter (Drilling Manual 2021)*	As seen in the image, the PDC cutters have a minor breakage on some of the inserts. The cutters have been chipped in both the tungsten carbide base and the diamond layer. This failure often occurs due to excessive torque and sudden rock formation changes (Drilling Manual 2021; Tze-Pin et al. 1992).

 PDC Delamination (Drilling Manual 2021)	A majority, if not all, of the diamond layer has cleanly come off the tungsten carbide base. This delamination occurs at the interface between the diamond layer, and PDC is exposed. Excessive heat is one of the common causes of this failure (Che et al. 2012; Drilling Manual 2021). Delamination of the PDC diamond layer can also occur due to excessive axial loads applied on the PDC cutters (Zacny 2012).
 PDC Heat Failure (Drilling Manual 2021)	Thermal abrasive wear can cause the failure of PDC cutters, greatly reducing service life. Excessive cutting temperatures due to insufficient cooling and high rotational speed causes the PDC cutter to wear out. (Drilling Manual 2021; Zhang et al. 2020).
 PDC Erosion (Drilling Manual 2021)	Abrasive mud and rock formations can amplify the wear of PDC bits during operation. The jet nozzle's loss can also result in additional erosion on the PDC cutters due to the reduction of bit cleaning (Drilling Manual 2021; Timonin et al. 2017). Occasionally, the tungsten carbide layer is undamaged with the diamond layer, which causes less wear underneath the tungsten carbide substrate (Drilling Manual 2021).
 Broken Cutter (Drilling Manual 2021)	PDC cutters experience severe impact as seen in the case of bit whirl or scattered (occurring at irregular intervals) torque. This causes breakage of the cutter and damages the diamond layer and tungsten carbide substrate (Che et al. 2012; Drilling Manual 2021).

 *Lost Cutter (Drilling Manual 2021)*	Whether partial or complete, a lost cutter can occur due to the braze bond failing to retain the tungsten carbide base. These lost cutters can leave tiny fragments of tungsten carbide in the borehole (Drilling Manual 2021; Huang et al. 2018). This failure can reduce ROP, damage to other drill bit inserts due to impact with the lost cutter, and increase stress on other PDC cutters.
 *Bond Failure (Drilling Manual 2021)*	The braze joint between the PDC cutter and the bonded extension can shear or break off. These can result in the tungsten carbide base remaining in the cutter pocket while removing a significant portion. This form of failure is usually from a PDC manufacturing error (Drilling Manual 2021). This failure also can occur due to oxidation and contamination during the brazing process (Hoover & Pope 1981).
 *Cracked Diamond Layer (Drilling Manual 2021)*	Cracks in the diamond layer of cutters can arise due to excessive heat or abrasive impact. The cracks can appear as hairline cracks both radially and parallel to the tungsten carbide. These cracks in the diamond layer eventually lead to further severe issues on the drill bit (Drilling Manual 2021; Xu et al. 2017).
 *Spalling (Drilling Manual 2021)*	In this failure mode, spalling occurs in the form of chipped PDC elements. Even though the PDC layers are chipped, it usually does not reach the tungsten carbide interface. The cause for this failure is mainly due to the strong impact of the PDC layer with a hard formation from the application of excessive normal force (Drilling Manual 2021; Zacny 2012).

 *Reaming (Drilling Manual 2021)*	Reaming is an unwanted phenomenon when there is concentrated wear on the gage pads. In most cases, the PDC inserts experience minimal wear. This failure mode is mainly caused by drilling within a smaller bore diameter than the drill bit (Drilling Manual 2021).

3.6 Bearings of Low Torque Drill Bits

Bearings in roller-cone drill bits are vital components. Therefore, wear has a significant impact on the drill bit's life. Roller cone bearings are complex assembly that commonly comprises a small and a more considerable radial bearing in the form of a ball bearing for axial support and a plane thrust bearing to better support as described in Figure 20. Complex working conditions cause contact fatigue during drilling at high speeds, leading to bearing failure (Han et al. 2015).

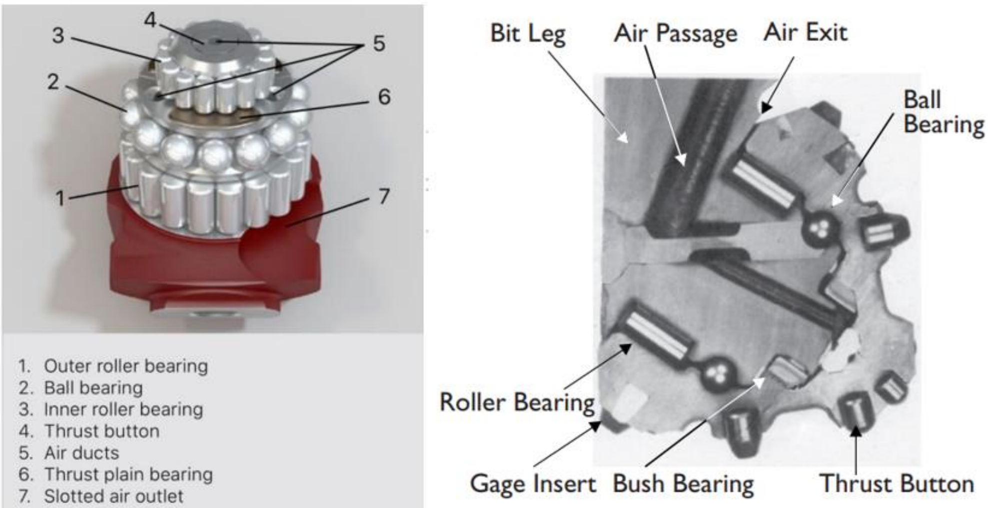


Figure 20: Bearing structure within roller bit (Rock Drilling Tools 2018) and sectional view of tricone bit (Gokhale 2010).

The bearing systems are designed to work in environments where the roller cone cutter experiences complete wear. Therefore, according to the International Association of Drilling Contractors (IADC), the bearing and seal life must be 1 million revolutions or more instead of the previously defined 300,000 revolutions (Rafezi & Hassani 2021). A bearing system consists of six essential parts; primary bearings, secondary bearings, seals, sleeve, cone supporting balls, and a lubrication system. Figure 21 displays an exploded view of a bearing system (Drilling Manual 2021).

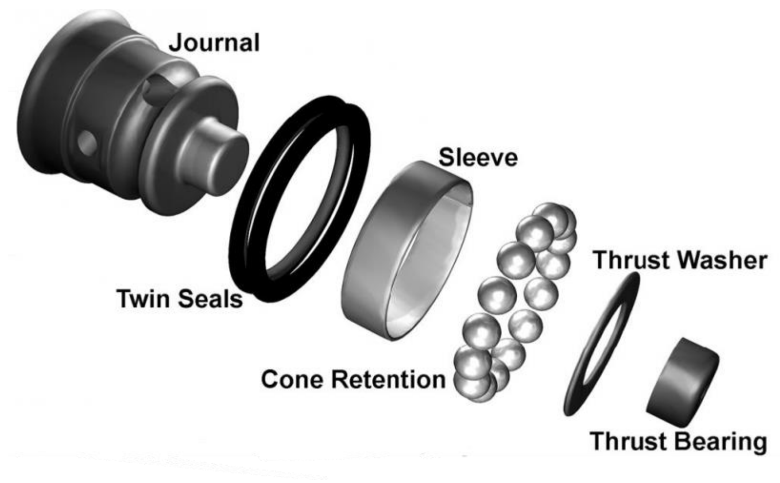


Figure 21: Components of a bearing system of a drill bit (Smith Bits 2021)

Primary bearings are used to reduce friction, enable smooth rotation, and carry large loads. Therefore, these bearings are designed to be as large as possible within the available roller cone size. In contrast, the purpose of the secondary bearings is to supply extra load-bearing capacity. Thus, these bearings have a significantly lower diameter than primary bearings and are placed at the inner top area of the roller cone. Roller bearings and journal bearings are used as primary bearings, while ball bearings are used as secondary bearings (Drilling Manual 2021).

There are three types of bearing systems: roller bearings, journal bearing, and open bearing systems, also known as non-sealed bearing systems. Figure 22 shows (a) roller bearing system and (b) journal bearing system components. The major difference is the change in primary bearings. Thus, a roller bearing is used in the roller bearing system, and a journal bearing is used in the journal bearing system. In comparison, open bearing systems do not use any seals, and they require frequent cleaning of debris.

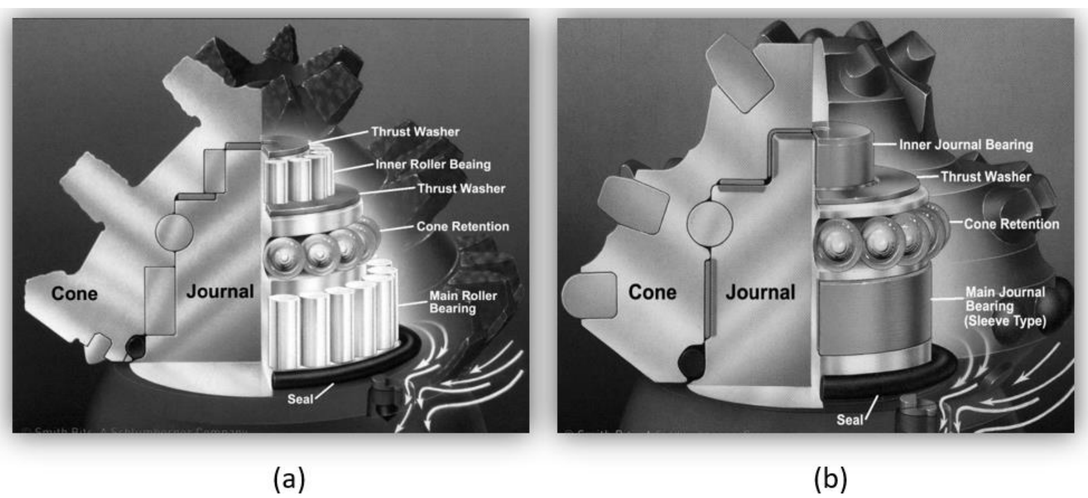


Figure 22: Comparison between (a) roller bearing system and (b) journal bearing system (Smith bits 2021)

Bearing seals buffer the rock cuttings entering and the lubricant running away from the bearing system. A thrust washer is placed between the primary and secondary bearings to resist axial loading on the roller cone. Cone supporting balls are retention features incorporated in most roller cones to prevent the roller cone from separating from the journals. Lastly, the lubrication system consists of a lubricant (highly viscous grease or oil) across the bearing life cycle to extend the bearings and seal life (Drilling Manual 2021). The common failure modes of bearings are described in Table 9.

Table 9: A summary of common failure modes of drill bit bearings

Mode of Failure	Description
Fracture  *Ball-bearing fracture inside roller cone (Huang et al. 2013)*	Bearing fracture is a type of fatigue failure and is generally caused due to overload and fit clearance between the roller cone and the bearings. Fracture concentration is noticed on the most undersized diameter bearings (Huang et al. 2013).
Plastic Deformation  *Pits (Plastic deformation) on the surface of journal bearings (Huang et al. 2013)*	High stresses, temperature, unequal load distribution and unsatisfactory lubrication cause bearing plastic deformation. Severe pits and overtime decay causes the bearings to soften. Larger fit clearance between the bearings and the roller cones results in extreme vibrations, which causes pits in the root of bearings (Huang et al. 2013).
Adhesive Wear  *Bearing adhesive wear (Huang et al. 2013)*	Adhesive wear occurs by the rise in temperature due to friction caused by intense wear and insufficient lubrication, causing an overtime decay, softening, and adhesive phenomenon (Huang et al. 2013).

Drill bits operate in extreme environments where abrasive drilling mud, chemicals, water and rock cutting enter the roller cones. CTD causes the lubricant to experience pressure pulses that exert lateral loading on the bearings. Therefore, bearing seals prevent abrasive materials from entering and the lubricant from escaping the roller cone. O- ring seals are the most common types of seals used in roller cones. Synthetic rubber (elastomer) is used to manufacture O-rings that resist harsh environmental conditions such as high temperature, pressure, and chemicals (Drilling Manual 2021; Zeng, Zhou & Ma 2018; Zhou et al. 2014).

Premature bearing seal failures account for roughly 30% of bearing failures (Huang & Li 2018). To date, several studies have been aimed to improve the cone-bit bearing ring. Finite element analysis (FEA) of tricone bit determined that stress concentration and uneven pressure distribution occurred at the seal (Zhou et al. 2014). This resulted in the rubber rings being unequally compressed, and the metal ring structure had uneven pressure distribution. In addition, the grease became unable to act as a lubricant in these areas resulting in excessive wear (Zhou et al. 2014).

A study has addressed some of these problems through FEA (Zeng, Zhou & Ma 2020). It concluded that an increased width of the sealing face to 3.4 mm and an increase of the back supporting angle to 11 degrees resulted in a 14% drop in the average compression ratio. The wear of the improved design resulted in approximately 20-38% reduced wear of the bearing seals (Zeng, Zhou & Ma 2020). A ribbed tooth sealing structure was shown to reduce the overall contact surface, thus improving the heat dissipation, with additional lubrication reservoir from the additional gap (Huang & Li 2018). The findings have yet to be combined with all the parameters and obtain a truly optimised roller cone bit bearing seal. Furthermore, lab or field testing for the performance benefits of improved bearing seals has yet to be conducted. Therefore, additional research is required to determine the practical improvements of improved bearing seals.

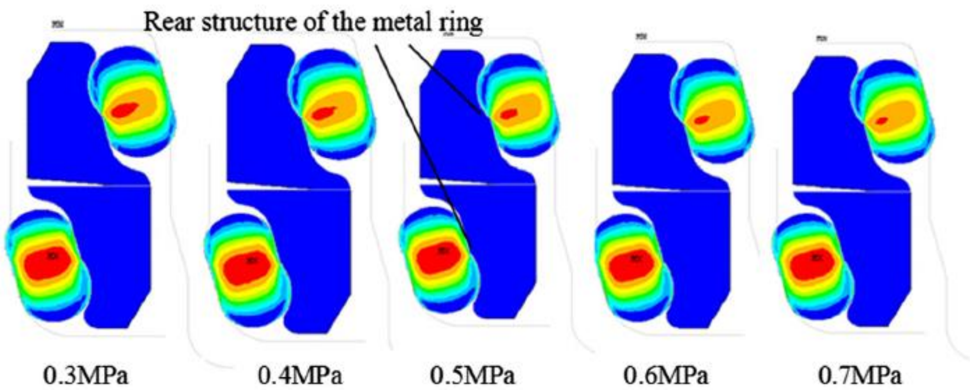


Figure 23: Strain distribution of seals under various pressures (Zhou et al. 2014)

Sliding thrust, rolling element and plain journal bearings are commonly used in drilling operations. However, thrust bearing usage shortens bit life and restricts its performance, particularly under 300 rpm, elevated load on a bit, and intense shock loads. Therefore, a thrust load-bearing was developed. This bearing provided substantial performance advancement during experiments and could operate under higher rpm and load on bit than traditional thrust bearings (Kalsi et al. 2007). However, this type of bearing was tested only in ambient temperatures between 80 and 136 degrees Celsius, which can lead to a potential failure while drilling in sub-zero or elevated temperatures ranging from -78°C to 200°C. During various conditions, thermal stress due to drilling can affect the material's mechanical properties, mainly while drilling and tensile with compressive stresses are involved (Noda 1991).

Bearing sealings are the first in the defence line and have a significant impact on operational life. In conducted drilling operations experiment, temperatures within the drill bit reached an estimated temperature of 143 degrees Celsius, which reduced the flow resistance of a grease, leading to a smaller bearing characteristics number. Bearing characteristic number indicates load conditions such as WOB, rotational speed, and flow resistance (Suto & Takahashi 2011). This suggests that it is challenging to preserve consistent grease film thickness within the bearing, which leads to increased inner frictions. A roller-cone drill bit's temperature would rise and lead to the O-rings' thermal damage and adhesive wear in a simpler term. During drilling in elevated temperatures and inclined rollers, bearing conditions advance only to boundary lubrication, which leads to accelerated wear (Suto & Takahashi 2011).

3.7 Knowledge Gaps

The main gaps that have been identified can be classified mainly as design, materials and bearings. Individual research gaps of each of these are outlined below:

- Design: out of the existing concepts, the cone-hybrid PDC drill bit provides promising results regarding reduced wear and high ROP. However, this concept has been tested under specific rock types and is unsuitable for drilling in soft formations.
- Excessive insert wear occurs mainly in the gauge row of a roller cone drill bit under a soft-medium rock formation. The literature review has not identified any solution to address this issue using alternative materials for the specific drilling condition or a combination of various alternating inserts made of several materials in a single row.
- PDC insert geometry: PDC inserts are the most crucial part of drilling and removing rock material. While there are many drilling conditions, no specific geometry combination of front and back rows is identified to be suitable for operating in low torque conditions in coiled tube drilling operations.
- Bearings: bearings are highly susceptible to damage, and there is no definite concept that

outweighs the others. There is no existing method to maintain proper lubrication within a bearing during drilling operation in temperatures exceeding 150°C. Bearing seals can withstand the soft formations but cannot handle hard formations, which causes the drill bit to detach and fall inside the drilling hole.

The research project aims to create a detailed design of a new low torque drill bit to extend a drill bit's life in various drilling conditions by addressing the literature review gaps and increasing the efficiency of the exploration operations.

4. Research Aims and Objectives

Coiled tube drilling involves different bit designs to force out soft soil or drill in hard substances. The broad aim is to provide an innovative drill bit design adequate for hard rock, which conventional hydraulic percussive methods cannot fragment. The research project will comprise of:

1. A design of a novel drill bit will be established on existing bit designs offered for medium-hard rock hardness, distinguishing characteristics of commercially available and novel bit designs for increased operational life and rate of penetration.
2. Determine the geometry of the PDC inserts and their back-rake angle configuration to maximize stress on the rock and increase the penetration rate.
3. Determine suitable drill bit materials for medium- hard rock hardness range through literature and existing products and validate their suitability to the design. Specific considerations will be made to decrease excessive wear and increase the impact on rock.
4. Address bearing failure by selecting bearing from a commercially available catalogue and adapting the design to contain the selected bearings within the roller cone to reduce bearing wear and prevent foreign objects in the bearing system.

5. Design Approach and Results

The research was based on a thorough literature review of the existing designs and material composition. Multiple conceptual designs were developed and proposed to MinEx for feedback. A selection matrix with feedback from MinEx was used to select the final conceptual design. The chosen concept underwent several design improvements and was validated with finite element analysis for possible failure modes. Materials of the drill bit were chosen based on their mechanical properties through literature. All required modifications to the mechanical design were made to optimise the results for increased penetration rate. The proposed plan is described in Figure 24.

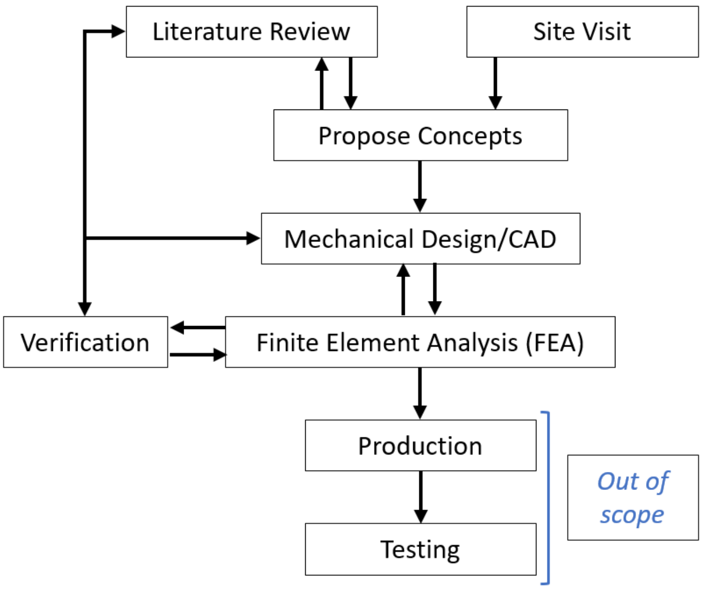


Figure 24: Flowchart of the proposed research plan

5.1 Research Methodology

A combination of detailed design and quantitative numerical analysis/simulations formed much of this project. Previous researchers on drill-bits have utilised similar methodologies (Shi, Zhu & Luo 2017; Zeng, Zhou & Ma 2020; Zhou et al. 2014).

The use of quantitative case studies is a well-established approach in mining drill bits (Prakash & Mukhopadhyay 2018). Other studies have used quantitative experimental studies through physical drill-bit models (Franca 2011; Niu et al. 2019). These methodologies require either extensive data sets or specific tools and time to be used in this project. A literature-based design method in conjunction with numerical simulations for analytical verification is suitable for this project. Analytical verification of drill bits by utilising an FEA package is common in drill bit design (Pryhorovska, Chaplinskiy & Kudriavtsev 2015; Toshniyozov, Toshov & Songyong 2020).

5.2 Research Methods

This project consisted of several different methods to achieve the outlined aims and objectives. A detailed design method was used to establish the most appropriate design for further analysis. A chronological list of steps below outlines how the aims were addressed.

5.3 Materials and Bearings Approach

A comprehensive literature review on current design and reviewing manufacturers' catalogues was the steppingstone for the actual research project. A review has been done to identify types of drill bits, their modes of operations, failure modes, structures, and their use for different rock formations. Material selection through literature review and experimental data was used to determine the appropriate material composition of the drill-bit design. The main gaps in the research are listed in Section 3.7 Knowledge Gaps. A comprehensive literature review of bearings and catalogues were used as a basis for bearing selection. Roller and ball bearings were selected from the SKF bearing catalogue according to design requirements. Several constraints, such as bearing size and other factors addressed in the selection matrix for the best fit. PDC and roller cone inserts were chosen based on literature recommendations. A workshop visit was done to enhance understanding of the industry partner's drill bit structure and design requirements.

Figure 25 describes the material selection procedure for the hybrid drill bit. The first step was formulating the design requirements based on the information gathered through the inputs made by MinEx CRC. The next step was conducting a thorough literature review on the types of materials used for each part of the drill bit, along with their optimal working environments. Experimental material testing was considered. However, since most of the material properties were found in the literature, the desired materials for every drill bit part were shortlisted. The final chosen materials are shown in Table 10 and were based on the FEA testing, literature evidence, and engineering judgement.

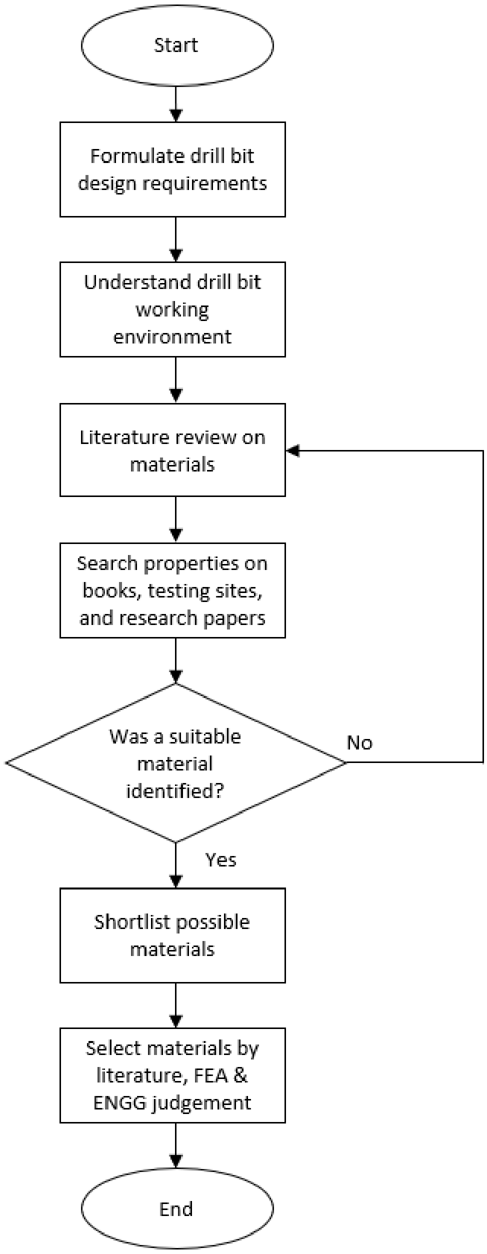


Figure 25: Material selection approach flow diagram

Figure 26 shows a flow diagram outlining the bearing selection approach. The bearing selection procedure started by conducting a literature review on the bearing systems, types of bearings, and bearing failure modes. The literature suggested that roller bearing systems are suitable for target medium-hard formations. Roller bearing systems uses primary and secondary bearings as roller bearings and ball bearings, respectively. Ball bearings enable low friction movement and resist axial and radial loads.

In contrast, roller bearings improve the system's stability, rigidity, and maximum load-carrying ability leading to the increased operational life of a drill bit. Next, bearing selection requirements such as available dimensions, force on roller cones, WOB, and a minimum safety factor of 3 were formulated.

The mineral exploration industry has no set safety factor standards as it relies on design, drilling purpose and drilling environment. Every bearing manufacturers sets its standards; therefore, a safety factor of 3 was selected to resist possible shock loads, enable accurate bearing rotation, and prevent permanent plastic deformation experienced by bearings. Since the SKF bearing catalogues had both the bearings (primary and secondary) for the hybrid bit, bearings were selected and not designed. Finally, the SKF bearing specification calculator calculated the technical specifications and compared them against the formulated requirements. The values exceeded the defined conditions, and engineering judgement supported the final bearing selection.

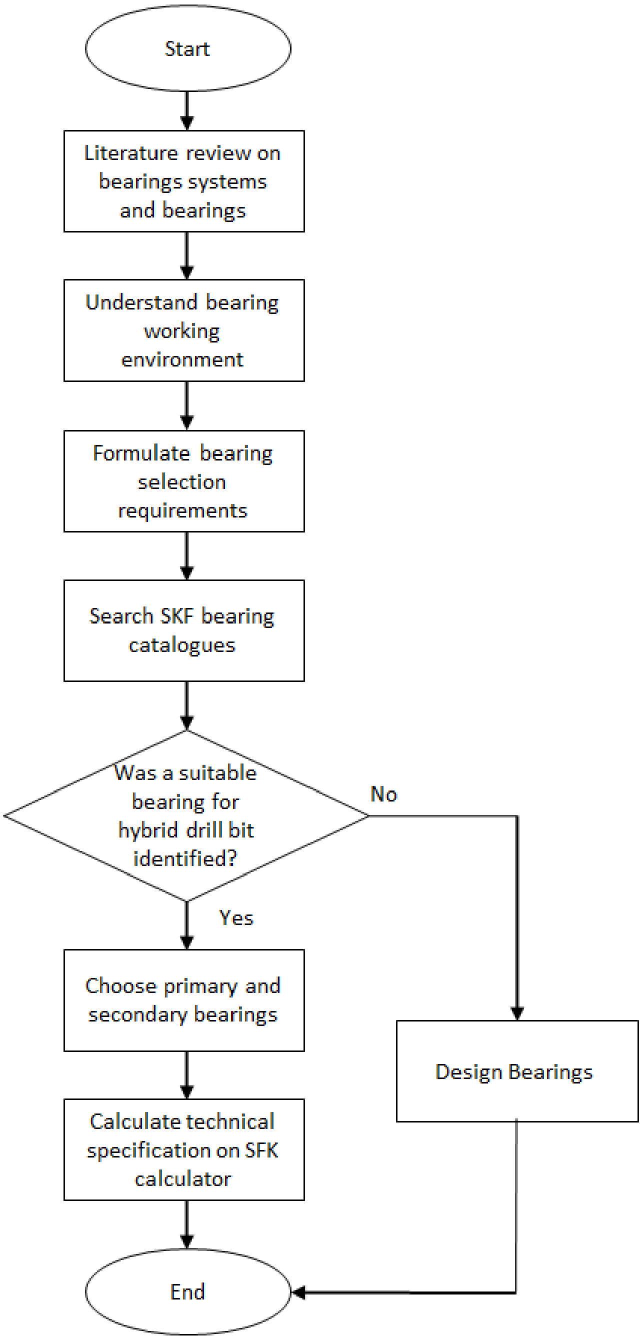


Figure 26: Bearing selection approach flow diagram

5.3.1 Material Selection

Materials play a vital role in the overall life and performance of the drill bits under distinct working conditions. Thus, choosing the most appropriate materials for operating the hybrid drill bit in medium-hard rock formations was essential. Sedimentary rocks such as limestone and shale were the target rocks. Table 10 describes the materials that were selected for the hybrid drill bit design.

Table 10: Selected materials for parts and their summary of features

Part	Material	Features
Drill bit body & Roller cone	Alloy steel 8720	High Young's modulus, easy to manufacture, high strength, ductility and toughness, high corrosion resistance, higher hardness, medium-high density, high yield strength
Roller cone inserts & PDC insert base	Tungsten carbide	High hardness, high strength at elevated temperatures, high corrosion resistance, oxidation resistance, high density, high resistance to deflection and deformation, excellent wear resistance.
PDC insert tip	Polycrystalline diamond compact	High hardness, high strength, high toughness, high thermal conductivity, high impact resistance, and wear resistance.

5.3.2 Bearing Selection

As mentioned in the literature review – Section 2.8, the roller cones use three types of bearings: roller bearing, ball bearing and journal bearings. Two bearings were selected for the hybrid drill bit design due to limited space and the lower loads acting on the bit, in contrast to using a roller design with no cutters. If a tricone or roller cone design with no cutters were selected, more bearings would be required to compensate for the high loads. The roller cones selected two appropriate types of bearings by considering the maximum physical dimensions allowed within the roller cone and the load on the bearing. The literature identified that a 1 mm overhang distance between the roller cone inserts and the PDC inserts allows for a WOB distribution of approximately 40% on the cutters based on previous research. This permits the use of two bearings and ensures a higher safety factor. Therefore:

$$WOB = 8.7\ kN$$

$$Force\ on\ 2\ rollers = 8740 \times 0.6 = 5.2\ kN$$

Since the design has two rollers:

$$Force\ on\ each\ roller = \frac{5244}{2} = 2.6\ kN$$

The selected bearings were chosen in the SKF bearing catalogue (SKF Bearings n.d.). The bearings chosen were ensured to have a safety factor of 3 or more using the SKF selection tool to withstand the maximum forces acting on the bearings during operation, accounting for the worst-case scenario of

2.6 kN per bearing. Figure 27 shows both of the selected bearings. The roller bearing (a) has a maximum allowable load of 11.2 kN, and the ball bearing (b) has a maximum load capacity of 8.7 kN. Both bearings are of a thrust type bearing as identified in the literature.

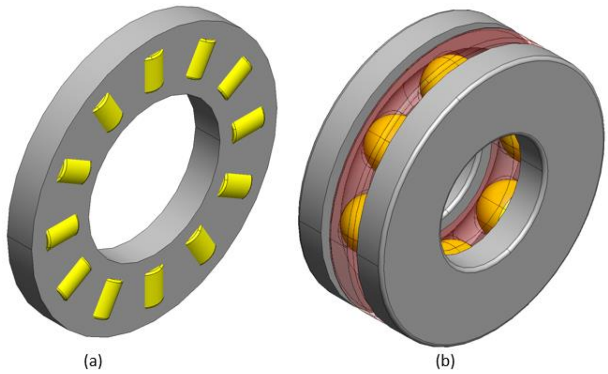


Figure 27: Selected bearings: (a) Roller bearings and (b) ball bearing (SKF Bearings n.d.)

Table 11 below shows some of the technical data considerations for the roller and ball bearings. The complete list of all technical details can be seen in Appendix D – Bearing Technical Specifications.

Table 11: Technical specifications of selected bearings for the design

Bearing type	Bore diameter (mm)	Outside diameter (mm)	Thickness (mm)	Static load rating (kN)	Safety factor
Cylindrical roller thrust bearings	15	28	3.5	11.2	4.69
Thrust Ball bearings	10	24	9	8.71	10.4

5.4 Verification and Validation

5.4.1 Verification and Validation Approach

The verification and validation approach was based on a 'Simulation and experimental study on temperature and stress field of full-sized PDC bits in rock breaking process' (Zhang et al. 2020). This paper was chosen due to its similarity of working conditions. The verification process was followed to validate procedures and matched similar results. An applied WOB of 3 kN and rotational speed of 400 rpm was set (Zhang et al. 2020). A mesh of 1 mm was applied on both the contact surfaces of the rock and the PDC. The analysis was conducted through an explicit dynamics analysis using the ANSYS FEA package. The model, as shown in Figure 28, depicts the boundary conditions applied to the model. Model replication was as accurate as possible with the limited information provided. A similar meshing approach was applied with consideration of the total number of meshing elements.

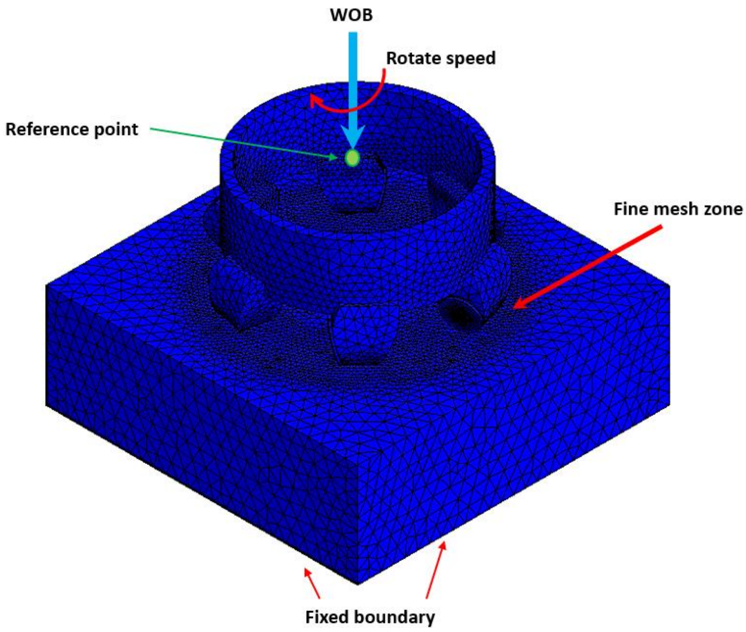


Figure 28: Overview of explicit FE model of a PDC drag bit cutting into rock, showing loads and mesh

5.4.2 Verification Model Results

A verification model based on a literature paper by Zhang et al. (2020) was created to simulate the ROP of a PDC Drill bit. An explicit dynamics simulation was completed through ANSYS with the model displayed in Figure 29. The model was recreated with some estimated dimensions as not all dimensions of the PDC drill bit was disclosed. The model was simulated to determine the rock breaking features through erosion settings in an explicit dynamic's simulation. After reaching the rock formations ' stress values, initial testing was conducted in a transient-structural analysis to attempt APDL coding of death elements. The code and analysis setup can be viewed in Appendix E – APDL Commands. An explicit analysis was set up with the same boundary conditions to achieve a similar ROP to the results shown in the paper.

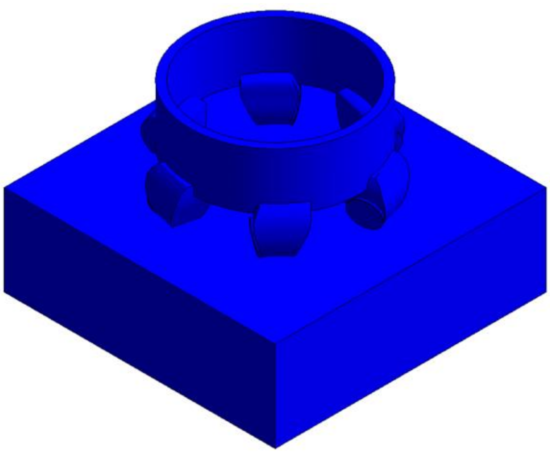
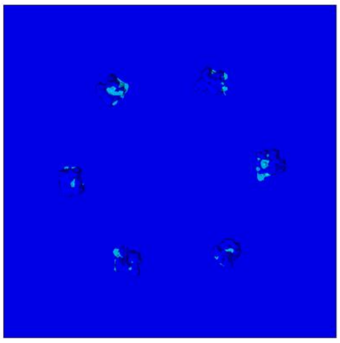
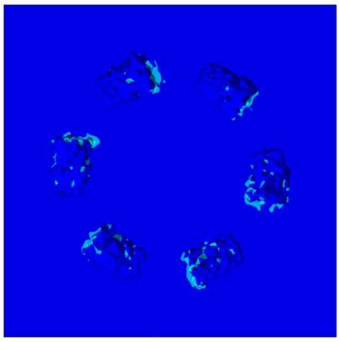
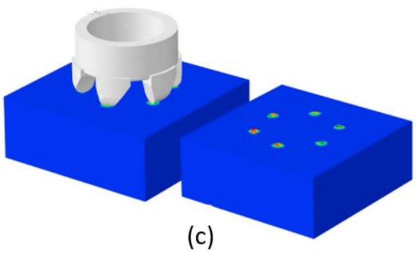


Figure 29: Replicated model using SolidWorks, meshed finely at contact regions.

The results in Figure 30 indicate rock fracture as the 3 KN load is applied with a continual shearing of the rock surface as the PDC cutter shears the rock formation during its rotations. Visual comparisons between the penetration rate at both 0.13 and 0.18 seconds figures are closely similar to the explicit dynamics analysis. Figure 30 (a) & (b) are results obtained through ANSYS comparing the research papers using ABAQUS software. As seen in Figure 30, (a) & (c) are closely similar in indentation depth and size at 0.13 seconds. Figure 30 (b) & (d) are taken at 0.18 seconds, and these results indicate a geometrical difference between the FE models due to unspecified dimensions. However, the ROP is almost identical to the research paper.


(a)


(b)


(c)

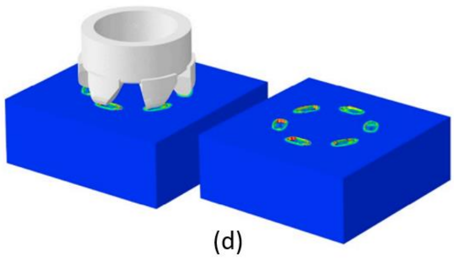
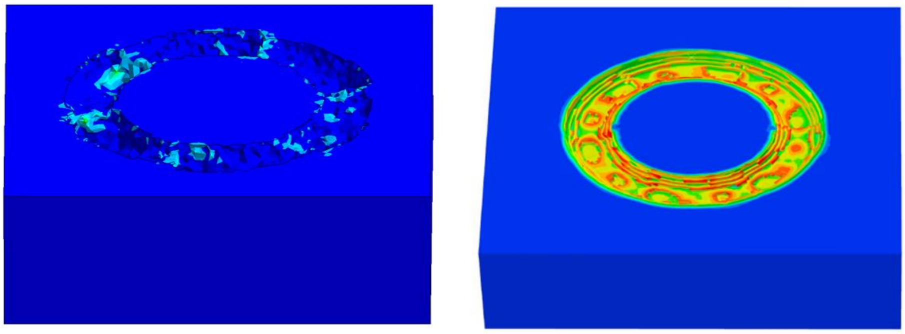

(d)

Figure 30: Comparison between results of research paper and ANSYS explicit dynamics. (a) & (b) are new results, and (c) & (d) Zhang et al. (2020)

Figure 31 below is a more precise comparison between the erosion of rock formations in both ANSYS explicit dynamics and ABAQUS. Cleaner, more homogenous shearing of rock formation can be seen in Figure 31 b). This is likely due to a finer and more refined meshing. This difference in meshing element sizes is a plausible result of differences in penetration. The removal of elements during the simulation results in no stress fields higher than the specified material strength of the given rock formation. The explicit analysis maintained an accurate replication of the ROP of the drill bit at the given times provided in the paper. However, meshing constraints in the ANSYS student version may have resulted in higher ROP at times greater than 0.45 due to larger meshing elements than the meshing shown in the research paper. Residual stress can be seen in Figure 31 (b), while Figure 31 (a) does not. This is likely due to the difference in FEA packages used. Eroded elements are removed after the threshold of the material properties are reached in explicit dynamics; therefore, the model would not display high stress at the bottom of the rock.



(a) (b)

Figure 31: Visual comparison between (a) ANSYS explicit dynamics and (b) Zhang et al. (2020) ABAQUS results

5.4.3 Cantilever Verification Calculations

A simple cantilever FE model was made to simulate the force at an edge of a steel plate with dimensions similar to a single primary blade cutter. This aims to validate the methodology of evaluating the stress applied on the cutters while experiencing torque on the bit. A 550 N force was applied at a 5^{o} angle on 60 (length) × 50 (width) × 11 (thickness) mm plate for verifying the results. A summary of the results is shown in Table 12 below. Complete calculation of cantilever shown in Appendix G – Cantilever Beam Verification Hand Calculations.

Table 12: A summary cantilever verification of results

Parameter	Result
Reaction force	R_{AH} = 47.93 N R_{AY} = 547.9 N
Bending moment	32.6 kN.mm
Moment of inertia	5545.83 mm^4
Maximum stress	-32.43 N/mm^2
Minimum stress	32.263 N/mm^2

The value obtained by the hand calculations (32.3 MPa) is close to the verification model's (37.4 MPa), as described in Figure 32. Beam theory assumptions can explain the 13% difference. In hand calculations, the load is only applied at a point representing the entire surface in the Eulerian beam theory. In contrast, the FEA package applies the load at the entire surface. The difference is slight and can be explained by Eulerian Beam Theory, in which the cross-section cannot change, but when dealing with a thick solid object, it can change. Another explanation for this is the difference between where the load was applied. Ideally, the load should be applied to the entire face, but this is treated as a point load in beam theory.

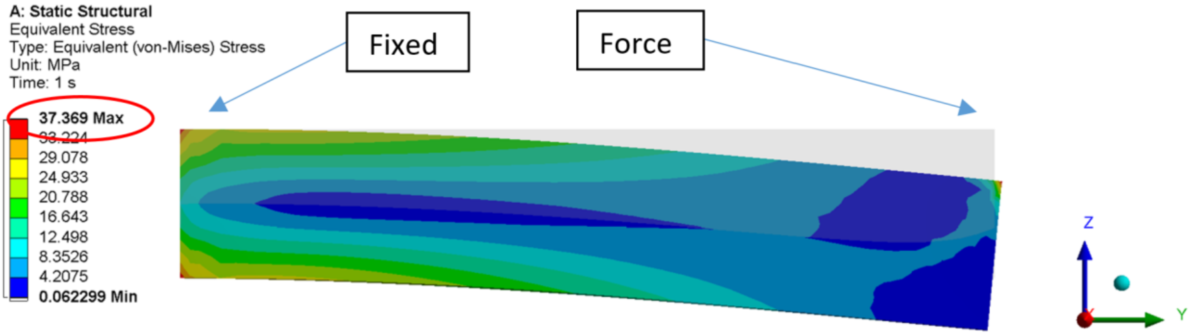


Figure 32: Cantilever stress evaluation

5.5 Conceptual Design

5.5.1 Conceptual Design Approach

Several designs of potential drill bits with PDC inserts were made. An extensive literature review was conducted on recent drill bit technologies and commercially available mining drill bits to determine standard failure modes and issues of existing mineral exploration drill bits. From information gathered in the literature and design features and constraints provided by MinEx, initial concept models were made of the drill bit inserts. Several drill bit designs were made, and a decision-matrix method was used to determine the most suitable design for further FEA static and explicit dynamics testing. Designs focused on addressing common issues of drill bits under medium-hard formation, which reflected on the decision matrix. The design criteria within the selection matrix consist of ROP, service life, ease of design, reliability and meeting design constraints. Table 13 below summarises the design constraints with inputs from MinEx.

Table 13: Design features and requirements/constraints for the design of a drill bit as per correspondence from MinEx

Feature	Requirements & Constraints
Torque input	The maximum torque input is 550 Nm
Weight on bit	Max WOB 800kg. With added percussive force blowing with a maximum energy per blow at 70 Hz, providing 200 Joules per blow (probably more expected energy per blow is around 90-100 J/blow when drilling).
Physical dimensions	The required bore diameter through the bit is a minimum of 25 mm. The required outer overall diameter is 94 mm. Pin size 2-3/8" API REG. Coiled tube wall thickness of 2.7 mm.
Rotational speed	150 RPM
Target rock formations	Shale: 67.5 MPa (UCS) Limestone: 125 MPa (UCS)
Cooling – fluid flow with regards to the drill bit	N/A (out of scope)
Drilling depth	1000 metres

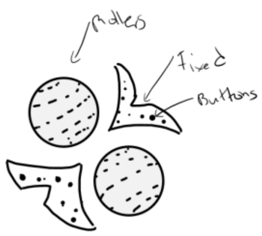
The above constraints aided to formulate a general idea of the design required based on the literature review of different concepts and their limitations. For example, from the above Table 13, the two most constraining features are torque and WOB, which eliminates cutters designs since they require minimal torque of 2450 Nm for a pin size of 2-3/8" (Product Portfolio 2014).

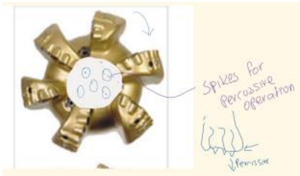
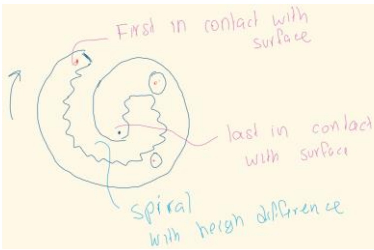
5.5.2 Conceptual Design Selection

Concept design selection was motivated by the design features and constraints defined by MinEx. The literature identified multiple potential concepts, but those were insufficient in operating under the low torque or WOB, limited CTD. Several conceptual designs based on commercially available bits were obtained to select the most suitable design for CTD and were further shortlisted to be presented to MinEx for their inputs.

Table 14 displays the four shortlisted concepts outlining their pros and cons for CTD and medium hard formations. Modifications were suggested on each design for improvement. The preferences, as shown below, are based on our findings from the existing design in the literature. In addition, eight initially considered designs are outlined in Appendix C – Alternative Drill Bit Concepts. These designs were discarded due to their inability to meet the design constraints and requirements.

Table 14: A summary of final concepts for evaluation

	Concept	Pros	Cons	Modifications on the concept
1	***Hybrid drill bit***  *(Niu et al. 2019)*  	- PDC and tricone in one bit provides an increase in ROP - Reduced torque requirements in comparison to standalone designs - Increased impact resistance	- Complicated design - Shorter bit life (bearing failure) - Inadequate cooling - Limited cutting evacuation	- Reduce the overall size to suit coiled tube drilling - Decrease the size of the drag bit and increase the size of rollers - Two rollers instead of three to increase the overall size of roller cones

2	***Direct impact PDC drill bit***  *(adapted from Niu et al. 2019)*	- Drill bit buttons reduce torque-on-bit (TOB) through a percussive operation - Higher ROP - Simple design - Good cooling	- Spikes may erode very fast, would require geometry alteration - Requires very high percussive energy	- Alternate geometry of the buttons - Modify cutting angles and reduce overall size.
3	***Spiral drill bit***  	- Good cooling and lubrication - Good cutting evacuation - Increased bit life - Simple design	- It relies mainly on the shearing operation - May not fit in desired formations - May require increased torque	- Increase the thickness of the spiral - Cutting surface change from 'saw' to inserts/buttons - Additional buttons for percussion - Add roller cutters along the wall
4	***PDC cutters drill bit***  *(adapted from Niu et al. 2019)*  *(Split Blade 2018)*	- Increased ROP - Faster cutting evacuation - Good lubrication flow - Faster evacuation of cuttings	- Buttons can detach - Requires high torque in harder formations	- Alter angles of contact points - The inner cutter rotates in the opposite direction of the outer bit - Modify bit insert geometry - Reduce cutting area size between outer diameter-gap of the cutter - Reduce back-rake angle

Hybrid Drill Bit

Size constraints were a significant concern as the overall diameter of the drill bit must fit within 94mm. This was the significant factor for choosing two rollers and four cutters. In addition, by having two roller cones, their physical dimensions can be larger, resulting in being mounted on larger bearings that can withstand higher stresses and increase the drill bit's life. Larger roller cones also allow larger roller cone inserts, extending a drill bit's life. Moreover, roller cones enable to achieve lower operational torque in comparison to conventional PDC drill bits. In simple terms, roller cones crush the rock, which decreases the amount of torque for the shearing and cutting operations.

Direct Impact PDC Drill Bit

The direct impact drill bit was the second concept suggested by the project team. This concept consists of the traditional PDC cutters and inserts, but it also has spikes to crush the rock with the percussive operation energy. The traditional PDC drill bits use a transverse shearing motion over conventional crushing on a rock. This concept combines rock crushing action with its spikes and the shearing action achieved by cutters. Therefore, the button on the drill bit facilitates lower torque on the bit through percussive operation, and higher ROP is achieved. The drawback of such a design is that it requires very high percussive energy, and the spikes erode rapidly due to the constant crushing action.

Spiral Drill Bit

Spiral drill bit was not found in the reviewed literature but a concept brainstormed by the project team. The idea behind this concept is to use the spiral motion to shear the rock. The additional idea was to add a flat roller cone along the spiral walls to increase the ROP by fragmenting the rock. One of the main drawbacks of the spiral concept is that it does not fit design constraints in target formations and may require high torque to operate. Although the spiral concept could fit well within the 94mm overall diameter limit and ease of design, the concept was eliminated during the selection matrix process due to the low score.

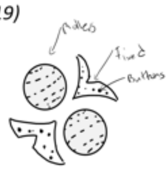
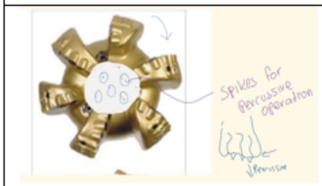
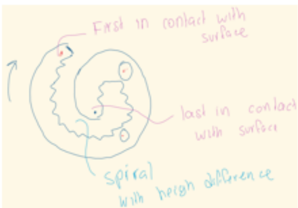
PDC Cutters Drill Bit

Optimal PDC arrangement can enhance the overall performance of PDC drill bits. The separation of blades with distinct inner and outer sections allows for efficient rock chip evacuations. The addition of optimised fluid channels further increases the ROP of the drill bit. An increased back-rake and side rake angles of the inner blades provides reduced PDC cutter wear, increasing the PDC bit's longevity. While this option is viable for its effective ROP, the required torque to shear rock formations dramatically exceeds the torque constraints of CTD operations.

5.5.3 Final Concept Selection

Table 15 describes the scoring of the concepts and their selection according to five criteria: ROP, service life, ease of design, reliability and meeting constraints. The criteria were scored on a scale of 1-20 based on importance rating. The importance ratings to each selection criterion were assigned based on engineering judgment and each criterion's importance to the project's desired aim. For instance, 'Meets Constraints' was assigned an importance rating of 20, as it holds a higher value than the rest of the parameters. The selected concept was the hybrid drill bit with the highest final score. Therefore, this design was used as the basis for the next stage of CAD and FE modelling.

Table 15: Concept selection matrix

	ROP	Service Life	Ease of Design	Reliability	Meets Constraints		
	Importance	Importance	Importance	Importance	Importance		
(Higher is better)	10	8	6	7.5	20		
	Rating	Rating	Rating	Rating	Rating	Raw Score	Final Score
 *(Niu et al. 2019)* 	9	5	1	4	20	39	566
 *Image adapted from (Niu et al. 2019)*	6	2	8	3	4	23	226.5
	7	8	2	6	10	33	391
 *Image adapted from (Niu et al. 2019)*	9	6	8	7	4	34	318.5

5.6 Drill Bit Design

CAD design was based on the initial concepts with changes to the cutters' geometry. The chosen concept was the hybrid drill bit with two roller cones and two primary and secondary cutters. The literature identified this concept as successful in operating under low torque and WOB and providing high ROP with low energy requirements compared to a PDC drill bit that requires high torque and a roller cone drill bit that requires high WOB. The hybrid combination provides the benefits of both drill bit types considering the design features and constraints.

The initial concept was "swept" with highly curved cutter geometry and allowed limited and inconsistent PDC inserts, which are crucial for ROP. The other issue identified with this concept is the allowable size of the roller cones. Due to the high curvature of the cutters, it created limited space for the cones if primary and secondary cutters were selected. Therefore, this concept was declined in the early stages.

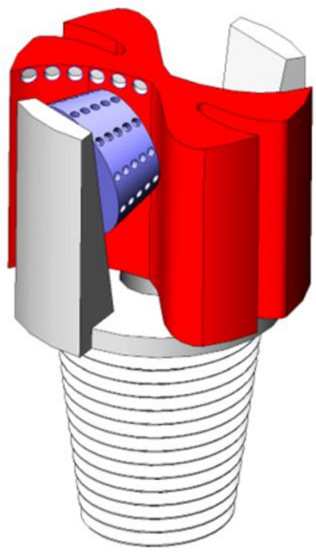


Figure 33: Swept cutters concept

The next concept was similar in functionality but had toothed cutters geometry. The idea behind this concept was to allow interchangeable geometry for PDC inserts placement. However, it allowed only a limited number of PDC inserts on both the primary and secondary cutters, reducing the ROP and increasing the required torque to operate. The potential solution to the number of PDC inserts is to reduce the contact area of each tooth, but that would require a smaller diameter PDC and, as a result, reduced drill bit's operational life as the contact area decreases. Moreover, the stress on the PDC increases and the rock fracture relies more on the PDC, which requires higher torque.

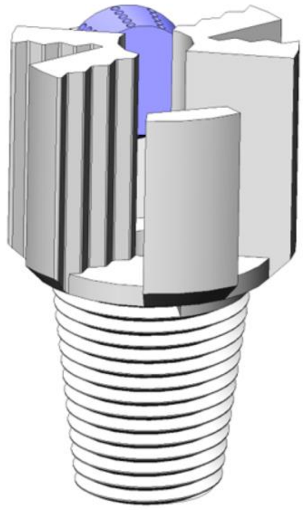


Figure 34: Toothed cutters concept

The last two concepts suggested, twisted cutters and straight cutters, offered more uniform spacing between the PDC inserts and their size. In addition, the straight cutters and the twisted concepts allowed larger dimensions for the roller cones. As a result, larger bearing for longer operation life and capacity to withstand higher stresses. Larger roller cones also allow mounting larger roller cones inserts and increase their number. The more roller cone inserts are present, the less torque is required since the inserts crush the rock before the cutters are engaged.

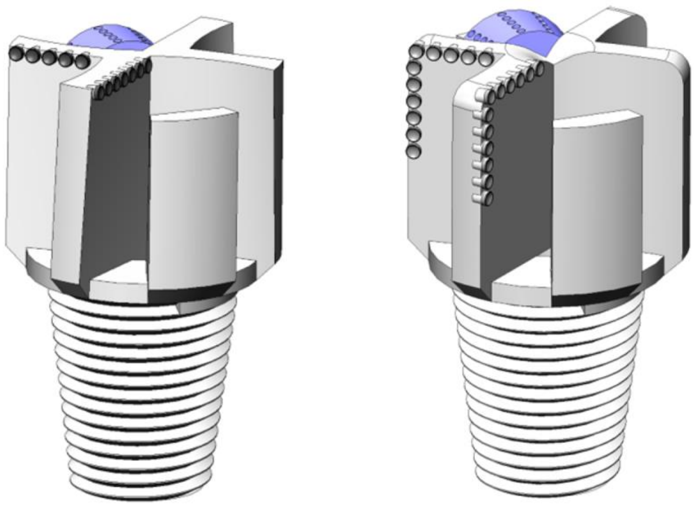


Figure 35: Twisted cutters (left) and straight cutters (right)

5.6.1 FEA of Drill Bit Design Approach

Finite element analysis through the ANSYS Simulation package was utilised to determine the static stresses of the drill-bit design and make any necessary alterations to the design for optimal performance. ANSYS FEA package was also used for explicit dynamics to determine the ROP of the complete design shown in the final design section. This is a common approach to assessing designs' feasibility and analysing interactions between the drill bit and rock formations (Dong & Chen 2018; Kong, Liang & Zhang 2017). The FEA consisted of the drill bit inserts and the complete drill bit design. Simplified CAD models were made in SOLIDWORKS to ease and accelerate the process of FEA. FEA of the complete design was performed to analyse its overall performance on limestone rock formations. The analysis consisted of static analysis, dynamic analysis with its interaction of the rock formation. Full design FEA of percussive drill bit has previously been utilised in numerous studies to determine its interaction between rock formations, the drill bits rate of penetration and stress concentrations for excessive wear (Cirimello et al. 2018; Dong & Chen 2018; Lazizjon & Muhriddin 2020; Saksala et al. 2018; Shi, Zhu & Luo 2017).

5.6.2 Selected Design Results

FEA on both drill bits types was completed to estimate the stress regions and evaluate if the maximum stress does not exceed the maximum allowed stress for the 8720 alloy steel material. Those analyses are part of the evaluation made to assess the normal stress on the rock in the CAD Design section. The FEA setup was set identical in terms of mesh, WOB, and configuration of PDC inserts. The scales on the left of Figures 38 and 39 below are adjusted to provide a better visual comparison of the stresses. Figure 36 shows the stress distribution along the straight. It can be seen that the maximum stress evaluated was approximately 380 MPa. However, these high stresses are due to the sharp edges of the simplified FE model without features and would not be present in the final design. Therefore a more reasonable maximum stress would be approximately 200 MPa, as seen in the figure below.

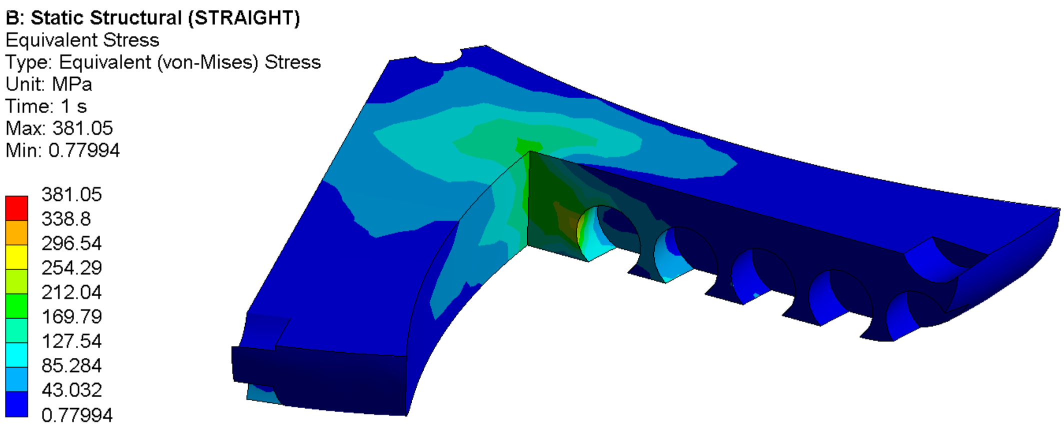


Figure 36: Evaluating stress using FEA on straight cutter's simplified model

Figure 37 shows the stress distribution along with the twisted cutters. In both cases, the high-stress regions result in sharp edges caused by singularities in sharp edges, as previously mentioned in the straight cutters. The approximate maximum stress of 150 MPa was observed in Figure 37, 25% less than the straight cutters. The stress concentration can be ignored due to singularities in sharp geometry. Since the focus of this project is on increased ROP rather than drill bit life and following the stress on rock results in the CAD Design section, the straight cutters selected to progress with to the final design. Moreover, the maximum stresses evaluated are lower than the maximum allowed yield stress of the cutters' material.

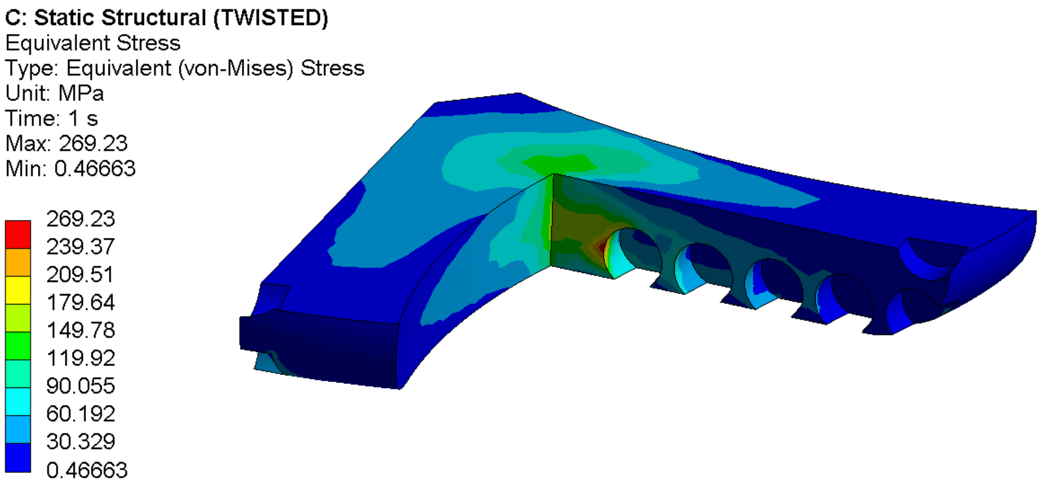


Figure 37: Evaluating stress using FEA on twisted cutter's simplified model

Since the two concepts fulfilled the design constraints and requirements, the concepts were tested under FEA to evaluate their stress distribution. Due to software limitations and to reduce the solving time, a reduced size model was used to evaluate a half rock. The FEA configuration was set identical in terms of boundary conditions and meshing. For this study, limestone was selected as the rock due to its stronger nature with compressive strength of 110 MPa, compared to shale with compressive strength of 80 MPa.

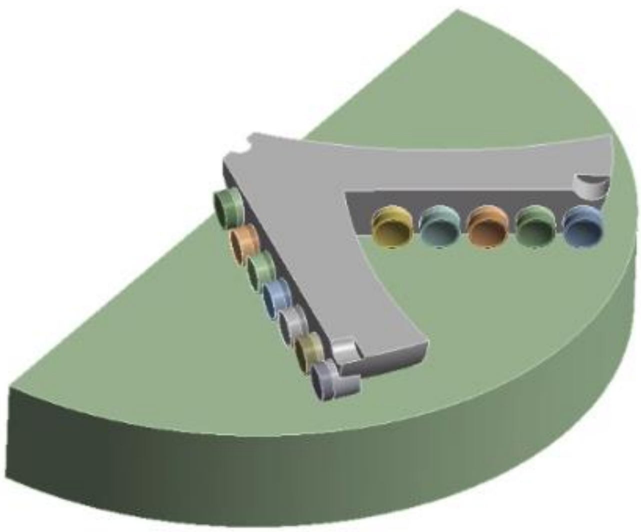


Figure 38: Setup configuration for evaluating the normal stress on the rock

Figure 39 shows the normal stress on the rock with straight cutters. The maximum value is 104 MPa.

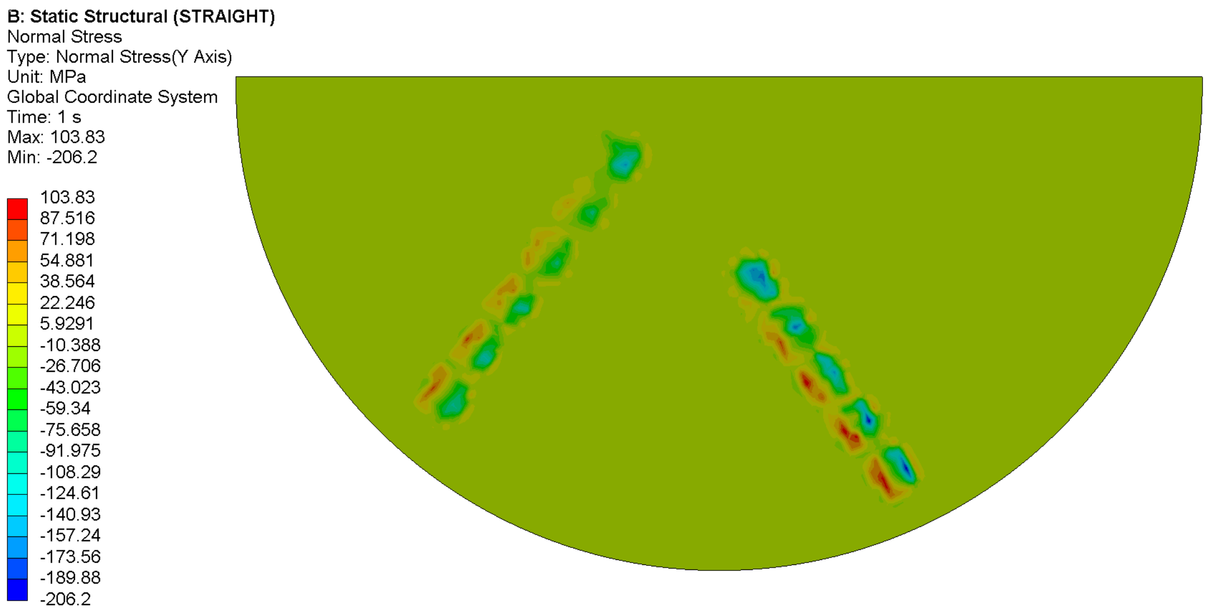


Figure 39: Evaluating normal stress on limestone rock with straight cutters

Figure 40 shows the normal stress on the rock resulting from the twisted cutters. The maximum stress value recorded is 75 MPa.

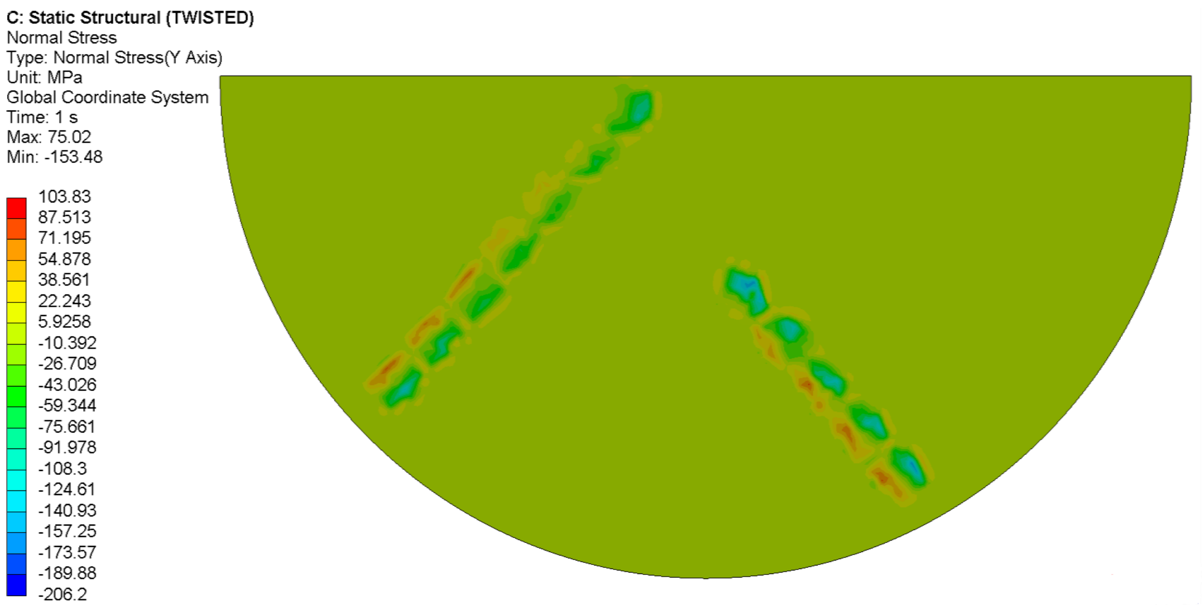


Figure 40: Evaluating normal stress on limestone rock with twisted cutters

From the comparisons above, the normal stress resulting on the rock when tested with straight cutters was higher by 28%. Since the focus of this project was increased ROP, the straight cutters concept was selected for the final design. The stress resulting from straight cutters is sufficient to reach the maximum compressive strength of limestone. In addition, with the aid of percussive shocks, the rock is highly likely to break under the worst-case load scenario. The selected straight cutters design is shown in Figure 41, with primary and secondary cutters blades and their rotational direction.

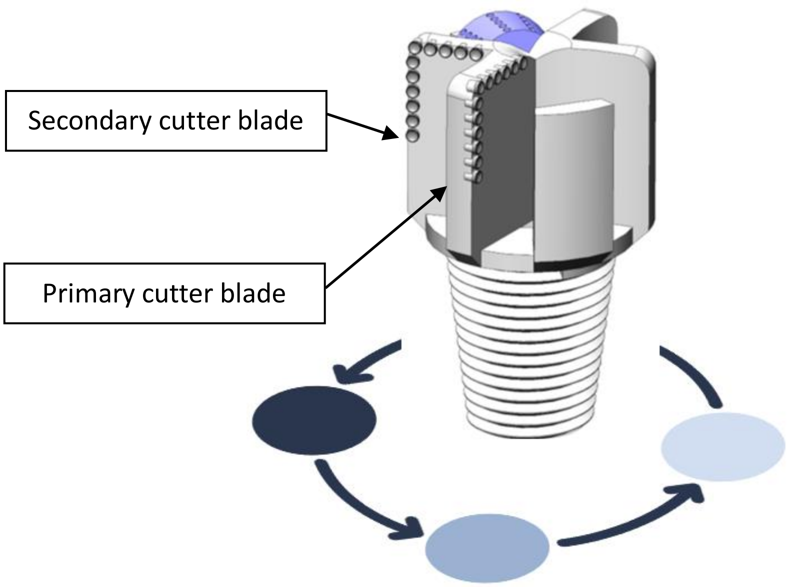


Figure 41: Selected straight cutters concept based on FEA results with the rotational direction

5.7 Inserts Design

PDC inserts were designed with 5 mm length overall, leaving the base with 3.5 mm and the PDC with a layer of 1.5 mm. All the five discussed concepts were designed for the final selection.

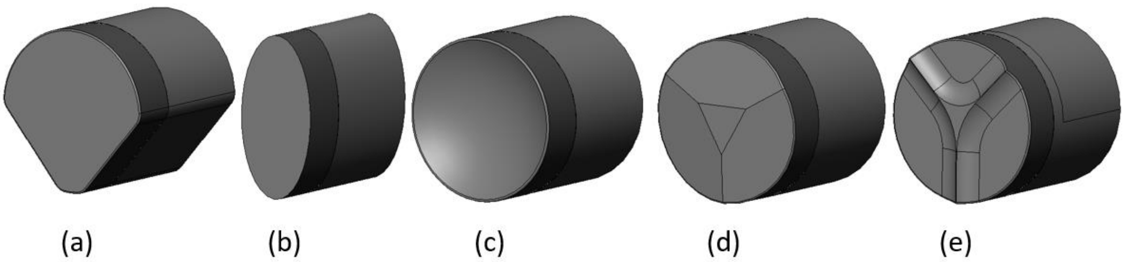


Figure 42: PDC inserts; (a) Fang, (b) Oval, (c) Scoop, (d) Three-Ridged, (e) Triforce

Further analysis on selecting an appropriate back rake angle is discussed in the FEA section. The roller cone insert was designed with a 3 mm diameter and had the geometry identified in the literature for medium-hard formations. Figure 43 shows the roller cone insert used in the design and assembled with the roller cones.

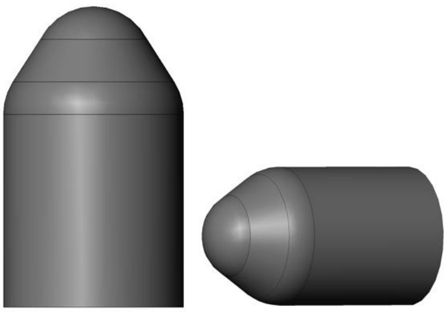


Figure 43: Geometry of a roller cone tungsten carbide insert

For the assembly process of the design, the PDC inserts are designed to be brazed into the drill bit. For this, a tight clearance was left to prevent dislocation during the brazing process. Roller cone inserts are designed to be shrink fit in the roller cone and sintered. For the CAD stage, the design focuses on general geometry with minimal features. The final features and drill bit final design with the selected angles of the PDC inserts and their types are presented in the final design section.

5.7.1 FEA of PDC Inserts Approach

The bit-rock interaction of various geometric button inserts was analysed to determine the most effective back-rake angle. Similar methods have been utilised to verify optimal PDC cutter structures and failure analysis of inserts (Benavides-Serrano et al. 2019; Kong, Liang & Zhang 2017; Pryhorovska, Chaplinskiy & Kudriavtsev 2015). The analysis consists of static-structural analysis and explicit dynamic analysis.

FEA models of multiple commercially available and researched designs were made to determine an optimum angle for each PDC cutter insert. Back-rake angles of 1,3, 5 and 10 degrees were chosen for a static-structural analysis in ANSYS. Figure 44 is an example of a singular PDC cutter consisting of its tungsten carbide base, and PDC were assembled at a specified angle with the rock. Limestone rock properties were chosen as this is one of the target formations for the design of this drill bit. Limestone possesses higher UCS than shale. Therefore, it will be the primary rock formation used in FEA. The block was dimensioned at 8 mm across by 25 mm wide and a 25 mm depth. A downwards force was applied to the PDC to simulate the WOB. Another force was applied on the back surface of the PDC for the constant torque provided as the drill bit rotates.

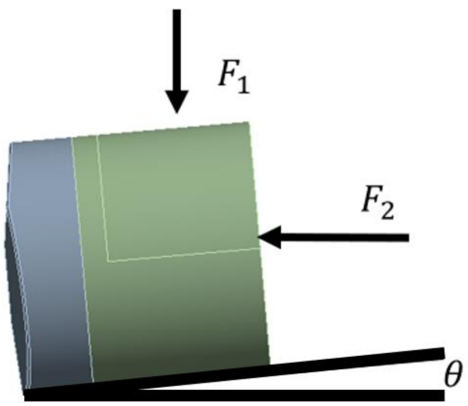


Figure 44: Constant forces and variable angles applied on PDC

Figure 45 visually illustrates the static analysis setup. Due to the symmetrical nature of the model, it was split along the z-axis to reduce FEA runtime and allow for additional mesh refinement at areas of interest, such as the contact regions between the PDC and limestone. The limestone block is fixed on the bottom. A circular section of 4 mm at the rock's surface finely meshed where the expected interaction between the PDC cutter occurred. The stresses were obtained on both the rock and PDC.

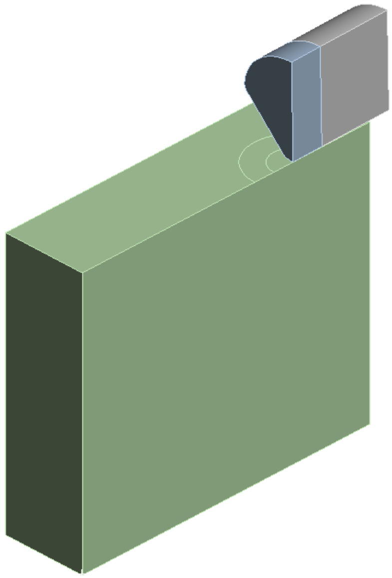


Figure 45: PDC and limestone static analysis simplified model

A Mesh independence study was conducted on a number of the FEA setups to ensure the results did not change due to the number of nodes in the mesh. The graph below in Figure 46 shows the impact of mesh size and penetration depth of the PDC cutter. Approximately 74,000 nodes were required to ensure the mesh size was independent of the results obtained.

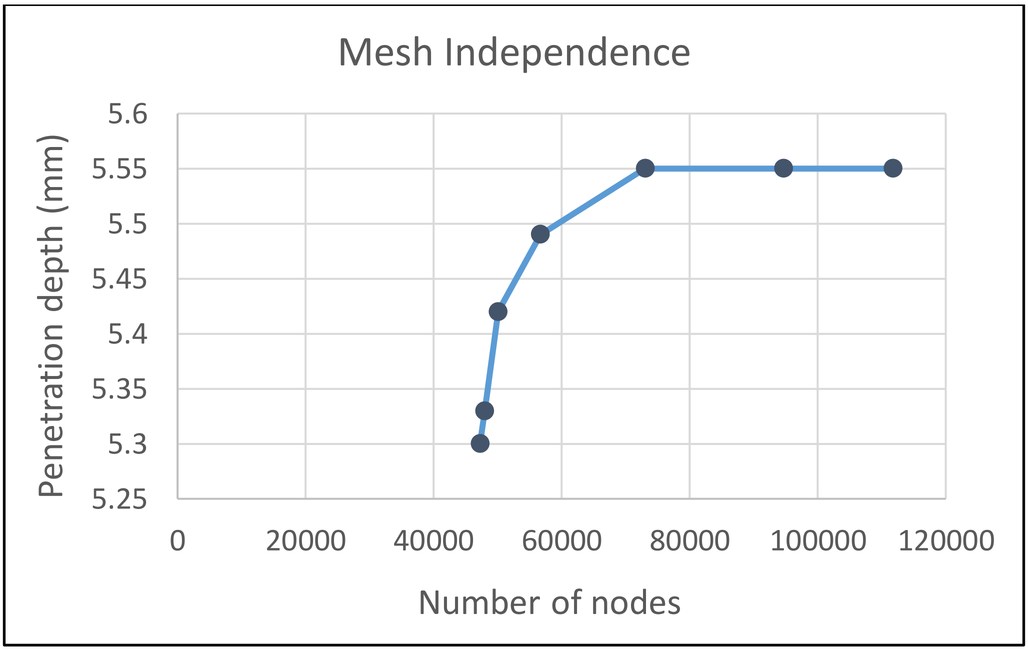


Figure 46: Three ridged PDC cutter setup at 10 degrees back-rake-angle

5.7.2 FEA of PDC Inserts Results

A series of FE analyses were undertaken to compare design features and inform the final bit design. FEA of both fang and three ridged PDC cutters were analysed to determine each PDC geometry's most optimal back-rake angle. The largest penetration depth in the YZ plane would be considered the most optimal back-rake angle for ROP as it considers both the WOB and the maximum torque at the most outer drill bit. A range of back-rake angles of 1,3,5, 10, 15 & 25 degrees was tested to determine the best angle. The type of rock used with its mechanical properties is limestone, which is more challenging to fracture than shale, the other target rock formation.

Figure 47 below illustrates the difference between 1 and 10 degrees back rake angles on the three-ridged PDC cutter. The colour scale has been set to display regions of the limestone which experience a force greater than the UCS of the material to be red and any area unaffected to be green. Figure 47 (a) shows that the stresses below the contact region are larger than (b). This is likely due to the larger contact region between the PDC and limestone from such a minor angle. Figure 47 (b) showed a penetration depth in regions below the Y-axis and the Z direction.

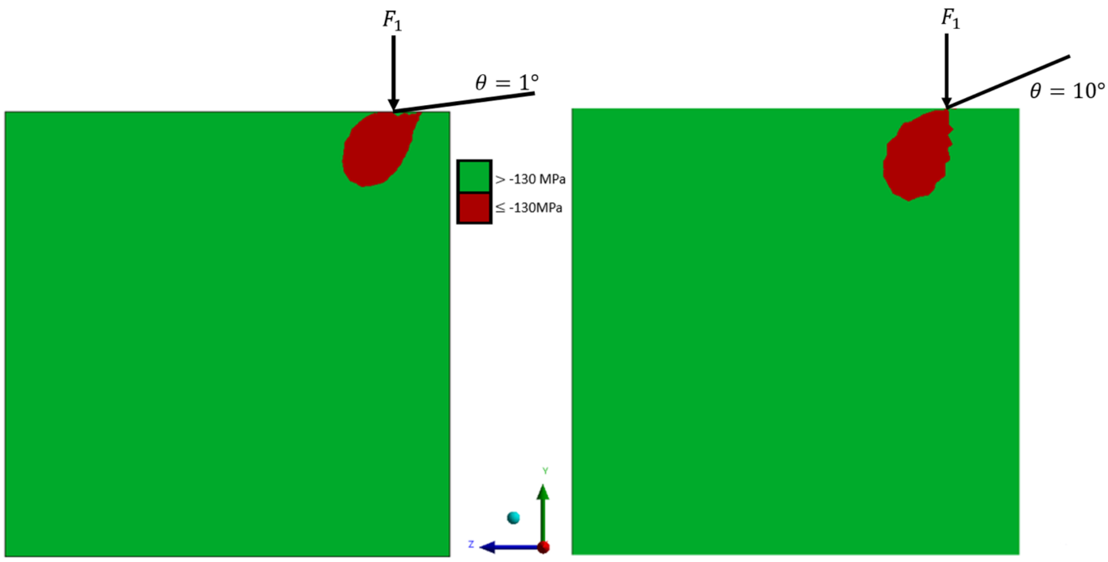


Figure 47: Stress on limestone with PDC (a) back-rake angle 1 degree & (b) back-rake angle 10 degrees

Figure 48 displays the penetration depth for both the fang and three-ridged PDC at different back-rake angles. A back-rake angle of 10 degrees was shown to have a more significant impact on the limestone than lower back-rake angles with a penetration depth at 5.62 mm for the fang and 5.48 mm for the three-ridged PDC. The penetration depth was considered at the YZ plane as this is affected by both the WOB and TOB. The analysis indicates a linear trend of increasing penetration depth as the back-rake-angle is increased. However, further analysis with back rake angles beyond 10 degrees resulted in pivot errors producing an FEA that could not be run. This indicates that the static analysis for initial penetration depth cannot be obtained at greater than 15 degrees. A probable cause for this is the large force applied at the back of the PDC cutter, equivalent to the maximum torque applied. The WOB applied to a singular PDC cutter is not large enough to penetrate the rock surface at higher back rake angles, resulting in pivot errors.

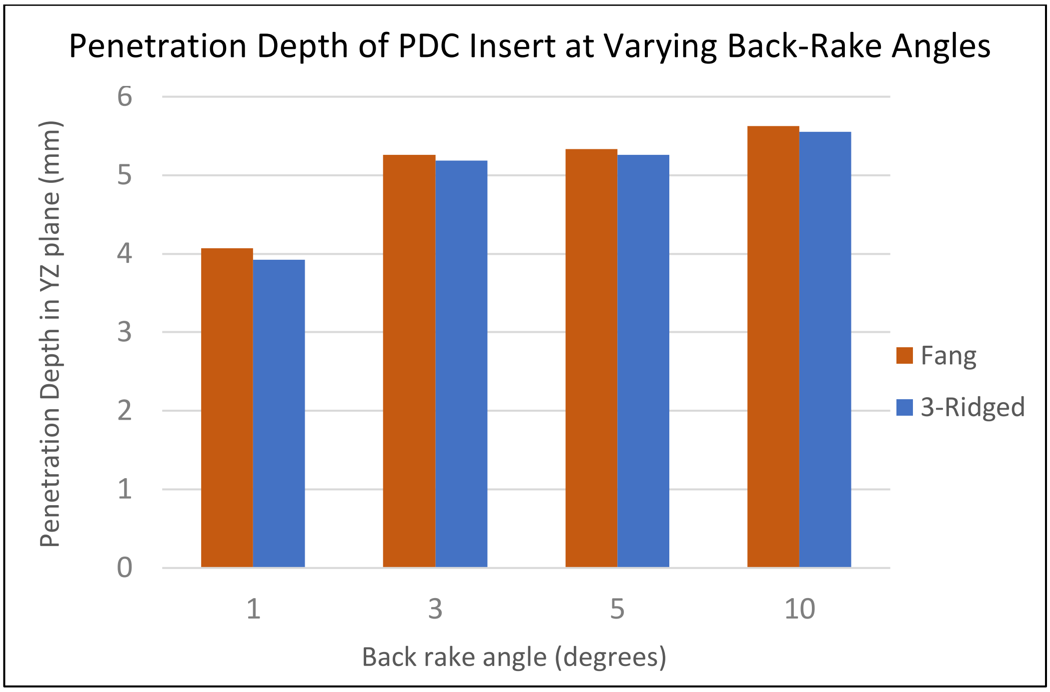


Figure 48: Summary of PDC insert penetration depths at different back-rake angles

6. Final Design and Results

The final design of the project was evolved from the initial concept as shown in Figure 49. It is of a hybrid drill bit type with four cutters and two roller cones. The main idea behind this concept was to incorporate the advantages of both the PDC and the roller cone drill bit to achieve high ROP with low TOB. The drill bit body has an internal bore size of 25 mm to allow drilling fluid flow. Figure 49 shows the evolution of the designs from initial concepts to the final featured design. The initial design contained the most basic features of a hybrid drill bit, which was further refined once the physical constraints were visually demonstrated.

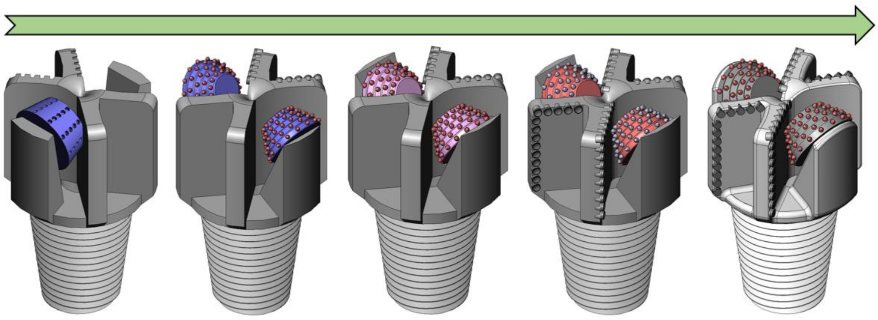


Figure 49: Hybrid dual-cone final design evolution from left to right

6.1 Model of the Final Design

The final design model, as shown in Figure 50, has complete geometrical features. The fillet and other features were designed to reduce stress concentration areas and the torque required by avoiding sharp geometry interacting with downhole formations. The pin size is 2-3/8" API REG according to design requirements. The spacing between the cutters was designed to remove fragmented particles up the hole and allow drilling fluid's circular flow to cool the drill bit's working components and maintain the ROP while drilling over time. The centre notch was designed to distribute fluid flow in the case of inclined drilling scenarios.

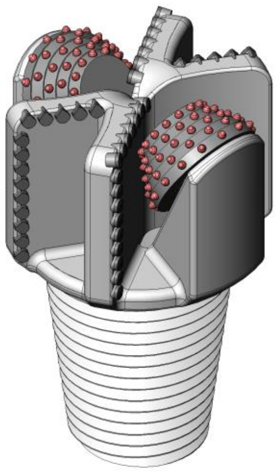


Figure 50: Final design isometric view – dual-cone hybrid drill bit

The straight cutters design allows interchangeable PDC inserts interaction with the rock by changing the placement of the PDC between the primary and secondary cutters. In simple words, some formation areas remain intact due to spacing between the PDC inserts when the primary cutter's PDC inserts complete the interaction with the rock. In order to overcome this issue, the secondary PDC insert is placed in between the primary PDC inserts when a rotation motion progresses. The secondary PDC inserts complete the crushing action, thus, increase the cutting efficiency and the ROP. The interchangeable placement also allows efficient particle evacuation and reduce the risk of "stick-slip", a scenario where a drill bit is stagnated due to accumulation of debris.

Figure 51 shows a top section view of the drill bit design with the middle clearance hole diameter of 25 mm, allowing fluid flow from the CT to help cooling and particle evacuation. The fluid dynamics of the design with the interaction of particulate matter and clearance of the borehole was not considered for this project.

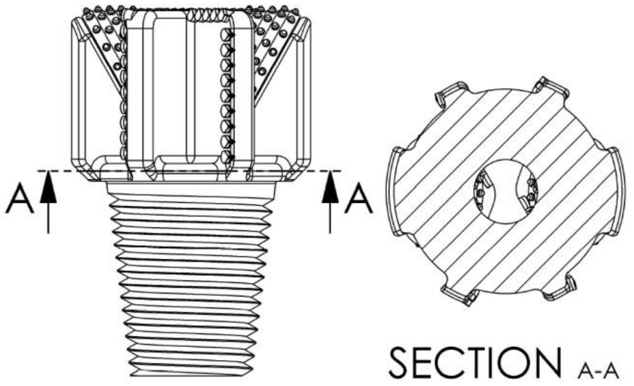


Figure 51: Straight cutters top section view of the centre 25 mm drill bit bore diameter

Figure 52 below shows the cross-section of the roller cones, where the bearing system resides. The bearings were housed in the roller cones cut-out sections, while additional fluid channels such as the lubricant reservoir were not included in this design as it is not within the scope. Cooling channels were also out of scope for this project, but the drill bit body allows those to be considered.

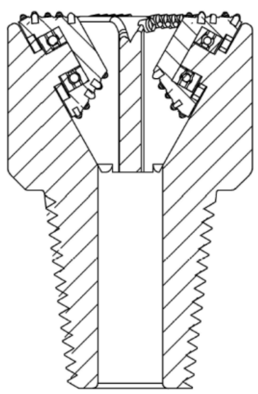


Figure 52: Hybrid dual-cone drill bit – section view

The ROP performance impact of the side-rake angle has a lower overall impact on the rate of penetration compared to the back-rake angle for the design. Therefore, a focus on the optimal back-rake angle for the designs was decided.

Three views of the final design are shown in Figure 53 below. The roller cones were mounted on a rounded-edge bit leg. The bit leg was designed with sufficient volume and size to contain cooling channels and lubrication reservoirs to extend bearings' operational life for future work.

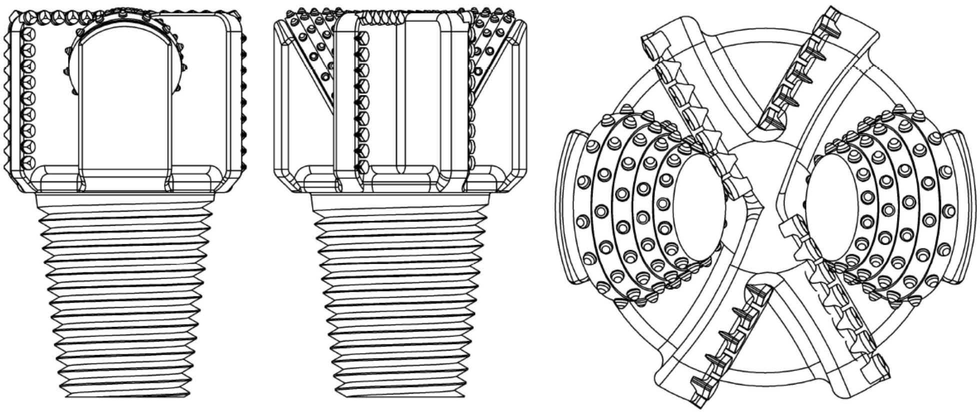


Figure 53: Hybrid dual-cone final design - front, right, and top views

An elevated clearance of 1 mm between the peak height of roller inserts and PDC cutters was made. This ensures that the roller inserts interacted with the rock formations first, resulting in crushed rock segmentations. Therefore, reduce the required force for the PDC cutters to shear the rock formation, and reduce the torque required to complete the shearing by the cutters. A 1 mm gap provided a WOB distribution of approximately 60% between the roller inserts and 40% on PDC cutters.

The roller cones are designed to the maximum allowable size without interfering with the cutters to include larger bearings and maximise the surface area to contain a large spread of roller cone inserts and individual sizes.

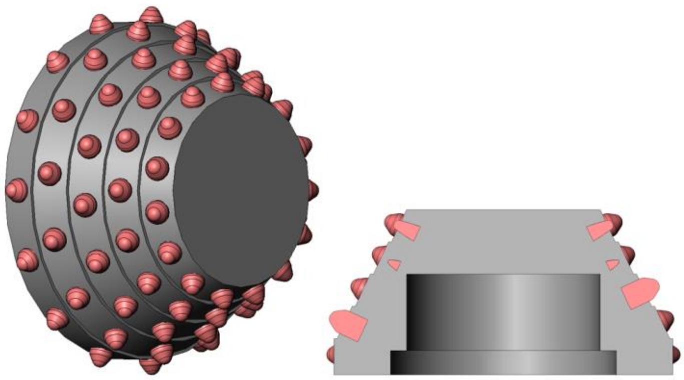


Figure 54: Roller cone with inserts

The roller cones have two thrust bearings: roller and ball. The roller cone consists of five stages, containing 3 mm diameter tungsten carbide inserts spaced equally around the perimeter. A large number of inserts allow a more efficient stress distribution and compensate for the relatively small insert diameter. The roller cones were designed with five stages to utilise the limited distance between the drill bit leg and the cutters and prevent large rock fragments from being jammed while the drill bit rotates. The largest possible cones also allow having larger bearings with a higher factor of safety and the ability to withstand high loads. The exploded view of the roller cones assembly is shown in Figure 55 below.

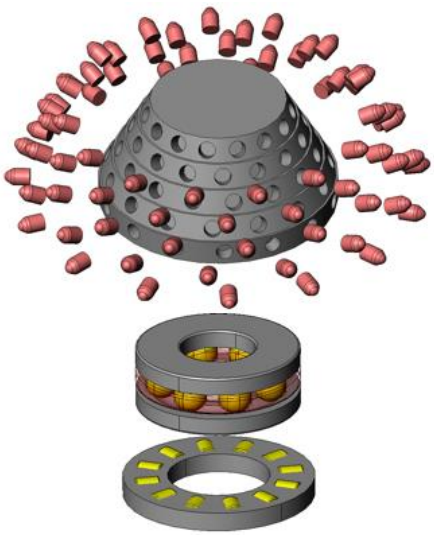


Figure 55: Exploded view of roller cone components

The final design contains two types of PDC inserts, fang and three-ridged. The primary PDC inserts are the three-ridged, and the secondary is the fang. The reason for having two different PDC inserts is to compensate for the spacing between the primary cutters when it completes the rotational motion on the rock. The geometry of the fang was selected due to its sharp geometry and to fit in between the primary three-ridged inserts and leave no surface area of the rock intact. Both mounted with a back rake angle of 10 degrees as it was shown to be the best in terms of penetration depth. The PDC inserts are mounted with different horizontal spacing between the primary and the secondary cutters. This allows the secondary cutter PDC to fragment regions out of contact with the primary cutters due to horizontal spacing.

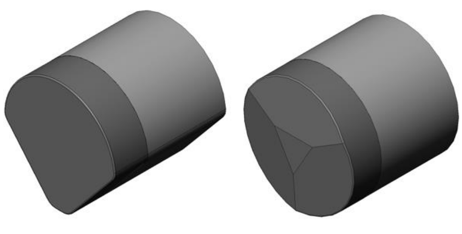


Figure 56: PDC inserts – fang (left) and three-ridged (right)

The overhang distance of 1 mm was designed for higher efficiency in WOB distribution between the roller cones and the PDC inserts, as shown in Figure 57 below.

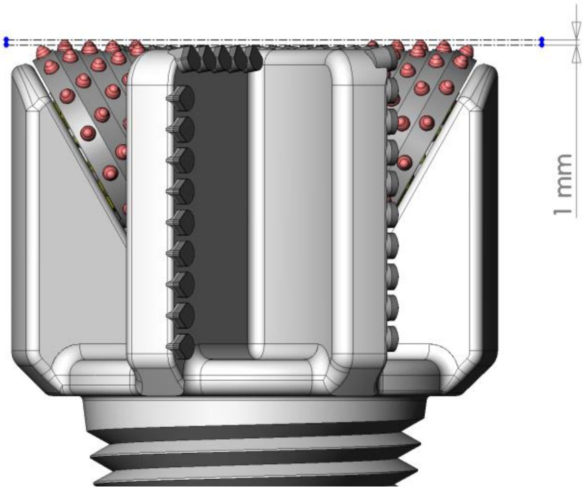


Figure 57: Overhand distance between roller cone inserts and PDC units

The final design drawing of the dual cone hybrid drill bit with BOM is described in Figure 58 below. Further evaluation of the drill bit was done under explicit dynamics FEA to evaluate its penetration performance.

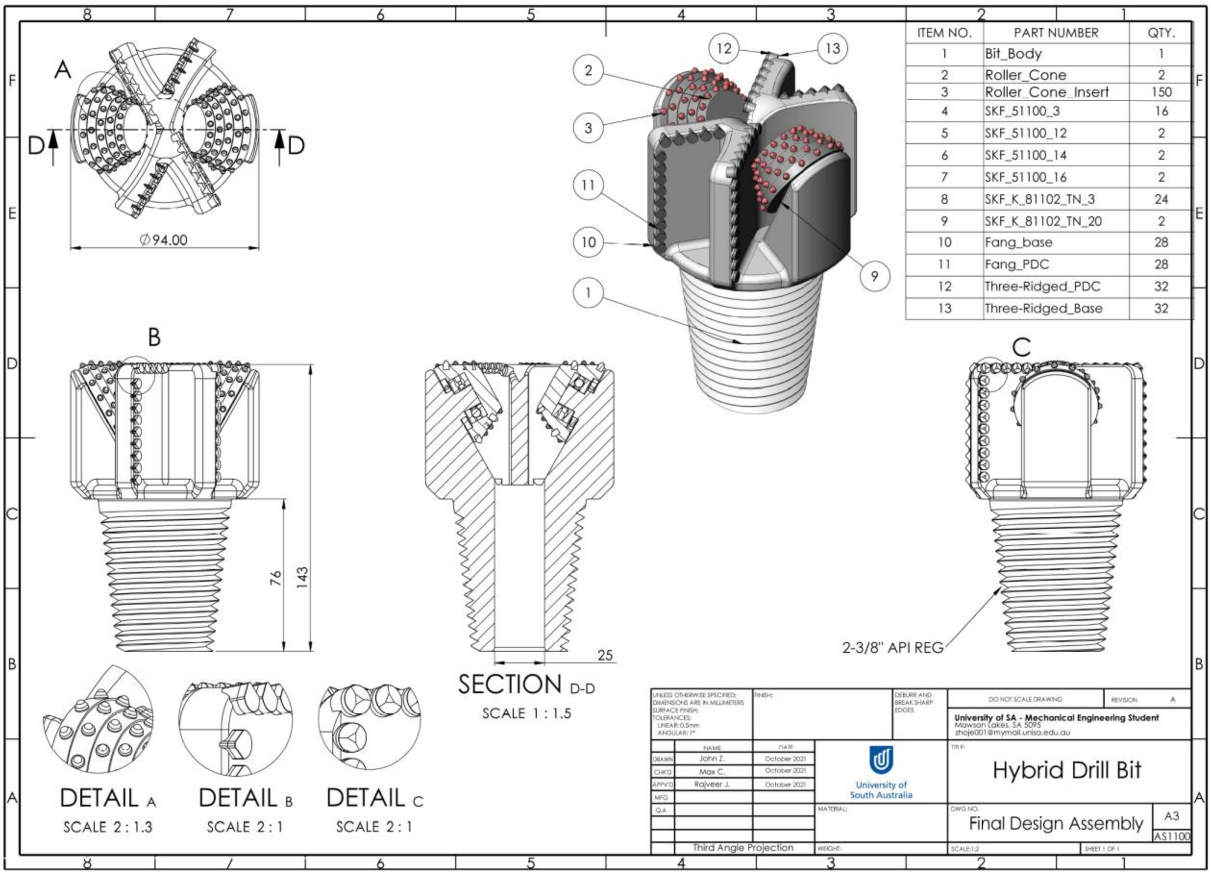


Figure 58: Hybrid dual-cone drill bit - assembly drawing with BOM

6.2 Explicit Dynamics

An explicit dynamics analysis of the complete model design was set up to simulate the drill bit's use in operating conditions. The explicit dynamics of the verification model shown in Section 5.4.2 Verification Model Results was used to simulate the boundary conditions for the full design accurately. However, the ROP of both models cannot be compared due to different WOB and rotational velocity. An 8750N downwards force was applied on top of the bit, along with a 150 RPM rotational velocity. An assumption has been made that the rock formation consists of only one particular rock type. The rock formation was set with limestone properties and fixed at the bottom. Figure 59 shows the cylindrical rock model with a thickness of 40 mm and an outer diameter of 160 mm. A frictional coefficient of 0.4 was set for contacts between the PDC and limestone. A fine meshing region of 100 mm diameter with the contact surface between the PDC and limestone was set at 1 mm. The side PDC cutters and thread were removed to reduce the required meshing nodes/elements.

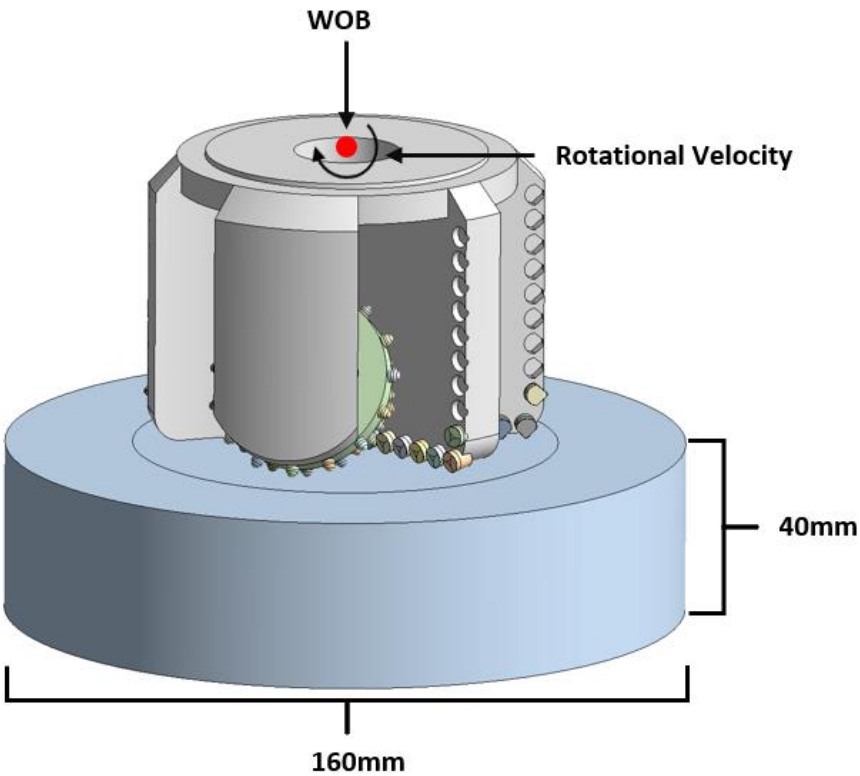


Figure 59: An overview of the explicit dynamics set-up of the final design

Figure 60 below shows the initial rock breaking stages that occurred in the explicit dynamics. As previously mentioned, the 1mm overhang distance between the roller cone inserts and PDC can be seen in Figure 60 part (a). The initial indentations of the limestone from the 1 mm overhang reduced the torque required for the PDC cutters to shear the rock. As the drill bit continues, shown in Figure 60 part (b), the PDC cutters begin to contact the limestone. Figure 60 part (c) shows the rock breakage due to the WOB. It shows the initial PDC cutters and roller inserts effect on the limestone. Figure 60, part (d) displays the initial rotation of the drill bit. The outlined stresses just behind the PDC cutters have not exceeded the UCS of limestone as it is a flat surface. The limestone will begin to remove them as it continues to rotate.

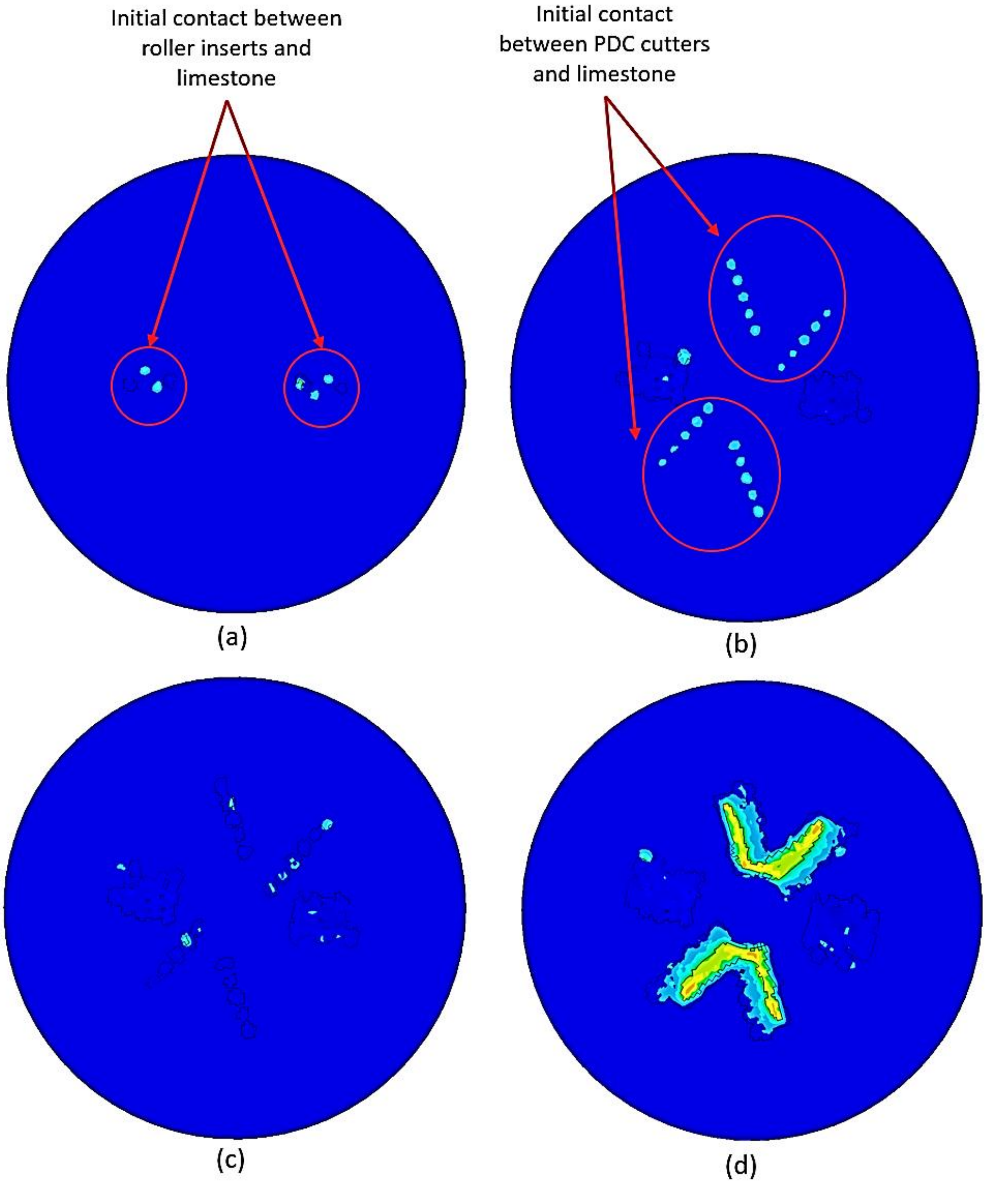


Figure 60: Initial stages of the explicit dynamics of the full model and its interaction with limestone. (a) roller cones first contact, (b) PDC initial contact, (c) WOB begins to fracture the limestone on all contacts, (d) rotation of the bit begins

Figure 61 below shows the penetration depth of the full design drill bit after one full revolution. The deepest penetrations on the rock reached approximately 6 mm, while the centre remained untouched due to the geometrical shape of the drill bit body. Several rotations would be required before rock breakage can occur in the centre. With an approximate depth known, an estimated ROP can be calculated. A rotational speed of 150 RPM, a penetration depth of 6 mm x 150 = 900 mm per minute.

Therefore the rate of penetration is estimated to be 54 metres per hour. In comparison to the average rate of penetration of 15 metres per hour of the drilling experiments conducted by MinEx with the RoXplorer, the dual cone hybrid drill bit provides approximately three times higher ROP as evaluated from explicit dynamics simulation. The estimated rate of penetration does not consider the transition between different rock formations with varying UCS. Critical performance factors such as thermal loads, wear of bit and fluid particle evacuation were out of scope for this project, which may impact the rate of penetration.

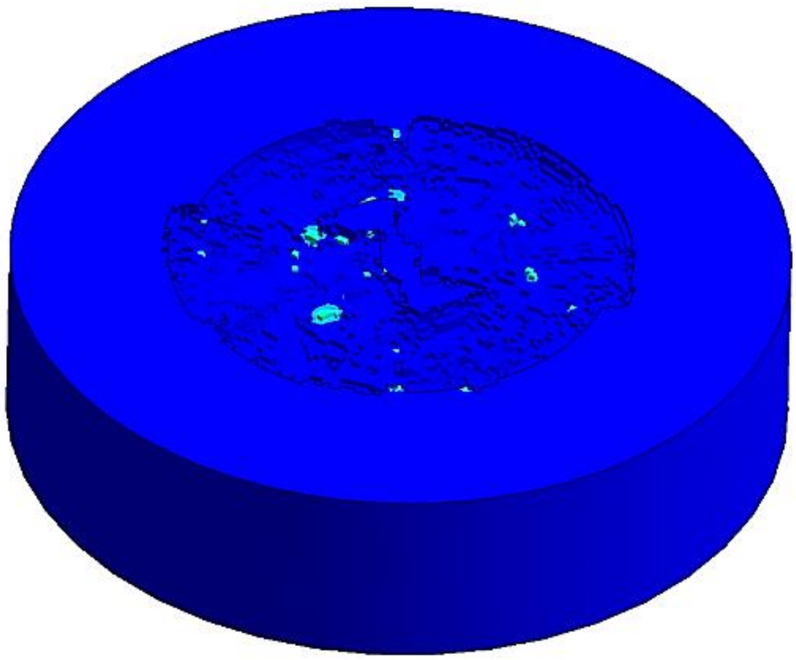


Figure 61: Rock breakage after one full rotation of the drill bit design

It is critical for a full drill bit design to be evaluated with thermal loads and consideration of drill bit wear, as these are major contributing factors to a consistent ROP. As previously mentioned in Section 3.5 Common Failure Modes, fluids and the evacuation of rock particles can reduce the rate of penetration. For further improvements in ROP, additional design evaluation is required, as outlined in Section 6.3.

6.3 Future Work

The research that has been undertaken for this thesis has highlighted several topics on which future research would be beneficial. There were several areas with a lack of information identified in the literature review. While some of the gaps addressed with the thesis aims and objectives, the following future work topics could further expand on and focus on improving the drill bit further:

- The project did not consider fluid flow necessary for cooling the drill bit's components such as bearings, evacuating debris, and preventing "stick-slip". The project also did not cover bearing sealings and ways to prevent foreign objects from damaging the bearings.
- Thermal analysis was not considered in this research. The implication of excessive heat deteriorates the drill bit's life and accelerates its components' mechanical failure. It is recommended to conduct a comprehensive FEA study of the component and analyse their dynamical behaviour in low and high temperatures.
- Identify a proper bearing sealing between geometry and mounting method on a roller cone and cone leg surface to increase bearings' operational life.
- For placing the PDC on the cutters, only the back-rake angle was investigated and optimised without considering the side rake angle. It is recommended to investigate the effect of side rake angle in explicit dynamics study for further improvement in ROP.
- Produce a working model of the design and evaluate its performance under actual drilling working conditions.

7. Conclusions

A novel hybrid drill bit design was created to satisfy limitations in current CTD operations for mineral exploration. The PDC inserts were selected, and their geometrical positioning enhanced ROP by creating high stress on a rock. The drilling performance of the design was evaluated with explicit dynamics simulation by considering all the requirements and constraints. The bearings were selected for increased operational life with a high factor of safety. The materials of drill bit components and the drill bit body were selected for increased durability as identified in the literature and validated with FEA to withstand the stresses during drilling operations. The project delivered a concept of a hybrid drill bit with significant scope for future work. From explicit dynamics FEA, the ROP increased three times compared to the drilling experiments conducted by MinEx using the RoXplorer drill rig. The main findings are outlined below:

- A hybrid drill bit equipped with straight cutters was chosen to be the most effective design for limestone and shale formations with reduced required TOB and increased ROP.
- A back-rake-angle of 10° provided the highest depth on penetration in limestone for both PDC geometries.
- The PDC selected for primary cutters was the three-ridged type, and the fang was selected for the secondary cutters, with interchangeable geometry of horizontal placement.

In summary, the aims and objectives have been successfully achieved. The novel hybrid dual-cone hybrid drill bit design will allow more efficient operations for mineral exploration and enhance the productivity of coiled tubing drilling.

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Appendix A – Material Properties

Table 16: Tungsten Carbide Properties (Gokhale 2010; Properties: Tungsten Carbide - An Overview n.d.; Tungsten Carbide | Properties, Price & Application 2021)

Property	Minimum Value	Maximum Value	Unit
Atomic Volume (AVG)	0.0062	0.0064	m^3/kmol
Density	15.25	15.88	g/cm^3
Energy Content	150	200	Mj/kg
Bulk Modulus	350	400	GPa
Compressive Strength	3347	6833	MPa
Ductility	0.005	0.0074	MPa
Elastic Limit	335	530	MPa
Endurance Limit	285	420	MPa
Fracture Toughness	2	3.8	MPa.$m^{1/2}$
Hardness	17000	36000	MPa
Loss Coefficient	5e-005	0.0001	-
Modulus of Rupture	482	820	MPa
Poisson's Ratio	0.2	0.22	-
Shear Modulus	243	283	GPa
Tensile Strength	370	530	MPa
Youngs Modulus	600	686	GPa
Latent Heat of Fusion	330	560	Kj/kg
Maximum Service Temperature	1000	1050	K
Melting Point	3000	3193	K
Minimum Service Temperature	0 or-459.67	-	K or F
Specific Heat	184	292	J/kg.K
Thermal Conductivity	28	88	W/m.K
Thermal Expansion	4.5	7.1	10^{-6}/k
Resistivity	41.7	100	10^{-8} omh.m

Table 17: Titanium properties (Properties: Titanium (Ti) - Properties, Applications 2019)

Property	Minimum Value	Maximum Value	Unit
Atomic Volume (AVG)	0.01	0.011	m^3/kmol
Density	4.505	4.515	g/cm^3
Energy Content	750	1250	Mj/kg
Bulk Modulus	111	135	GPa
Compressive Strength	130	170	MPa
Ductility	0.25	04	MPa
Elastic Limit	172	240	MPa
Endurance Limit	176	223	MPa

Fracture Toughness	55	60	$MPa.m^{1/2}$
Hardness	1150	1250	MPa
Loss Coefficient	0.002	0.003	-
Modulus of Rupture	130	170	MPa
Poisson's Ratio	0.35	0.37	-
Shear Modulus	36	39	GPa
Tensile Strength	240	360	MPa
Youngs Modulus	100	105	GPa
Latent Heat of Fusion	360	370	Kj/kg
Maximum Service Temperature	570	600	K
Melting Point	1940	1944	K
Minimum Service Temperature	0 or -459.67		K or F
Specific Heat	539	541	J/kg.K
Thermal Conductivity	16.3	18	W/m.K
Thermal Expansion	8.5	9.3	10^{-6}/K
Resistivity	55	57.5	10^{-8} omh.m

Table 18: Limestone properties (Gokhale 2010; Kwietniewski, Miedzińska & Niezgoda 2018)

Property	Value	Unit
Specific Gravity	2.68	Kg/m^3
Compressive Strength	98-124	MPa
Poisson's Ratio	0.28	-
Modulus of rigidity	26500	MPa
Young's Modulus	68.1	GPa
Uniaxial compressive strength	120-130	MPa
Point load index	2-4	MPa
Schmidt hardness by L-hammer	30-40	MPa
Vickers hardness	125-350	-
Powder factor	0.25 -0.40	Kg/m^3
Density	2.67-2.72	g/cm^3
Porosity	0.27-4.1	%
Schmidt hardness index	35-51	-
Cerhard abrasivity index	1-2.5	-
Tensile strength	5.65-6.27	MPa
Cohesion	6-14	MPa
Punch Shear Strength	11.55-12.79	MPa
Thermal Conductivity	2.98-3.32	$Wm^{-1}K^{-1}$
Thermal diffusivity	2.09-2.28	mm^2s^{-1}
Specific heat capacity	1.406-1.598	$MJm^{-3}K^{-1}$

Table 19: Shale properties (Bol et al. 1994; Tumac et al. 2006; Gokhale 2010)

Property	Value	Unit
UCS	60-75	MPa
Vickers hardness	300-525	-
Powder factor	0.15-0.25	kg/m^3
Density	2-2.4	g/cm^3
Porosity	20-50	%
Cehar abrasivity index	0.6-1.8	-
Young's Modulus	6.9-68.9	MPa
Poisson's ratio	0.28-0.43	-
Modulus of Elasticity	10-35	GPa
Modulus of rupture	0.002-0.005	GPa
Compressive Strength	30.3-130	MPa
Permeability	1.09-e-9 – 0.00001	-
Hardness Mohs	2-3	-
CTE, Linear	9-15	Um/m C
Specific heat capacity	0.42 – 2.79	J/g-C
Thermal conductivity	0.4-3.3	W/m-K

Table 20: Vickers hardness values of a wide range of rock formations (Gokhale 2010)

Rock type	Vickers hardness
Amphibolite	500-700
Andesite	550-775
Anorthosite	600-800
Basalt	450-750
Black Shale	300-525
Chromite	400-610
Cooper Ores	350-775
Diabase/Dolerite	525-825
Diorite	525-775
Epidotite	800-850
Gabbro	525-775
Gneiss	650-925
Granite/Granite Gneiss	725-925
Granodiorite	725-925
Granulite/Leptite	725-925
Grenn Schist	625-750
Greenstone	525-625
Hornfels	600-825
Limestone	125-350
Marble	125-250
Metadiabase	500-750
Metagabbro	450-775
Micagneiss	500-825
Micaschist	375-750

Nickel Ores	300-550
Norite	575-725
Porphyrite	550-850
Pyrite Ores	500-1450
Phyllite	400-700
Quartzite	900-1060
Rhyolite	775-925
Sandstone	550-1060
Serpentintie	100-300
Shale/Silstone	200-750
Skarn	450-750
Sphalite Ores	200-850
Tonalite	725-925
Tuffite	150-850

Appendix B – Material Properties Visual Comparison

The graphs in Appendix B show the comparison of distinct properties between the materials and target rock formations. An average property value was chosen for the properties that have a range. For instance, tungsten carbide has a density range between 15.25 - 15.88 g/cm^3. Therefore graphs show an average value of 15.565 g/cm^3. Similarly, all the properties having a range are represented by an average value. These average property values were chosen for running FEA to maintain consistency and obtain as accurate results as possible.

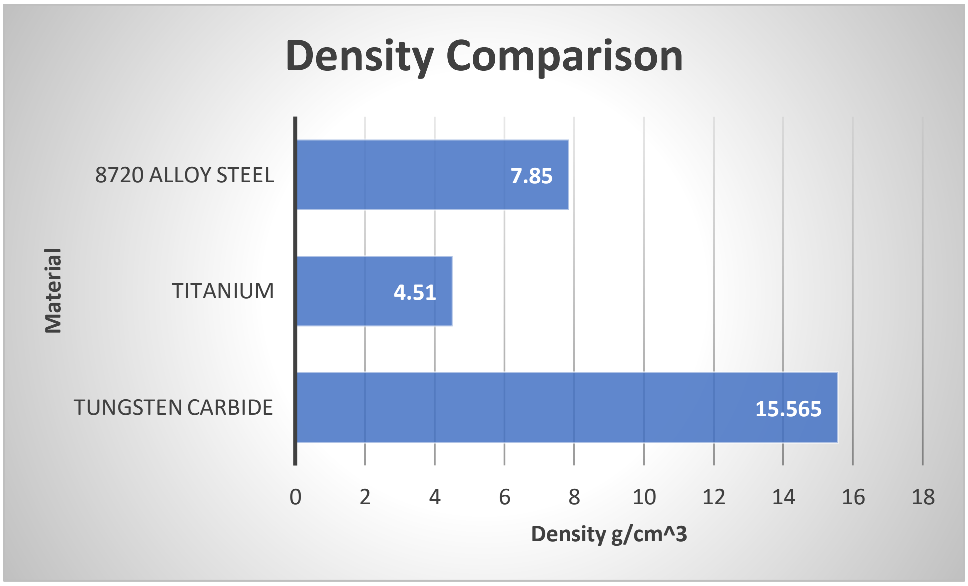


Figure 62: Density comparison of materials (AISI / Alloy Steel 8720 2015; Gokhale 2010; Properties: Titanium (Ti) - Properties, Applications 2019)

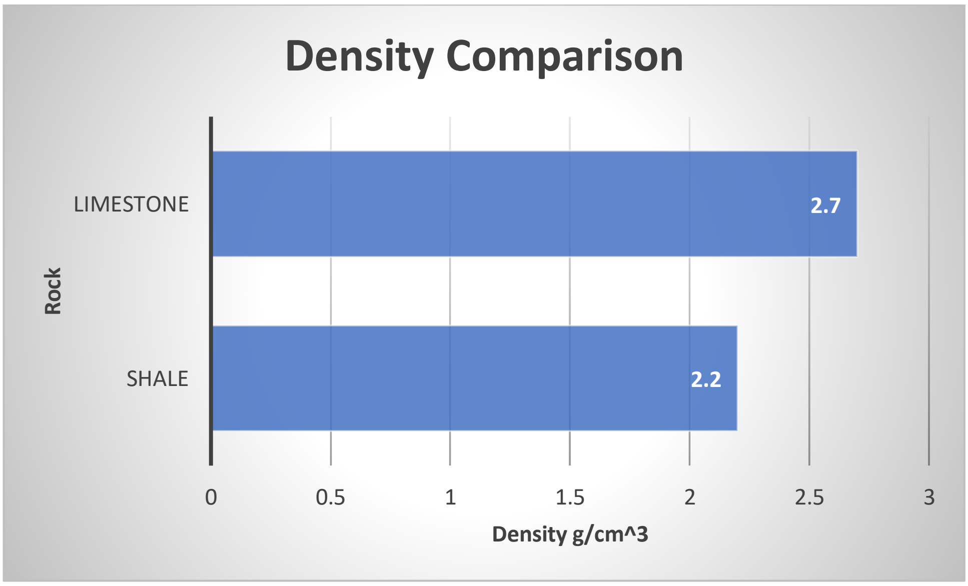


Figure 63: Density comparison of medium-hard rocks (Gokhale 2010; Kwietniewski, Miedzińska & Niezgoda 2018; Tumac et al. 2006)

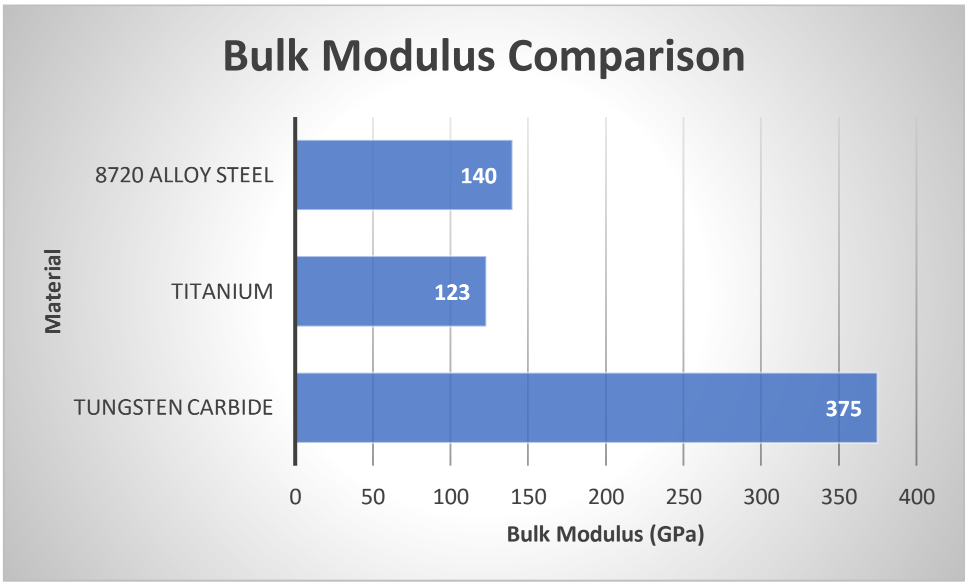


Figure 64: Bulk modulus comparison of materials (AISI / Alloy Steel 8720 2015; Gokhale 2010; Properties: Titanium (Ti) - Properties, Applications 2019; Properties: Tungsten Carbide - An Overview n.d.)

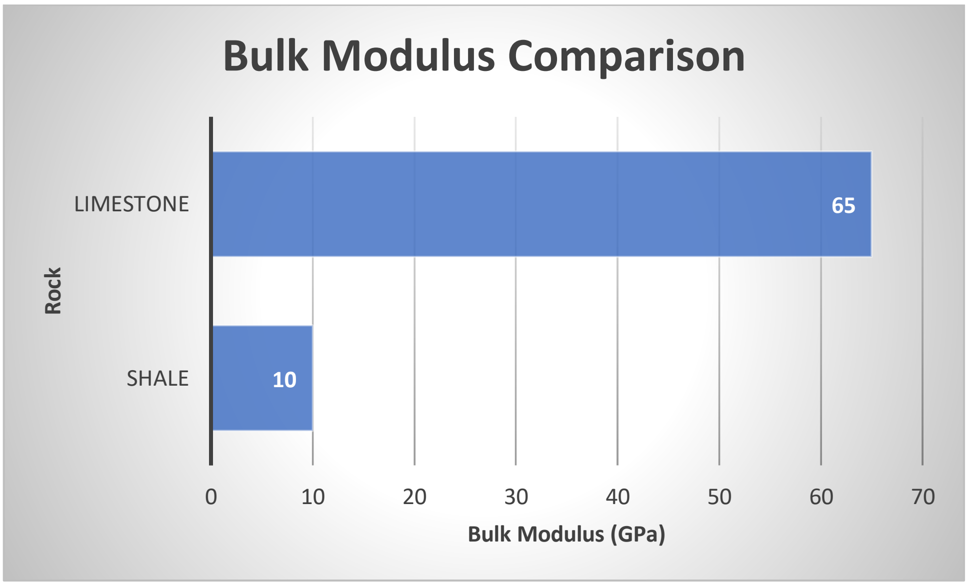


Figure 65: Bulk Modulus Comparison of medium-hard rocks (Gokhale 2010; Kwietniewski, Miedzińska & Niezgoda 2018)

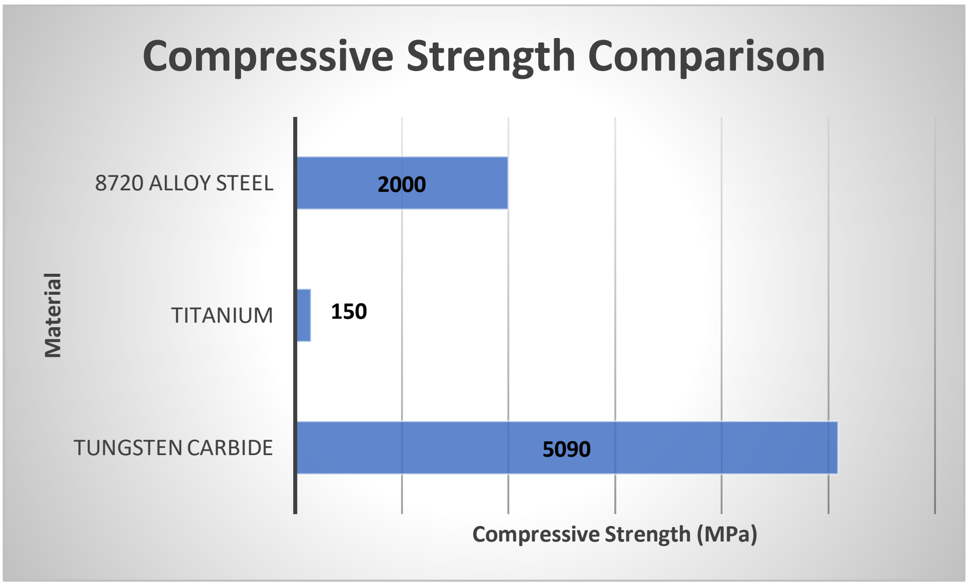


Figure 66: Compressive strength comparison of materials (AISI / Alloy Steel 8720 2015; Chuvil'deev et al. 2015; Properties: Titanium (Ti) - Properties, Applications 2019; Properties: Tungsten Carbide - An Overview n.d.)

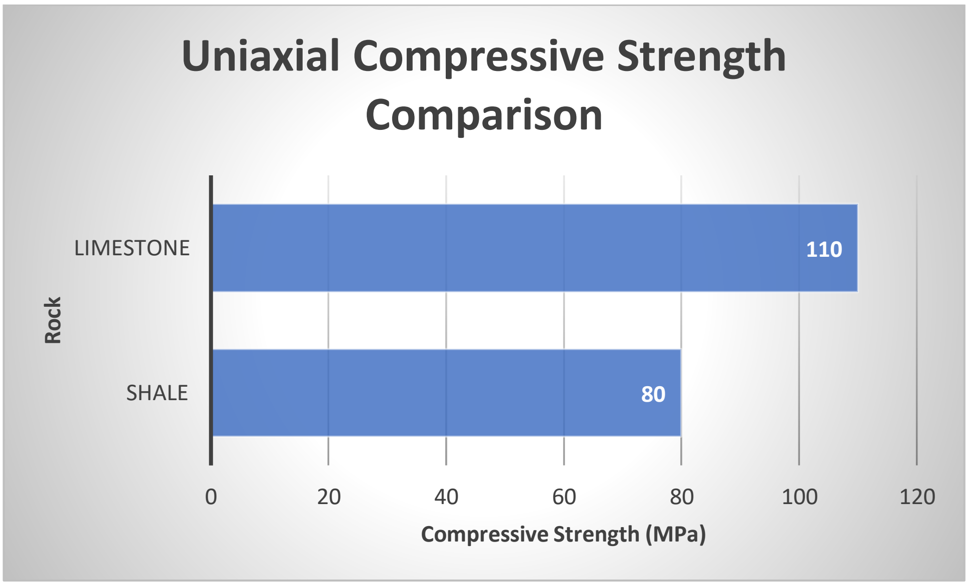


Figure 67: Compressive strength comparison of medium-hard rocks (Bol et al. 1994; Gokhale 2010; Tumac et al. 2006)

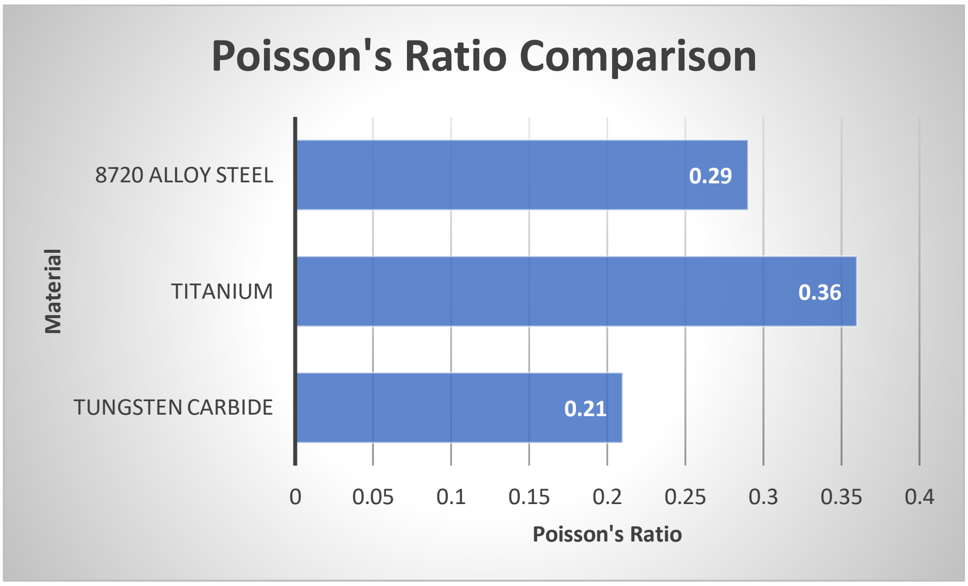


Figure 68: Poisson's ratio comparison of materials (AISI / Alloy Steel 8720 2015; Gokhale 2010; Properties: Titanium (Ti) - Properties, Applications 2019; Properties: Tungsten Carbide - An Overview n.d)

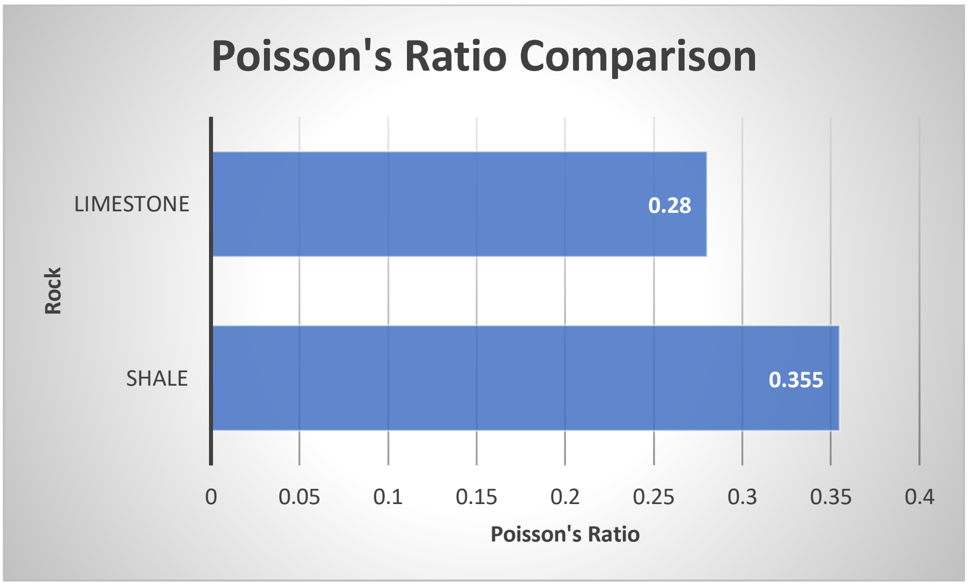


Figure 69: Poisson's ratio comparison of medium-hard rocks (Bol et al. 1994; Gokhale 2010; Kwietniewski, Miedzińska & Niezgoda 2018)

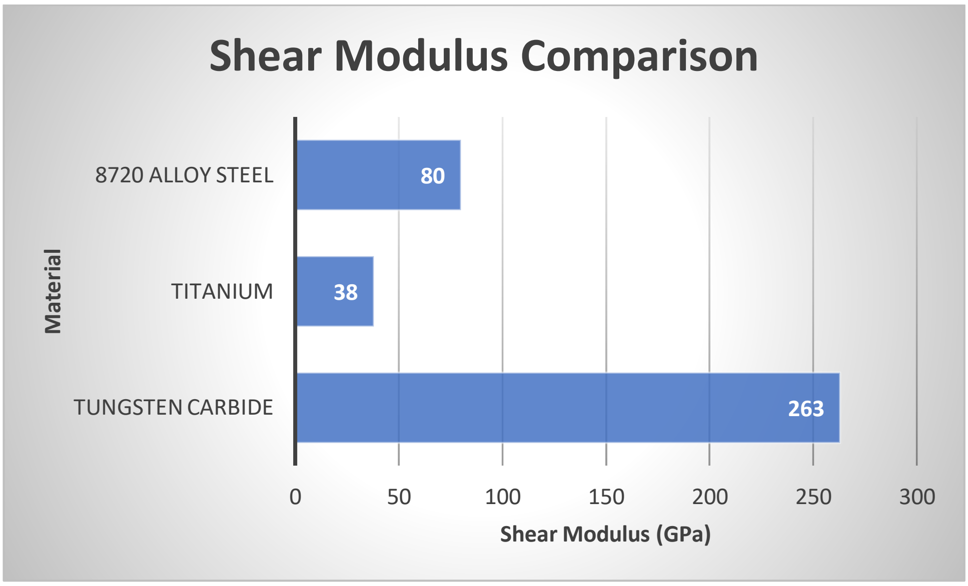


Figure 70: Shear modulus comparison of materials (AISI / Alloy Steel 8720 2015; Properties: Titanium (Ti) - Properties, Applications 2019; Properties: Tungsten Carbide - An Overview n.d)

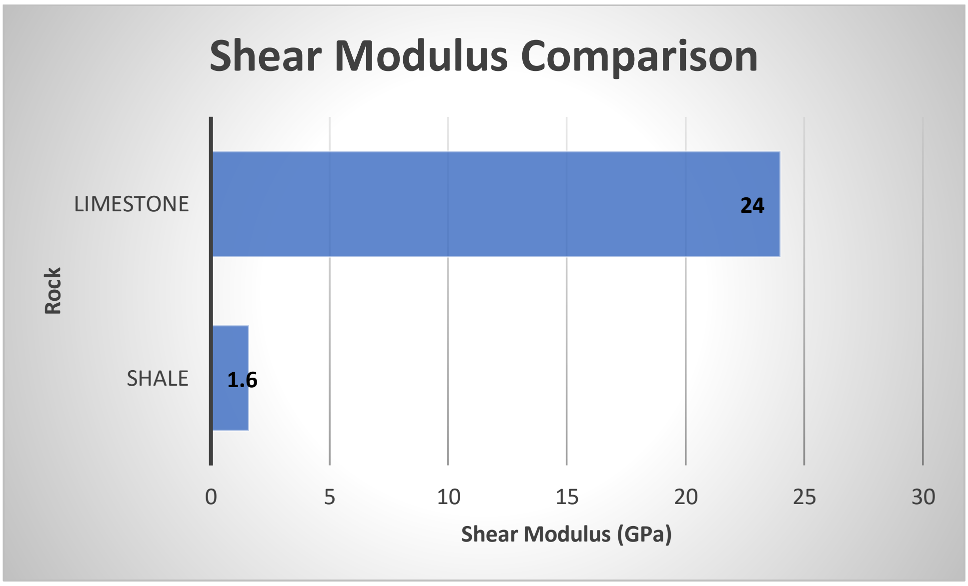


Figure 71: Shear modulus comparison of medium-hard rocks (Bol et al. 1994; Gokhale 2010; Tumac et al. 2006)

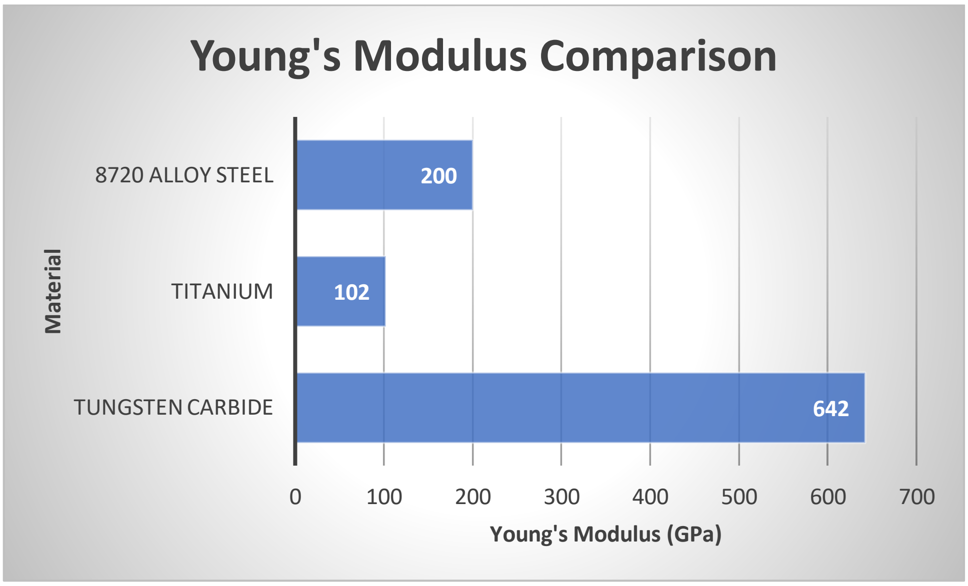


Figure 72: Young's modulus comparison of materials of materials (AISI / Alloy Steel 8720 2015; Chuvil'deev et al. 2015; Gokhale 2010; Properties: Titanium (Ti) - Properties, Applications 2019; Properties: Tungsten Carbide - An Overview n.d)

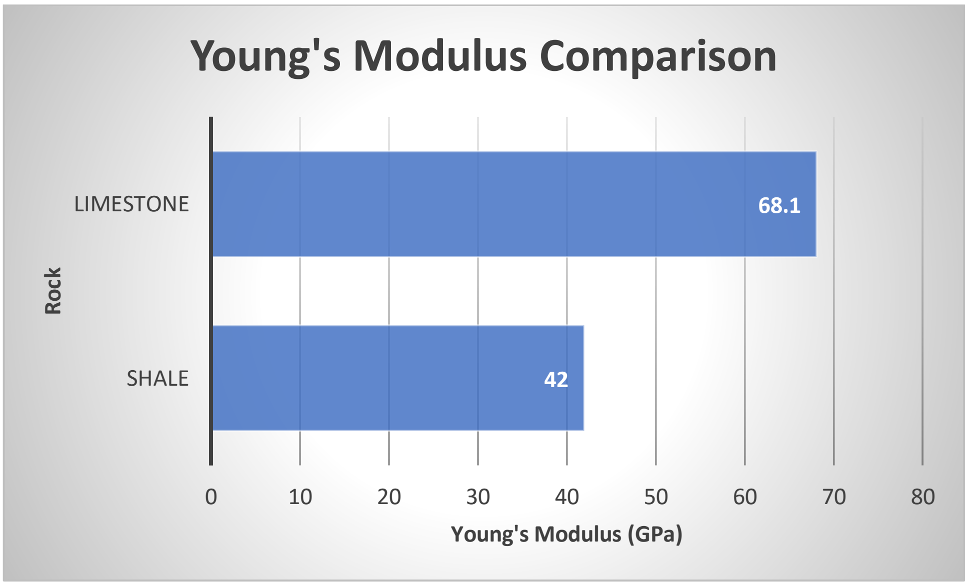


Figure 73: Young's modulus comparison of medium-hard rocks (Gokhale 2010; Kwietniewski, Miedzińska & Niezgoda 2018; Tumac et al. 2006)

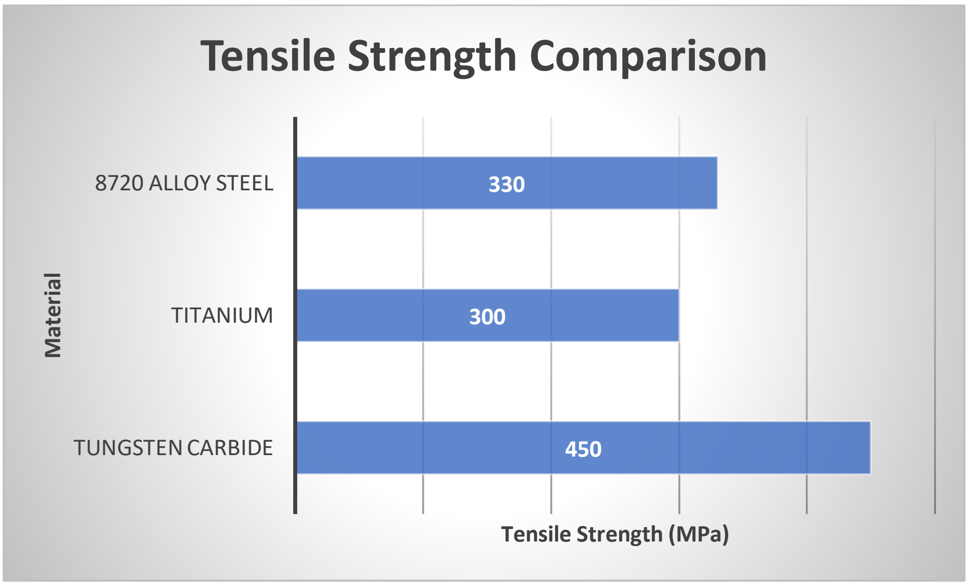


Figure 74: Tensile strength comparison of materials (AISI / Alloy Steel 8720 2015; Gokhale 2010; Properties: Titanium (Ti) - Properties, Applications 2019; Properties: Tungsten Carbide - An Overview n.d)

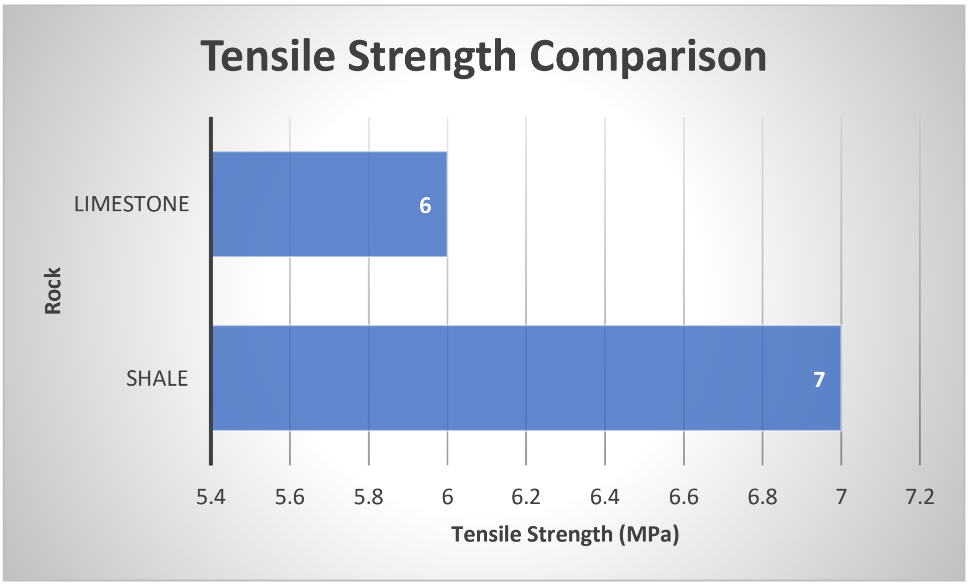
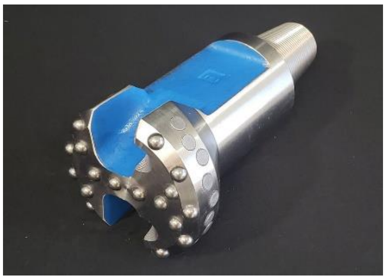


Figure 75: Tensile Strength Comparison of medium-hard rocks (Bol et al. 1994; Kwietniewski, Miedzińska & Niezgoda 2018; Tumac et al. 2006)

Appendix C – Alternative Drill Bit Concepts

Table 21: Other potential drill bit concepts

Concept/Inspiration	Pros	Cons	Suggested Improvements
 *(Diamond Tip Wet Drilling Bits n.d.)*	- Simple design - Good lubrication and cooling - Good cutting evacuation	- Inadequate for percussive operation - Issues with keeping carbide on the bit face - Lack of cutting surfaces for the required depth	- Multiple bits are combined to provide an additional cutting surface - Roller-cone instead of an additional arm
 *(94mm PDC step core drill bit crab coring bit NQ size for coal mining n.d.)*	- Good lubrication and cooling - Good cutting evacuation	- Complicated design - Unsatisfactory performance in desired formations - Requires high torque in comparison to roller bits - It does not suit percussive drilling	- Four roller cones surround this bit
 *(Two Cutter Wings Tungsten Carbide Coal Mining Drill Bit n.d.)*	- Good lubrication and cooling - Good cutting evacuation - Simple design - Low torque due to small size	- Not suitable for desired formations - Increased erosion of arms - Low impact resistance	- Reinforces the arms to increase durability - Alter contact points to conical shape to increase impact resistance
 *(Coal machinery and accessories 2020)*	- Good lubrication and cooling - Good cutting evacuation - Simple design - High ROP	- An issue with holding the carbide on the surface - Not suitable for hard formations - Low impact resistance	- Flatten the top and add buttons to increase the ability for percussion operations and increase the top contact area

 *(32mm 3 Wings PDC Drill Bit for Mining n.d.)*	- Good cooling - Good cutting evacuation - Simple design	- An issue with holding the carbide on the surface - Requires high torque - Low impact resistance	- Replace one of the 'arms' with a single-roller bit - Reduce overall size
 *(Stable Performance Eccentric Casing System Carbide Steel Material Made n.d.)*	- Percussive operations - Good cutting evacuation - Simple design	- Erode faster in an extended section - Geometry untested in CTD	
 *(Eccentric Bit - 4" x API 1-1/2" x 2-1/4" 2021)*	- Good cooling - Good particle evacuation - Percussive operation - Simple design	- Increased torque due to top cutouts	- Alter the geometry of the cutout - Increase the size of the cut out to add roller cones on each size
 *(PDC-CA-98-SB-Steel Body Concave PDC Bits n.d.)*	- Good cooling and drilling fluid flow - Good particle evacuation - Simple design	- Higher torque requirements - Poor performance in percussive operation	- Attach buttons on the top surface for percussive operation - Geometry and angle of the cutting surface

Appendix D – Bearing Technical Specifications

Thrust Ball Bearings

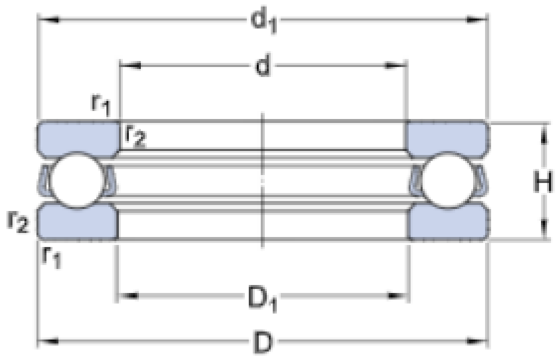


Figure 76: Bearing schematic diagram (SKF 2021)

Table 22: Dimensions of ball bearings (SKF 2021)

d	10 mm	Bore diameter
D	24 mm	Outside diameter
H	9 mm	Height
d1	24 mm	Outside diameter shaft washer
D1	11 mm	Inner diameter housing washer
r1, r2	min 0.3 mm	Chamfer dimension washer

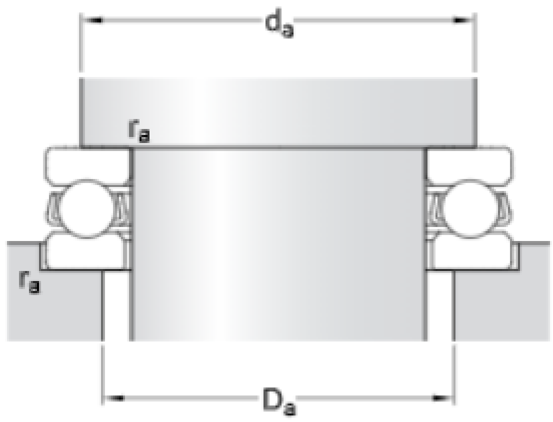


Figure 77: Abutment and radius bearing specifications (SKF 2021)

Table 23: Calculation data of ball bearings (SKF 2021)

da	min.19 mm	Abutment diameter shaft
Da	max.15 mm	Abutment diameter housing
ra	max.0.3 mm	Fillet radius
C	8.71 kN	Dynamic load rating
C_0	12.2 kN	Static load rating
P_U	0.45 KN	Fatigue load limit
A	0.001	Minimum load factor
m	0.02 kg	Bearing mass
-	9500 r/min	Reference speed
-	13000 r/min	Limiting speed

Cylindrical roller thrust bearings

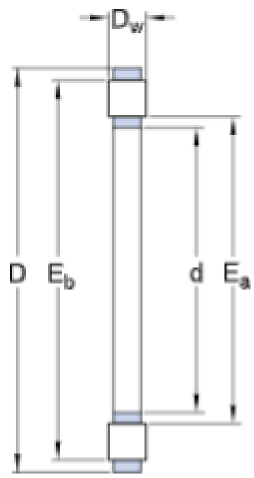


Figure 78: Cylindrical roller bearing schematic diagram (SFK Bearings n.d)

Table 24: Calculation data of cylindrical ball bearings (SKF Bearings n.d)

d	15 mm	Bore diameter
D	28 mm	Outside diameter
D_W	3.5 mm	Diameter roller
E_a	16 mm	Min raceway diameter
E_b	27 mm	Max raceway diameter
C	11.2 kN	Dynamic load rating
C_0	27 kN	Static load rating
P_U	2.45 kN	Fatigue load limit
A	0	Minimum load factor
m	0.006 kg	Bearing mass
-	4300 r/min	Reference speed
-	8500 r/min	Limiting speed

Appendix E – APDL Commands

The use of APDL commands was attempted to evaluate death elements in a transient-structural analysis. This code aims to employ *kill commands on selected nodes once these nodes reach equivalent stress equal to or greater than its material properties.

```
! kill elements for which nodes have values above a
designated value

*get,myncmls,active,,solu,ncmls ! cumulative number of
load steps

*if,myncmls,gt,0,then ! if this is after the first

cmsel,s,RockElements ! ELEMENT component to be checked

nsle ! nodes on these elements

SELTOL,1.0e-12 ! stay within range below

nsel,r,s,eqv,27,2000000 ! re-select nodes with results
above a value

SELTOL ! selection tolerance back to default

*get,numnode,node,,count ! how many nodes with result
above?

*if,numnode,gt,0,then

esln ! elements with any node selected

*get,numelem,elem,,count

*if,numelem,gt,0,then

ekill,all

*endif

*endif

allsel

*else

! if first load step, have result written to in-memory
database

fini

/config,noeldb,0 ! write results into the database

/solu ! continue with solution

*endif
```

Appendix F – PDC Back-Rake Angle Results

FANG: The following images are the directional stresses on the limestone when a fang PDC impacts the limestone at a particular back-rake angle.

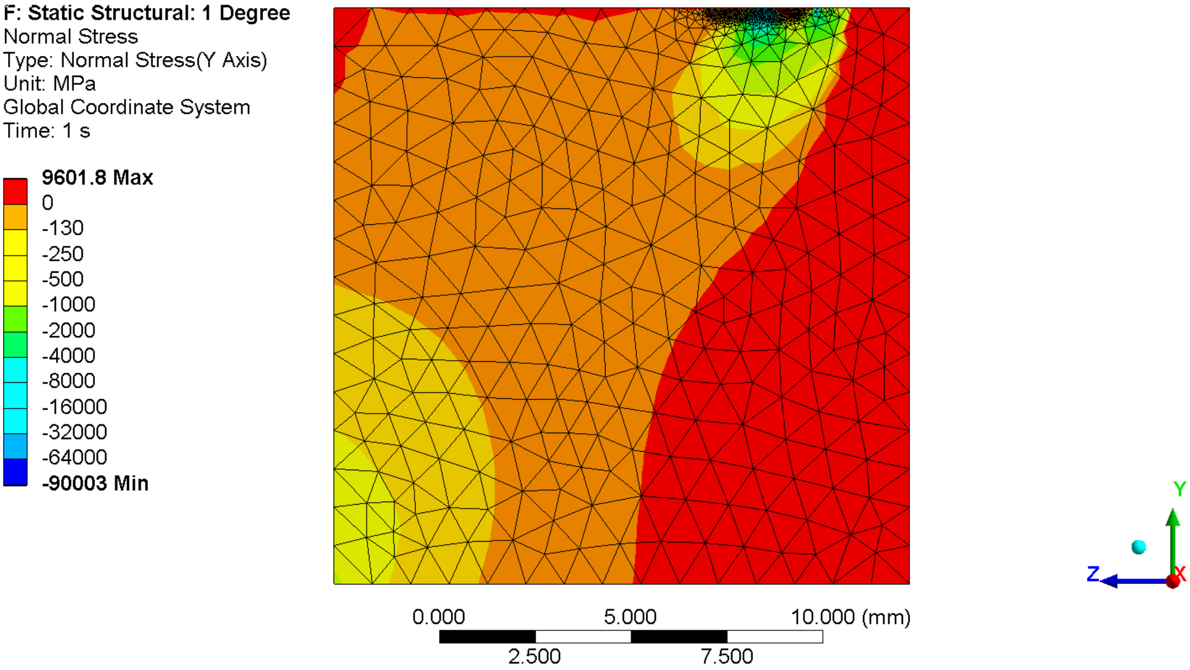


Figure 79: Stress on limestone with Fang PDC back-rake angle 1 degree

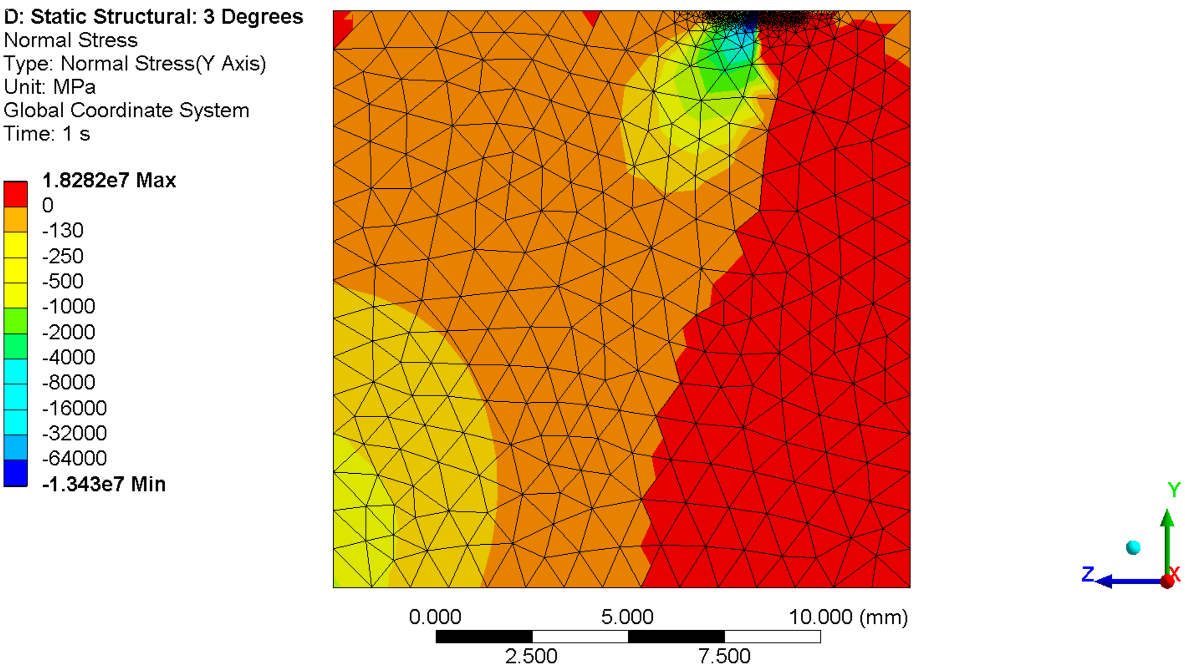


Figure 80: Stress on limestone with Fang PDC back-rake angle 3 degrees

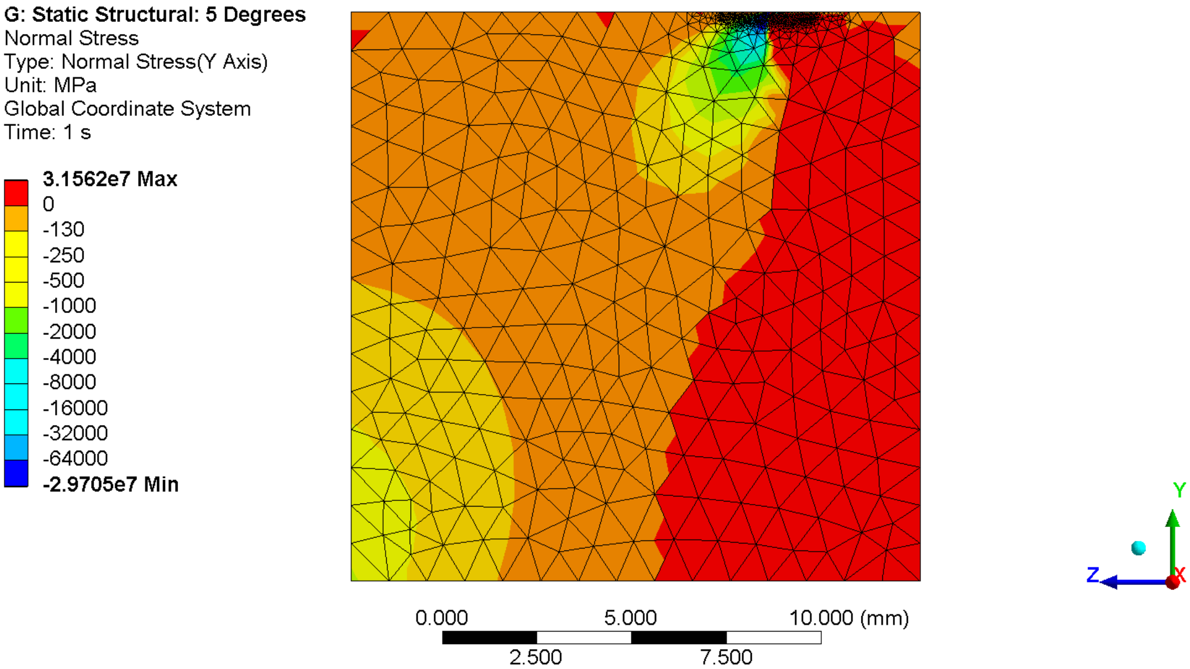


Figure 81: Stress on limestone with Fang PDC back-rake angle 5 degrees

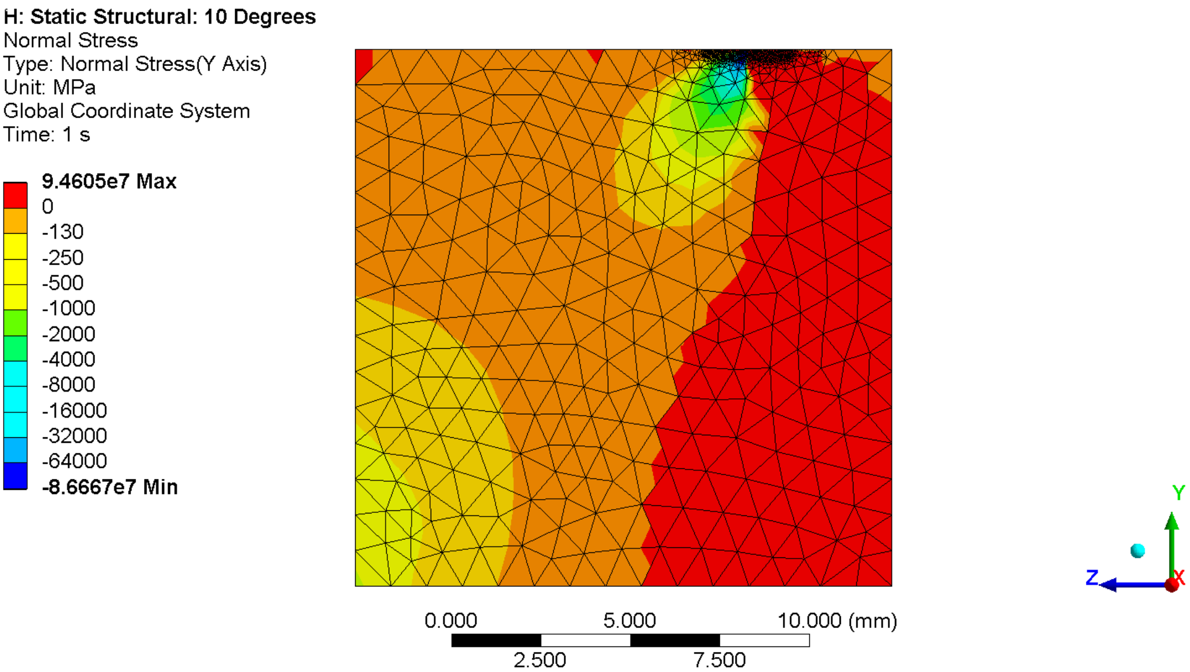


Figure 82: Stress on limestone with Fang PDC back-rake angle 10 degrees

Three-Ridged: The following images are the directional stresses on the limestone when three-ridged PDC impacts the limestone at a particular back-rake angle.

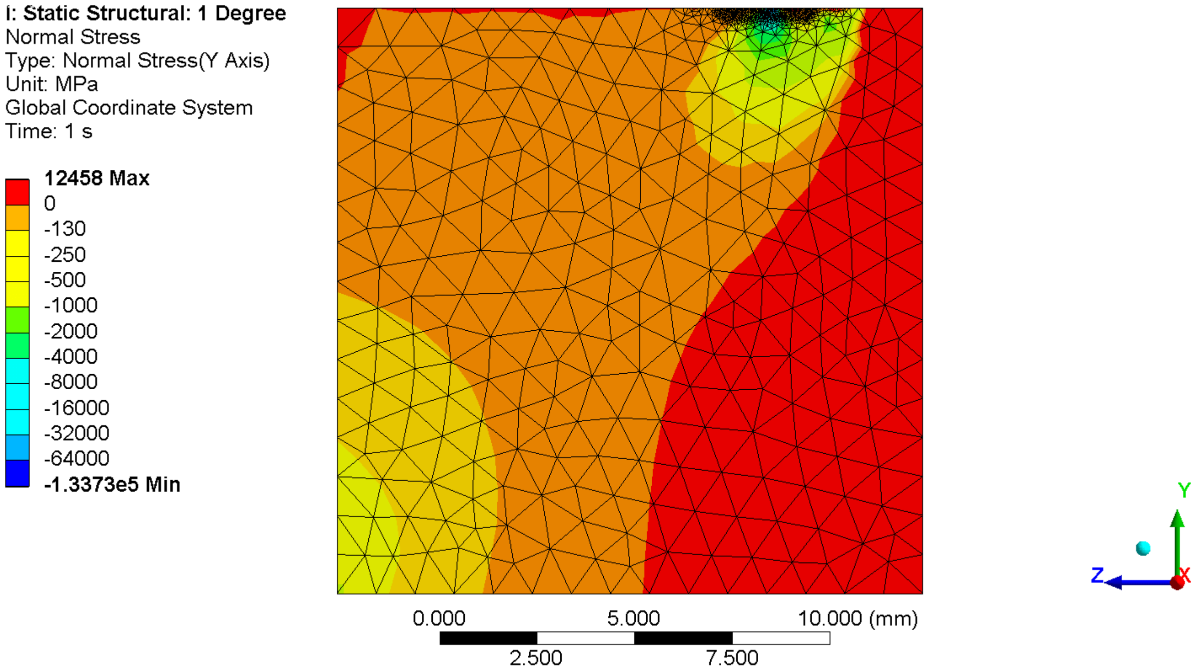


Figure 83: Stress on limestone with Three-Ridged PDC back-rake angle 1 degree

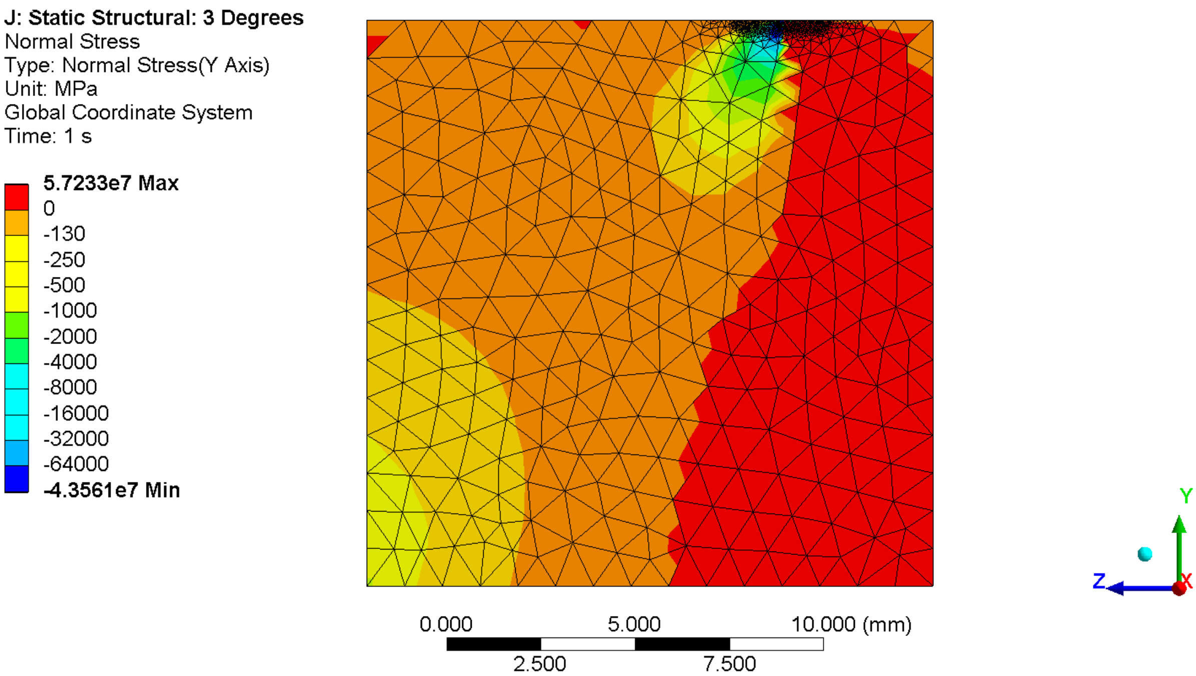


Figure 84: Stress on limestone with Three-Ridged PDC back-rake angle 3 degrees

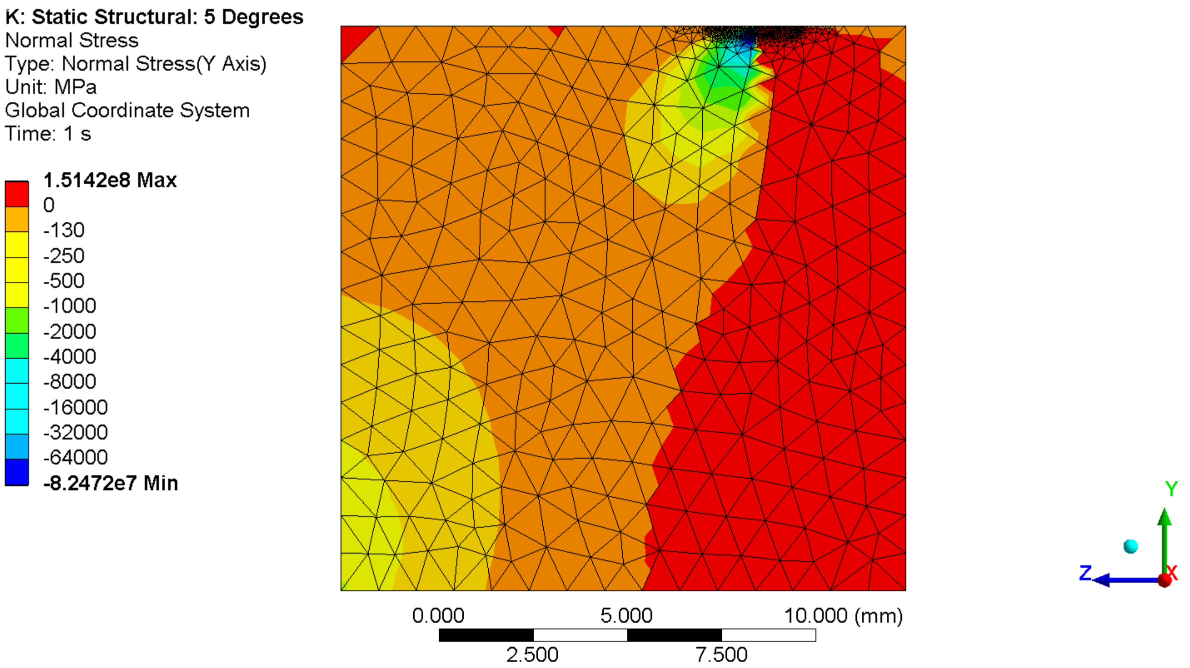


Figure 85: Stress on limestone with Three-Ridged PDC back-rake angle 5 degrees

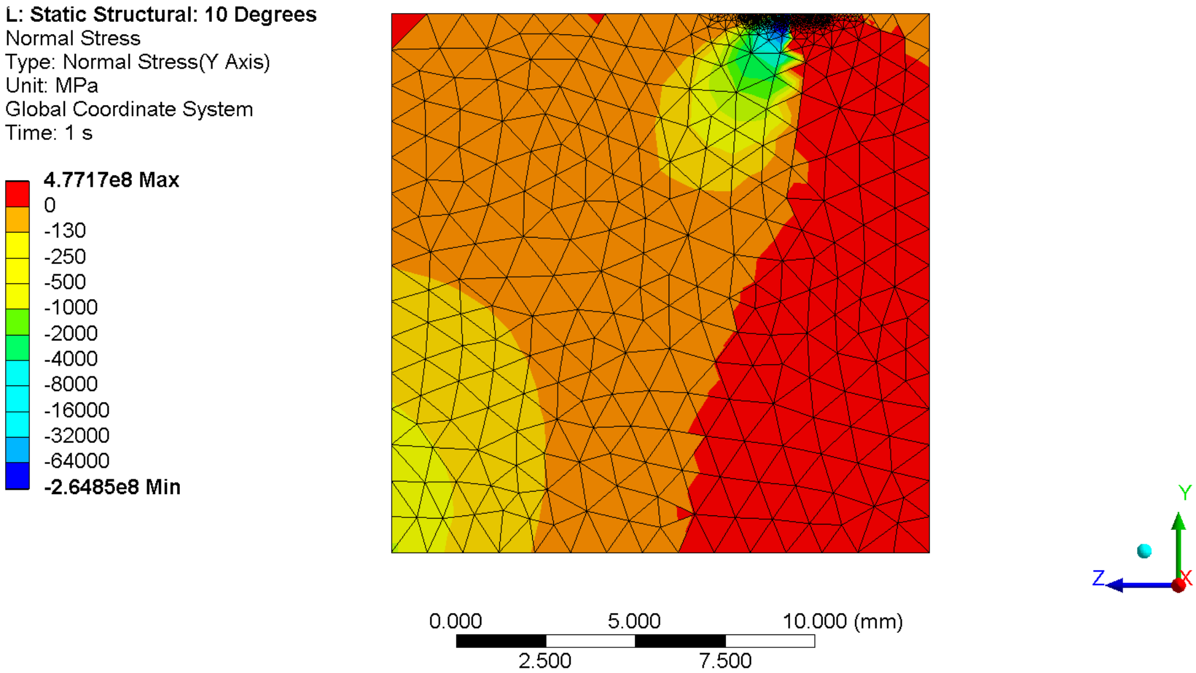


Figure 86: Stress on limestone with Three-Ridged PDC back-rake angle 10 degrees

Appendix G – Cantilever Beam Verification Hand Calculations

1. **Reaction forces**

$$\Sigma\, fx = 0$$

$$R_{AH} = 550\ Sin\ 5º$$

$$R_{AH} = 47.93\ N$$

$$\Sigma\, fy = 0$$

$$R_{Ay} = 550\ Cos\ 5º$$

$$R_{Ay} = 547.9\ N$$

2. **Bending Moment**

$$\Sigma\, M_A = 0$$

$$550\ Cos\ 5º\ \times 60\ mm - 550\ Sin\ 5º\ \times 5.5\ mm - M_A = 0$$

$$M_A = 32610\ N.mm$$

Compressive stress (σ_C) due to force of 550 Sin 5°

$$\sigma_C = -\frac{F}{A}$$

Where,

F = Sin force component

A = cross section area

$$\sigma_C = -\frac{550\ Sin\ 5º}{50\ \times 11}$$

$$\sigma_C = -0.087\ \frac{N}{mm^2}$$

Stresses due to bending

$(\sigma_b)_c$ = Compressive stress due to bending

$(\sigma_b)_t$ = Tensile stress due to bending

$$\sigma_b = \frac{My}{I}$$

Where,

I = Moment of Inertia

$$I = \frac{bh^3}{12}$$

$$I = \frac{50 \times 11^3}{12}$$

$$I = 5545.83\ mm^4$$

$$y = \frac{h}{2}$$

$$y = \frac{11}{2}$$

$$y = 5.5\ mm$$

Therefore,

$$(\sigma_b)\text{t} = \frac{32610 \times 5.5}{5545.83}$$

$$(\sigma_b)\text{t} = 32.34\ \frac{N}{mm^2}$$

$$(\sigma_b)\text{c} = \frac{32610 \times 5.5}{5545.83}$$

$$(\sigma_b)\text{c} = -32.35\ \frac{N}{mm^2}$$

3. **Maximum Stress**

$$\sigma_{max} = ((\sigma_b)\text{c} + \sigma_C)$$

$$\sigma_{max} = -(32.35 + 0.087)$$

$$\sigma_{max} = -32.437 \frac{N}{mm^2}$$

4. **Minimum Stress**

$$\sigma_{min} = ((\sigma_b)\text{t} + \sigma_C)$$

$$\sigma_{min} = (32.35 - 0.087)$$

$$\sigma_{min} = 32.263\ \frac{N}{mm^2}$$

Appendix H – Meeting Minutes

Meeting Minutes

Project	Honours Project A
Agenda	Meet with Supervisors and MinEx CRC members – meeting 1
Date	Monday, 1 March 2021
Location	University of South Australia, Mawson Lakes Campus P1-23
Attendees	Michael Evans (ME), Tim Lau (TL), Ben van der Hoek (BH), Soren Soe (SS), Shane Fox (SF), Rajveer Jandir (RJ), John Zhovnyak (JZ) and Max Cabato (MC)
Apologies	
Circulation	As above

Item	Minutes	Action by	Date
	Overview First meeting to discuss the MinEx projects and get more details		
1	Meeting with MinEx team - Soren, project leader - Shane, Mech Engineering - Ben geologist,		
2.	SS. mineral exploration, projects related to coil tubing drillings, fluid plant, drilling. Practical Research Organisation. Sponsors by large companies, $1000 budget for multiple projects, support, conference workshop, Requirements for $1000 budget • Annual conference in Adelaide participates, November. • 1 hour zoom call, meeting other honours project. Flexibility on project		
3.	ME: SP5 9.0 20 hours a week SP2 4.5 10hour a week Individual, Wk13 progress proposal report2 ME, TL weekly meetings, progress of current tasks.		
4.	Possible topics 6,8,10 from the MinEx list Project 6. SS: Optimisation of various processes (e.g. drilling, sampling, whole site processes) to reduce costs compared to current baseline drilling processes. • Several generations behind a modern manufacturing. • Goal to minimise 15by15 size drill site. • Optimisation of logistical processes to reduce time and cost. • Order of process optimisation, comparison of current process for possible improvements. • Logistical challenges could include, remote environment, no internet connection etc.		
	TL – literature review, researching current approaches from other companies.		
5.	SS: project 8 Coil tubing drilling. Low torque		

	Design/analyses of a new drill bit for cutting hard rock, focussing on survivability, bit design, materials etc. • There is opportunity to design a bit, have it built (funded by MinEx) and tested on-site. • Lit review. • Hard formations, improvement on tools for, challenge: facilities for testing, • Tool or bit increase performance for impact resistance. • What improvements could be made to increase performance. Provided Everything, with information • FEA package, Solid works no point in learning new software. • If design is credible and possibility of working it will be built for full scale testing, field testing. NO problem with materials.		
6.	10. SS, SF, BH • Conventional is rod handling, automation is difficult due to cyclic pattern. • Automation of process in drill site, industry in approx. 50years behind • Technical solution to the processes • Finding way to automate assemble, sampling, unloading drill tools, • Soft automation, Propose and priorities automation options to save costs (save money, save time, reduce injury risk) on drill sites.		
7.	SS: 1 vibration, isolation of electronic devices and vibration, analysis interest in project 1		
8.	Additional information from ME (follow up email): - <u>Lean drill site of the future</u> Optimisation of various processes (e.g. drilling, sampling, whole site processes) to reduce costs compared to current baseline drilling processes - <u>Low torque drill bit</u> Design/analyses of a new drill bit for cutting hard rock, focussing on survivability, bit design, materials etc. There is opportunity to design a bit, have it built (funded by MinEx) and tested on-site. *Note: Upon reflection, I think this might need two people working on it, but it might come down to the specific scope* - <u>Automation roadmap</u> Propose and priorities automation options to save costs (save money, save time, reduce injury risk) on drill sites. The minerals industry is ~50 years behind with this. Your decision is coupled with the choice of if you all choose the same theme or work individually. There are pros and cons to this (some summarised below). *Pros of working as a team/on the same theme:*		

	• Improved deliverable scope (e.g. you would need to work as a three to design a new bit, or produce a comprehensive drill site plan) • Encourages better teamwork and support within your group (which will be important as the year goes on) • Possibly improved focus and motivation for achieving your project aims • Working within the same theme can still be presented as 'a group project' of individuals *Pros of working on different themes* • Easier to justify $1k each for spending • Easier to align aims to your own interests • Easier to delineate roles, responsibilities and outcomes Once you've got an idea, we'll discuss/negotiate with Soren to sort out the project scope. Ultimately, you need to a project you're enthusiastic about. I would, however, recommend you at least be open similar themes to help the report be cohesive.		

General Wrap Up			
1	**With information provided from MinEx members and Supervisor determine best project to move forward on.**	**JZ/RJ/MC**	**03/03/21**

Originated by: M. Cabato	**Approved by**:

Meeting Minutes

Project	Design of low torque drilling tools.
Agenda	Honours Project final decision and next steps.
Date	Friday, 4 March 2020
Location	Teams
Attendees	Michael Evans (ME), Max Cabato (MC), John Zhovnyak (JZ) & Rajveer Jandir (RJ)
Apologies	Tim Lau (TL)
Circulation	As above

Item	Minutes	Action by	Date
	Overview **Meeting to make a final decision on the project. The final decision made was design of low torque drilling tools.**		
1	Asked about the Process about drill bit.	JZ	3/4/2021
2	It is like this, don't know if it's a percussive one. In the other link there were other designs.		
3	Cooling tubes? Yes.	JZ	
4	Cooling would be external using fluid, but that is all part of the design. Might have to calculate Convective heat transfer coefficient using Nusselt number.		
5	Scope is on set by us, i.e., how in depth we want to go. Challenging in terms of spikes. Shock loads prohibited. The impact of cone on different angles will have to be calculated. Must iterate different designs to see which one's more effective bit. You can change angle relative to surface. Would not have to do the whole thing. ME will provide FEA support.		
6	RJ asked do we have to deal with vibrations?		
7	ME suggested you do not have to do analytical vibration analysis. But might have to look at motor vibrations, to see if are not hitting it at natural frequency (DEALING WITH SHAPE AND MASS).		
8	Happy to be the project manager.	ME	
9	Decision made by us via coin flip.	MC, RJ, JZ.	
10	ME wanted us to do drill bit because it has the better scope, which is beneficial not just for marking for future job potentials. Works or not is a different thing.		
11	Want to focus on every part, rather than splitting task. Because everyone should know CAD and FEA at a higher level.		
12	ME has 0 objections. But one person should be a lead for everything. CAD, overall design, materials etc. Once we are used to it, then we should		
13	Review of current design, best practices. By the end we will be knowledgeable, and able to find our strong and weak points.		
14	What is expected in SP2?		
15	Get started on the project, 20% of the mark for the project proposal is based on progress. By the end ME wants us to have material selected. Either finish verification or started with the project to get HD.		
16	Is it negotiable?	JZ	
17	The actual assignment for Honours A is interconnected. Literature review is leading FEA, design, material etc. it is just copied and pasted in the project		

	proposal for SP2. That is about 40% of mark for final report for SP2. In SP5 we continue with the same document.		
18	Asked about the work limit for SP5 report No word limit for SP5, but it is around 500 words per student + 100 extra words. So it would be around 16000 words.	JZ	
19	Build an overall engineering design, would not start CAD until agreed on a concept.		
20	Extended honours B is the same structure as honours B. Assessments are progress towards your final project.		
21	Next Step: Conversation with the MinEx team, to assess the requirement, challenges, which part needs redesign? Work out the aims and goals in terms of team or individual sense. ME aims towards 3-4, one could be final design, review of materials types, etc. But is flexible. First 6 weeks light and last 7 are heavy.		
22	Present a draft 4 weeks before the due date for feedback. Verification, conceptual design, preliminary material selection, will not be hard. If you want HD, spend 12 hrs a week. Invest time to get things sorted and get HD. It is a learning exercise in terms of setting goals. ME would give feedback on progress in terms of how we are doing.		
23	Rubric has changed since last year according to ME. No additional assignments apart from quizzes. But start your project in SP2 to have a good successful outcome.		
24	Assessment 3 requires progress in SP2. Discuss timeline with AsPr. Craig. ME Will talk to AsPr. Craig if we deviate from the timeline.	JZ	
25	Tee-up a meeting with MinEx for more information on administrative side (basically how to manage the project). Circulate the meeting minutes to ME. It will come handy. 15-week research project, timeline based on what JZ showed to ME. Honours A would not look like this.		
26	CFD and acoustic expertise from Cris (ME advice)		
27	Happy to help as much as he can, the further we go ME's role is just guidance and project support. But we need to take a lead on it. Short term, we have 3 things, material, design, and FEA of drill bits. Tools plural so expect to make more than a drill bit.	RJ, JZ & MC	

General Wrap Up			
1	**Send an email to ME and TL, about the final decision so ME and TL can setup a meeting with MinEx team.**	**JZ**	**4/3/2021**
2	**ME suggested start reading material for material, engineering design and FEA techniques.**	**JZ, MC, & RJ**	**8/3/2021**

Originated by: Rajveer Jandir	**Approved by**:

Meeting Minutes

Project	Design of low torque drilling tools.
Agenda	TBA
Date	Friday, 10 March 2020
Location	UniSA Mawson Lakes Campus, P1-49
Attendees	Michael Evans (ME), Tim Lau (TL), Soren Soe (SS), Rajveer Jandir (RJ), John Zhovnyak (JZ) and Max Cabato (MC)
Apologies	Shane Fox (SF), Ben van der Hoek (BH),
Circulation	As above

Item	Minutes	Action by	Date
1	Filling the application for funding $1k – approved by SS	ME	12/3/21
2	Kind of drills bits currently in use SS - Different drill bits used for different applications - For soil/clay – blade bit/drag bit - Coil tuning – low torque bit dur to excessive load on the drill bit. That is why lower torque is required - Fluid percussive hummer for rocks. Compressing high pressure and banging the rock. 70 hits per second, water hummer used. - SS to send the details. W50 & W70 are used. - Motor for turning the hummers. Max torque around 500NM	SS	
3	Challenges: - Drilling with diamond bit in a rock. Spinning fast. For fast drilling, turbine spinning at 8000 rpm. Bits are wearing quickly. There is a limited weight permittable on the bit. - Dimond bit high tensile heat-treated steel to hold the diamonds. - Percussive drilling, if formation is brittle, it breaks like an ice. The torque required to shear the chips is within available range. - Blade bit is hard top drill - Fluid is taking the particles away while drilling.		
4	Focus should be on, according to SS: - Combination of drilling methods - Coning tricone bits with a hummer. - Percussive with a tricone. - tricone bit could also be a dual cone. - Bearing are sensitive for failure due to percussive and sand blasting. - Focus on a concept that can be a roller bearing.		
5	Procedure: - Looking on existing concepts and how they can be improved. - Come up with a design/ solution of percussive low torque. SS to send the requirement	SS	
6	MinEx buy bits from other companies. "Wassara" company supply the hummer bits. Epiroc supply Tricone bits. - Soren to organise a site visit next week - Soren to invite project team for drilling experiment in the field - TBC	SS/ME	
7	Literature review: - Focus on problems - What questions are we trying to address? - Design/design calc/ FEA/ in depth materials		
8	Soren preference:		

	- Describe the challenge we have from engineering point of view. Bit that digs into formation. What is happening in that bit. What formation we can shear the formation and where not. - Build sort of engineering model. - Soren preference is to try the standard stuff in field and we have the idea of what fails first. - Tricone bit improved to survive longer – main idea - How hard is the rock? ME - Question about Design. ME - Process can be seen - Focus on that bit could be and the bearings.		
	Literature review focus on medium hard, narrow does on what is semi-successful. TL		
	Look of features in other drill that don't work in other situations. Hummer bit may not work in soft stuff. First four weeks. Look at what is there, what exist, and narrow the options.		
	ME to send an example of a good report & literature review	ME	
	Structure of literature review for AGENDA next week		
	Research proposal in the end of SP2 one document for all the team (bearing failure, why things are getting jammed, etc…)		
	ME mentions: - If need to contact 3rd party, use uni email and CC Michael. - How things fail. Why small bearings are so crappy. - Email craig and CC Tim and Michel. How does it work, do we still share the same aims? - We as a team are setting an agenda for the meeting	JZ	

General Wrap Up			
1	**Next week a visit at MinEx research hub – TBA**	**SS/ME**	
2	**Next weekly meeting to be organised by ME. Project team to suggest an agenda at least 24 hours before.**	**ME/JZ/MC/RJ**	

Originated by: John Zhovnyak	**Approved by**:

Meeting Minutes

Project	Honours Project A - Coiled Tubing Drilling for Mineral Exploration
Agenda	Preliminary Report, Resources
Date	17/03/21
Location	University of South Australia, Mawson Lakes Campus P2-47
Attendees	Michael Evans (ME), Tim Lau (TL), Rajveer Jandir (RJ), John Zhovnyak (JZ) and Max Cabato (MC)
Apologies	Ben van der Hoek (BH), Soren Soe (SS), Shane Fox (SF)
Circulation	As above

Item	Minutes	Action by	Date
	Overview Explanation of possible resources to be used in the project, from books, journal articles, government reports. General tips for Assessment 3A preliminary report and explanations of what is required. Best practices for use of information, citing.		
1	ME - Read the information and write down dot points. - Book, if the information is referenced find the original source of the 'idea/information'. - NO intext references in the book, avoid at all costs. - Technical Details, from manufacturer, - Testing details from academic journal - General broad ideas, books - Journal Papers for most up to date information.		
2	TL: Books, are good for generalisation Journal articles for specific details,		
3	ME: Find journal articles for assessment 3A. Sent documents this morning of examples. Examples of Design and build project. Read the report aims of the examples. Compare the example aims with ours. Pressurise combustor. Aims for this should be the same.		
4	JZ asks about assessment 3A introduction.		
5	Second point of template intro, MinEX. ME: Sentence of mining minerals into the economy. No existing drill bits in coil tube drilling. Background: expanding the statement of the problem. Provide references. Minimise the mention of MinEx in motivation. Input from MinEx engineering will be given.		

	No drill bit on the market Gap: No one has considered the technical challenges of combining these bits.		
6	ME: Paraphrase does not mean it's good. Lit. reviews are an analysis of facts. Not everything in the paper is right. Differing methods produce different results. Conflict of interest, research numbers can be fabricated. Multiple research papers to reference and fact check. Most research is publicly funded. 3-6 references to prove that it is fact.		
7	JZ questions of proposed research plan		
8	ME: review of designs, lit. review, FEA, etc. Provide reasons and back it up with lit review.		
9	ME: list of 4-5 journals not books, books do not have enough detail.		
10	ME: Look at papers that have cited the books		
11	ME: 10 years ago, for research papers are not definitive. Different fields move at different rates, Use cited references and look through all of it and find relevant journals. Springer Science Direct Use major journals. Government report, Aus. or US research produced by department of energy mostly likely reputable. Estimated costs in final report, research proposal.		
12	ME: Goal is to have a working product at the end. Expect to see in proposal report, Different concepts, Process of elimination, provide reasons,		
13	ME: Concepts completed in SP2 Technical material before SP5 After literature review submission, starting the project.		
14	TL: The project relies on others, can take weeks for certain information etc.		
15	ME: completely different to any other project in any courses. If FEA project SP2 completed verification		
16	ME: Manage it in context with other courses.		

General Wrap Up			
	ME to sign meeting minutes 1-4	**ME**	**18/03/21**
	ME email MinEx about meeting schedule next week	**ME**	**21/03/21**
	JZ, RJ, MC read through aims of the examples given by ME	**JZ, RJ, MC**	**19/03/21**
	Send our aims to ME as soon as possible	**JZ, RJ, MC**	**20/03/21**

Originated by: M. Cabato	**Approved by**:

Meeting Minutes

Project	Honours Project A - Coiled Tubing Drilling for Mineral Exploration
Agenda	• Looking at existing drill bits – visiting MineEx workshop • Literature Review • Document Writing • Meeting at MinEx workshop
Date	
Location	University of South Australia, MinEx workshop
Attendees	Michael Evans (ME), Rajveer Jandir (RJ), John Zhovnyak (JZ) and Max Cabato (MC), Soren Soe (SS), Luca
Apologies	Tim Lau (TL), Ben van der Hoek (BH), Shane Fox (SF)
Circulation	As above

Item	Minutes	Action by	Date
	Overview • Looking at existing drill bits – visiting MineEx workshop • Literature Review • Document Writing • Meeting at MinEx workshop		
1	Meeting at MinEx workshop: - SS presented the existing drill rigs. The two are capable of drilling in 500 & 1000m. - SS explained the way the drill rigs operate		
2	The existing rotational motor is a hydraulic motor activated by drilling fluid passing through the blades and generates and rotational motion. The hydraulic motor has a limited torque.		
3	Different types of drill bits were presented. SS explained the way they operate.		
4	MinEx aim for a drill bit which can have a combination of Tricone, PDC that can withstand percussive and rotational operation.		
5	One of the main issues is with the bearings. The small particles penetrate the bearing casing and cause failure.		
6	Luca suggested an optional concept having the Tricone in the perimeter and PDC in the centre. Luca to send ME additional information.	Luca	

General Wrap Up			
1	The team consolidated their understanding of the project and the expectations		
2	Literature review draft to be presented to ME	**JZ, MC, RJ**	**31/3/21**

Originated by: J. Zhovnyak	**Approved by**:

Meeting Minutes

Project	Honours Project A - Coiled Tubing Drilling for Mineral Exploration
Agenda	Literature Review
Date	31/03/21
Location	University of South Australia, Mawson Lakes Campus P1-23
Attendees	Michael Evans (ME), Tim Lau (TL), Rajveer Jandir (RJ), John Zhovnyak (JZ) and Max Cabato (MC)
Apologies	Ben van der Hoek (BH), Soren Soe (SS), Shane Fox (SF)
Circulation	As above

Item	Minutes	Action by	Date
	Overview Identifying credible sources Literature Structure tips: what is needed, how many sources expected and structuring the literature review.		
1	ME: Peer Reviewed articles – UniSA library can have errors, Can identify credibility of sources through other sites. Reputability of publishers etc.		
2	ME: Better to cite the original source than peer review source citing it. ie. cite ABS not a journal article citing ABS		
3	Does not need to all be peer reviewed articles.		
4	JZ: Which lit review do we put in the final thesis.		
5	ME: There's a small chance of everything overlap. Can focus of separate topics or share information and work on the same thing.		
6	TL: Shared information, shared document.		
7	ME: Responsibility for sections, reading through each other's works and drafting. Merging. Should have a collection of shared documents.		
8	RJ: Is word limit strict?		
	ME: Being concise is important		
9	TL: using tables and figures Convey message through these.		
10	ME: Lose marks if word count is well over.		
	TL:		
11	TL: Dot points can be useful Tell me why you are showing this figure. Write all the points, skeleton of the work.		
12	ME: headings, section headings, sub section headings, dot points. Write quickly and be very critical of the work. Edit multiple times.		
13	TL: Write carefully and well thought out, takes longer but less editing.		
14	ME: No middle ground between both styles.		
15	ME: Be more specific, write a sentence and it becomes the paragraph. Write a sentence that does not include the 'and' 'or' Distinct Paragraphs 'No suitable bearings for drill string applications'		
16	ME: Gaps flow on from the literature review, no need to reference gaps unless its very particular. Four Gaps are good.		
17	ME: Can't rely on a single paper to highlight your gap. Gap could have been filled without you knowing. Expect 15 references in lit review, read through roughly 50		

18	JZ: Questions about structure of lit review.		
19	ME: At least four paragraphs should be more. Write introduction, minerals are important. 1st Mineral exploration is important. Go through challenges. Size Cost Scale 2nd Drill strings Challenges, torque Mention problems Under certain hardness of rock, etc. These become the main paragraph of the lit review.		
20	TL: paragraph should have 1 take home message. For each problems described show what others have done. What does this literature show.		
21	ME: Intro Challenges Outstanding gaps – sentence with dot points.		
22	TL: sharing information on journal articles. Use a table to provide information in what articles have been read, who has read it and put comments on it.		

General Wrap Up			
	Send ME a structure of lit review template.	**JZ, MC, RJ**	

Originated by: Max Cabato	**Approved by**:

Meeting Minutes

Project	Honours Project A - Coiled Tubing Drilling for Mineral Exploration
Agenda	Feedback on Literature Review Draft, Structure, References and future expectations. What have we learned from Literature Review.
Date	07 April 2021
Location	University of South Australia, Mawson Lakes Campus P1-23
Attendees	Michael Evans (ME), Tim Lau (TL), Rajveer Jandir (RJ), John Zhovnyak (JZ) and Max Cabato (MC)
Apologies	Ben van der Hoek (BH), Soren Soe (SS), Shane Fox (SF),
Circulation	As above

Item	Minutes	Action by	Date
	Overview		
1	JZ: Asks about Structure TL: Key statements, start reading author A, identify key points, Random order, heading such as experiments. ME says please send Agenda email. Do not let the project slip. -Info categorization, sum up findings, questions to ask to MinEx, get project scope approved by MinEx. -Just set out the objectives.		
2	ME suggests send all meeting minutes we want signed via email. JZ asks for feedback on his draft report. ME says resend the structure.		
	MC asks wats expected from us ME says this keep reading more papers -Refine your gaps -Go back to aims to compare aims with gaps -Rediscuss aims, to check if they align with MC and TL. -Work out methodologies. -Aim has to be something that we can achieve -Make sure aims are achievable and worth. -Discuss methodology and put some preliminary work on it. -Should have access to FEA library for ANSYS. -Email Nikki Stanford and Frank for FE.		
	ME says - Compare designs and try to use selection criteria for a conceptual design by the end of this semester JZ asks SolidWorks or ANSYS. ME: Use ANSYS rather than SolidWorks. ME explains use simple designs for bearings and hemispherical models in ANSYS. -Do not import CAD models in ANSYS. -Use native tools for CAD and SolidWorks. -All concepts and designs should be on paper -Do not waste time by doing CAD as it takes a lot more time.		
	JZ: Can we get ANSYS. ME: ANSYS has student version, simple mesh can be done by us. - ME suggests he can run the FEA once we have put together everything. -ME talks about the action item (Craig Conversation) -Intellectual Property negotiation if we come up with a new idea		

	-If Soren suggests an idea Minex holds rights. - Rubric for research proposal.		
	MC asks about wear and tear on drill bit for different type of drilling methods. - Hammer type, tooth and wear and consistent impact on rocks, most methods seen are field tested or lab tested. -Type of fluids they use during rotary downhole motor. -Depending on fluid property in oil and gas industry. -PDC and tungsten carbide good for hard rocks. Slow in terms of penetration, percussive drilling shatters it. -Cost effectiveness is better for percussive, also depends on application. -TL asks in terms of geometry, does every bit have same geometry. -MC and JZ says no concrete formula for all. -One size does not fit all. JZ found gaps, such as all tests were done in laboratory so try to use the same experiments on field. TL asks about temperature. JZ says 700 degrees C and depends on the type of lubrication. -Problem with cooling is debris and it gets into bearings. -TL says: How to shield drill bit from debris, and increase the bit life. ME recalls Soren saying they use water only. -TL and ME suggest design a shield to protect the bearing and bit. -JZ explains the wear and tear process. JZ asks about time constraints and the scope.		
	JZ asks how to mention similar and distinct gaps. ME replies depends on the gaps and the efficiency obtained by addressing the gap. TL suggests a gap: design a bearing to protect it from debris. ME says address the debris issues.		
	ME illustrated the difference between failure and wear and team over the board.		
	-TL says design it to fail, so that we know when it fails. -ME analogy to soft soil, concrete soft and find the limit of the drill bit. - Fracture toughness and hardness. - ME displays over a diagram the fracture toughness, brittle fails well. - Talks about the fracture toughness test and three types of stresses.		
	ME displays Anderson Fracture Mechanics - Use this book to see how rocks crack.		
	ME talks about the forces and suggests identify the torque to find what is going to fracture.		
	ME says do not go into depth with minerals and be general. -Cut down on words and talk about different types of hybrid bits,		
	ME says add Monitoring for wear in Literature review		
	JZ asks for a feedback on his final paragraph. ME suggests reduce the unnecessary words.		
	ME says send availability via email.		

General Wrap Up			
	The group to focus on literature review assignment	**MC, RJ, JZ**	**11/04/21**

Originated by: Rajveer Jandir	**Approved by**:

Meeting Minutes

Project	Honours Project A - Coiled Tubing Drilling for Mineral Exploration
Agenda	• ME to instruct a better way for meeting minutes • Discussion on next stages of the project • Discussion on research proposal task • Discussion on spending allocated fund – what can be spent on • Scholarship/grant presentation
Date	14/04/2021
Location	Zoom – online
Attendees	Michael Evans (ME), Tim Lau (TL), Rajveer Jandir (RJ), John Zhovnyak (JZ) and Max Cabato (MC)
Apologies	Soren Soe (SS), Ben van der Hoek (BH), Shane Fox (SF)
Circulation	As above

Item	Minutes	Action by	Date
	Overview Post literature review submission meeting to discuss the agenda suggested above		
1	ME to instruct a better way for meeting minutes		
	-ME sent a suggested meeting minutes template and provided instruction how to work on it. -Need to keep a record of an evolution of an idea. Ideas need to be recorded. -Include headings of the sent by ME in the meeting minutes.	JZ/MC/RJ	
2	Discussion on next stages of the project & Discussion on research proposal task		
	- MC asks what what is the overall aim of the project. The overall aim is to design a drill bit that works in the type of ground that SS indicates (ME). -Objectives need to be broken down on how we are going to get to that aim. -ME asks about the shared aims and gaps found. ME advises to start sharing and copying the aims and gaps to one document. -ME asks about design gaps. How do we intend to address that. Doing FE involves a lot of FEA. How we plan to address those suggested gaps. -RJ identified gaps in bearings and materials. -TL advised to ask SS data of drilled bit data. Such as MATLAB of other output files. -ME asks if the bearing are sealed they can't be monitored. If something happens inside the bearing, we would see a change in temperature within the bearing. -ME advised to find correlation between different rock hardness. Then define material hardness required. -MC suggested to aim for the medium rock formation. RJ suggest working with 500nm torque as required by SS.		
3	Discussion on spending allocated fund – what can be spent on		
	- MC asks ME what the funds can be spent on. - ME went through the presentation required. - TL suggested the idea of the funding is related to the project. Such as accelerometers, sensors. Site visit can be also counted for the funding. - Project team to start working on the slides. Suggest what we plan to spend the money on.	MC/JZ/RJ	
4	Scholarship/grant presentation		
	- Two print to be covered by ME. - Individual presentation.		

General Wrap Up			
1	**Spend time and think what the funding can be spent on**	**JZ/MC/RJ**	**20/04/2021**

Originated by: J. Zhovnyak	**Approved by**:

Meeting Minutes

Project	Honours Project A - Coiled Tubing Drilling for Mineral Exploration
Agenda	• Presentation availability discussion • Funding ideas for the $1k • Next steps for research proposal
Date	21-04-21
Location	Zoom Meeting
Attendees	Michael Evans (ME), Tim Lau (TL), Rajveer Jandir (RJ), John Zhovnyak (JZ) and Max Cabato (MC)
Apologies	Ben van der Hoek (BH), Soren Soe (SS), Shane Fox (SF)
Circulation	As above

Item	Minutes	Action by	Date
1	**Purpose of Meeting**		
	To review previous action items, discuss MinEx Presentation logistics, Possible usage of funding and next steps for research proposal.		
2	**Meeting Agenda**		
	1. Apologies 2. Review Previous Action Items 3. Presentation availability discussion 4. To discuss MinEx presentations 5. Funding ideas for the $1k 6. Next steps for research proposal		
3	**Ongoing Action Items**		
	1. Keep records of evolution of ideas		
	2. MinEx presentations		
4	**Milestones**		
	MinEx CRC Presentation	JZ, RJ, MC	14/05/21
	Report Draft	JZ, RJ, MC	19/05/21
	Research Proposal Final Submission	JZ, RJ, MC	13/06/21
5	**Student Hours Worked**		
	John Zhovnyak		
	Rajveer Jandir		
	Max Cabato		
6	**Current Minutes (Notes, Decisions, Issues)**		
	ME: Milestone each week should be MinEx presentation, Report draft & Final report		
	TL: Add all the milestones for the entire year		
	JZ: Introduces previous action items,		
	ME: Add notes/workbook for anything done, Eg. ‘20mins reading this journal this is what was found’. Eg. Spent 30 minutes sketches Record thoughts		

	Don't throw any hard copies away until end of the year		
	JZ: showing pictures of MinEx visit		
	ME: "This PDC cutter is used for soft material such as cement" suggestion for presentation.		
	TL: Meeting minutes date use order of - year month day ME: This format works for large number of meetings		
	JZ: Presentation availability discussion		
	ME: Email Soren if we can reschedule our presentations to be later time due to assessed class. Ask to present for the last 30mins for MinEx ME: Email should come from us to Soren, but ME & TL should have a look at the email prior to sending. Contents of the email should include 12pm-3pm assessed class with an assessment due at 4pm. Does Soren think there is a possibility for time to be changed, noting that there are Other Universities involved. If not, ME will email PPC course coordinator about this		
	TL: Soren to schedule the presentations to be at 3:15pm,		
	ME: Useful for career and reputational damage to the university to MinEx CRC		
	ME: Use two computers or screen recorder to record the lecture,		
	ME: Share thoughts and to be able to explain something everyone learns.		
	ME: It is individual presentations, Literature, methodologies, approach, Think of something distinct for each of us. Talk about different aspects (aims) In practice we are working as a team, working together. Realistically, one will do CAD, FEA, materials. Go through this process, pick roles, and make it clear your doing this aspect and document it on Gannt chart. For the purpose of the MinEx talk have a set focus for each of us.		
	TL: Practice presentations in front of ME,TL		
	ME: Regards to email to Soren, Soren as to: and cc: Tim and Michael, before this show email ME and TL before sending.		
	JZ: Funding ideas		
	ME: Professional Software costs 6k, ANSYS is 2k for annual licence Library has the capacity to charge Books will most likely charge if conference/journal very unlikely to charge. Academic Articles should not be a problem, conference proceedings can be expensive External consultation – engineering certifications Materials/bearing/sensors – very broad Presentation in 14th of May Will have brainstorming session with Soren Email midday-Thursday		
	ME: need 3-4 aims, aim 4 is create appropriate design for manufacture.		
	ME: SMART goals, SMAR parts are key. Take inspiration of SMART and try write down 4 four aims with one as industry/manufacture ready design. Detailed drawings not locked in. ME wants to see some specific goals. For report 3 aims, for MinEx 1 for each of us TL: test, measure outcomes. ME: If using FEA how do you measure these outcomes?		

	ME: does not like Calibri, likes text in Times		
	TL: Tip use charts, block charts, mind map, dot points view ideas.		

Action Items			
1	**Rajveer to the update Gantt chart**	**RJ**	
2	**Specifically invite Soren to next face-face meeting**	**ME**	
3	**Write 3 aims how to achieve it email to ME**	**RJ, MC, JZ**	
4	**Rajveer to email draft ME, about MinEx Presentation situation**	**RJ**	**21/04/21**
5			

Student Hours Worked

Name	*Since last meeting*	*Total*
Rajveer Jandir	0	0
Max Cabato	0	0
John Zhovnyak	0	0

Originated by: Max Cabato	**Approved by**:		
Next meeting date:28/04/21			
1	**Agenda**		
	1. Presentation with MinEx – To discuss with Soren		
	2. Discussion about aims		
	3. Further discussion about research proposal		
	4. Discussion with Soren with how to proceed further		
	5. Ask Michael when draft for proposal is due		
2	**Review Previous Action Items**		
3			
4			
5			

Meeting Minutes

Project	Honours Project A - Coiled Tubing Drilling for Mineral Exploration
Agenda	1. To discuss the MinEx presentation with Soren. 2. Discussion on research proposal aims. 3. Further discussion about the research proposal. 4. Discussion with Soren on his expectation of the research proposal and aims. 5. Draft presentation discussion/expectations. 6. Draft research proposal expectations and due date.
Date	28/04/2021
Location	University of South Australia, Mawson Lakes Campus P1-23
Attendees	Michael Evans (ME), Tim Lau (TL), Ben van der Hoek (BH), Soren Soe (SS), Shane Fox (SF), Rajveer Jandir (RJ), John Zhovnyak (JZ) and Max Cabato (MC)
Apologies	Ben van der Hoek (BH), Soren Soe (SS), Shane Fox (SF)
Circulation	As above

Item	Minutes	Action by	Date
1	Purpose of Meeting		
	To review previous action items, discuss research proposal expectations and due date, discuss MinEx CRC project funding presentation.		
2	Meeting Agenda		
	1. Apologies 2. Review Previous Action Items 3. To discuss the MinEx presentation with Soren. 4. Discussion on research proposal aims. 5. Further discussion about the research proposal. 6. Discussion with Soren on his expectation of the research proposal and aims. 7. Draft presentation discussion/expectations. 8. Draft research proposal expectations and due date.		
3	Ongoing Action Items		
	1. MinEx CRC draft presentation		
	2. Research proposal draft		
4	Milestones		
	Preliminary Report		
	Literature Review		
	Quiz 1		
	Quiz 2		
5	Student Hours Worked		
	JZ:		
	RJ:		
	MC:		
6	Current Minutes (Notes, Decisions, Issues)		
	TL: Have a specific aim and ask why and how?		
	ME: Start with WHY? Why do the project? For intro		

	TL: Convince the reader why they should keep reading. ME: convince the reader why they should trust it.		
	ME: Narrow down the design TL: dot points down the information ME: self-referenced documents “preference against it" fine to do it		
	TL: demonstrates the into methodology. ME: Huge picture, future work, huge problem, and this is how you address. ME: The reader should look at the document as one person wrote it. Allocate sections and proof-read. TL: Non-students write Lit rev as a list. Ex: Author A did this, Author B… Convey relevant stuff and why it is important (Convey a story). JZ: Raise a point and back it up. ME: References should not be out of bracket (avoid). ME: Use a lot of references (multiple references in text to back up facts). ME: Spamming references across paragraphs. ME: That is a formatting discrepancy (Havard) so acceptable.		
	JZ: Research aims? ME: Last section should be knowledge gap. Conclude this is gaps and next section addresses the gaps. ME: Research aims and objective should have a into paragraph. ME: Aims should align with gaps. Last aim should have manufacturing, although manufacturing would not have much gaps. ME: Oversight and guidance will be provided but aims need to developed by us.		
	JZ: Research proposal linked to work in Honours B? ME: Honours A marking – Cris and ML Honours B marking- ML and other academic. TL: What are you doing with aims? TL: Material A contacts rock and binding and agents hold material B. How do you plan to justify your reasoning? ME: Materials A, B, C, D, E but lit rev of material A is not an aim. ME: Tool bits connected to some layer …. (show dynamic relationship by FEA) TL: Show justification by FEA (geometry, cutting angles, low Torque). ME: Bearing is mechanical design and not FEA. TL: Use signal processing to get previous data. ME: demonstrates the bearing on white board. Transient spectrum analnysis not required. Play with Forces and torque and see the results. (Spring connection and dampers) JZ: Safety issues to consider? ML: Risk of going under lockdown, someone gets hit by bus, someone gets removed from the project, supervisor leaves the university and address these issues. ML: Risk assessment – the nature of hazard without any checks or balance and control. Address mitigation. JZ: Logistics in Gantt chart? Detailed schedule. ML: Lead time if we are buying something.		
	ML: Ultimate outcome, broad aims. RJ: Which pictures to use? TL: Pictures, flowcharts and graphs with references. ML: Point towards question marks and synthesize. Draw numerical experiment and label as rock. JZ: Can use flowchart? ML: Nope, next semester there will be a presentation and viva. TL: Do not forget to put the aims in slides. ML: Draft presentation by next week and present by standing. ML: Slides up by next week 5th May.		

	ML: 16th May Draft research proposal. ML: Won't reply if draft is submitted in last week. ML: Everything already written can be done in the research proposal. ML: Hard drawn sketch used in presentation can be used in research proposal (Neat, tidy and hand drawn sketch). ML: Write Methodology section and put initial decisions.		
	JZ: Can we give up on the money? ME: Nope. Try to have good relationship with Soren.		

Action Items			
1	**Draft Presentation – 5th May**	**JZ, RJ, MC**	
2	**Research Proposal Draft – 16th May**	**JZ, RJ, MC**	
3	**Ask In class assessment extension from Dr. Lee**	**ML**	
4	**Email Soren**	**RJ**	
5	**n/a**		

Student Hours Worked

Name	***Since last meeting***	***Total***
Rajveer Jandir	2	2
Max Cabato	2	2
John Zhovnyak	2	2

Originated by: Rajveer Jandir	**Approved by**:		
Next meeting date: 5/05/2021			
1	**Agenda**		
	Draft Presentation		
	Research Proposal		
2	**Review Previous Action Items**		
3			
4			
5			

Meeting Minutes

Project	Honours Project A - Coiled Tubing Drilling for Mineral Exploration
Agenda	1. Apologies 2. Review Previous Action Items 3. Draft Presentation 4. Research Proposal
Date	05/05/2021
Location	University of South Australia, Mawson Lakes Campus P1-23
Attendees	Michael Evans (ME), Rajveer Jandir (RJ), John Zhovnyak (JZ) and Max Cabato (MC)
Apologies	Ben van der Hoek (BH), Soren Soe (SS), Shane Fox (SF), Tim Lau (TL),
Circulation	As above

Item	Minutes	Action by	Date
1	Purpose of Meeting		
	1. To review previous action items, discuss research proposal expectations and due date, discuss MinEx CRC project funding presentation. 2. Action from previous meeting: ~~- Draft presentations (JZ/MC/RJ)~~ ~~- Research proposal review~~ ~~- Ask in class assessment (TL/ME)~~ ~~- Email Soren (RJ)~~ 3. Review presentation and practice presentation		
2	Meeting Agenda		
3	1. Apologies 2. Review Previous Action Items 3. Draft Presentation 4. Research Proposal discussion		
4	ME recommends to start taking ANSYS tutorials. ME to provide assistance with ANSYS. Project team to decide if they are going to do FEA. Project team to decide if they want to use ANSYS/SolidWorks	JZ/RJ/MC	
5	Project team to download ANSYS student edition Project team to create account in Leap Australia Academic Portal.	JZ/RJ/MC	
6	RJ asks what happens with the Minex funding ME mentions that testing materials can be used.		
7	Project team to focus on conceptual design. Then think about materials currently used in the industry from existing specs. Bearing selection to follow same method by looking at catalogues. Project team to outline the idea on a paper. Initial FEA to rely on existing designs. Project team to find verification in literature (experimental).		
8	MC to find literature items of existing FEA. Potential verification models.	MC	Next meeting
9	ME to send ANSYS tutorials to project team	ME	
10	ME to email Soren about expenditure	ME	

Action Items			
1	ME to email Soren about expenditure		12/05/2021
2	MC to find literature items of existing FEA. Potential verification models.		12/05/2021
3	Project team to download ANSYS student edition		12/05/2021

	Project team to create account in Leap Australia Academic Portal.		
4	Project team to decide if they are going to do FEA. And the type of the package		12/05/2021
5	Project team to send ME their draft presentations	RJ/MC	06/05/2021

Student Hours Worked

Name	***Since last meeting***	***Total***
Rajveer Jandir	20	24
Max Cabato	20	24
John Zhovnyak	20	24

Originated by: John Zhovnyak	**Approved by**:		
	Agenda for the next meeting date: 12/05/2021		
1	**Practice presentation**		
2	**Discussion on FEA package following MC trials and the if we want to do FEA**		
3	**Ask ME if he discussed SS about the funding**		
4	**Review feedback on literature review and discuss next steps of research proposal**		
5	**Review Gannt chart**		
6			
7			

Meeting Minutes

Date of Meeting: (12/05/2021)

Location:	**UniSA Mawson Lakes Campus P1-23**
Minutes Prepared By:	Max Cabato
Start Time & End Time:	10am to 11am

1. Purpose of Meeting

To discuss the previous action items and practice the MinEx presentations.

2. Meeting Agenda

1. Apologies
2. Review Previous Action Items
    a. MC to find literature items of existing FEA. Potential verification models.
    b. Project team to download ANSYS student edition
    c. Project team to create account in Leap Australia Academic Portal
3. Practice presentation
4. Research Proposal to discuss further
    a. o Methods section
    b. o Design concepts
    c. o Project risk/management

3. Attendance at Meeting

Michael Evans (ME), Tim Lau (TL), Rajveer Jandir (RJ), John Zhovnyak (JZ) and Max Cabato (MC)

4. Apologies

Soren Soe (SS), Tim Lau (TL)

5. Current Minutes (Notes, Decisions, Issues)

JZ: Currently no feedback and marks from literature review

ME: Plenty of time to make revisions, Lit. Review feedback is not a stage gate.

ME: Ask if there is any feedback for the literature for review today, if there is anything glaring about the literature review.

ME: Sending a second or third draft of research proposal report to Soren.

RJ: Asks about methodology

ME: Material sample testing, bearing testing.

ME: There are numerous ways to do bearing testing, e.g. Using impact or hammer drill to apply forces on bearings and submerging it in 'soil-fluid mixture' and observing its effects.

ME: How best can we replicate these forces for lab testing to damage bearings.

RJ:

ME:

JZ: Asks regarding the MinEx Funding

ME: Obligations of funding - presentation and encouraged to attend conference, acknowledgments MinEx in whatever we do. MinEx needs a copy of the thesis/report.

ME: Thanking people and financial support of MinEx

ME: Practice the presentation so it feels natural and not fully scripted.

ME: Put public images of Coiled Tube Drilling in thesis aim.

ME: Gantt chart - suggest putting time off for JZ and planning ahead of time.

ME: Put milestones in the Gantt chart.

RJ: Practises Presentation

ME: Spit the methodology into several parts so the image is readable. (Regarding RJ presentation)

ME: "Current designs are unsuitable for this scale"

ME: Slide 3, too much info – focus on the bearings.

ME: "Visits will be undertaken" - comment on RJ slides

6. Action Items

Action	***Assigned to***	***Due date***	***Status***
Send gantt chart as PDF to Michael	RJ	13/05/21	
Start risk assesment	RJ/JZ/MC	19/05/21	
Work on research proposal draft	RJ/JZ/MC	16/05/21	

7. Next Meeting					
Date: (19/05/2021)		*Time:*	*10am*	*Location:*	*P1-23*

Agenda:

1. Apologies
2. Review Previous Action Items
3. Discuss the research proposal draft.
    a. Methods section
    b. Design concepts
    c. Project risk/management
    d. Review Gantt Chart
4. Review presentation performance

Meeting Minutes

Date of Meeting: (19/05/2021)

Location:	**UniSA Mawson Lakes Campus P1-23**
Minutes Prepared By:	Rajveer Jandir
Start Time & End Time:	10:00 am to 11:00 am

1. Purpose of Meeting

To discuss the previous action items and draft research proposal.

2. Meeting Agenda

1. Apologies
2. Review Previous Action Items
   a. Review Gantt chart.
   b. Start Risk assessment.
   c. Work on research proposal.
3. Discuss the research proposal draft items: Methods section, Design concept, Project/Risk management, and Review Gantt chart.
4. Review presentation performance.

3. Attendance at Meeting

Michael Evans (ME), Tim Lau (TL), Rajveer Jandir (RJ), John Zhovnyak (JZ) and Max Cabato (MC)

4. Apologies

Soren Soe (SS)

5. Current Minutes (Notes, Decisions, Issues)

MC starts the meeting with and asks about research proposal.

ME & TL congratulate us on lit review feedback.

JZ says he has started populating research proposal draft.

JZ asks about methodology section.

ME: Talk about conceptual approach and quantitative and qualitative methods. Call section 4 as methods as it is more than research such as aspect of design.

ME: Intro needs to be revised and find something generalised from ABS. Define the overall aim of the project in last paragraph of intro.

ME: Re shuffle paragraphs in introduction and background.

JZ: Keep Background topic or not?

TL: Get rid of it and replace.

ME: The title “background” needs to move down.

TL: paragraph must be dedicated to the image when they appear.

ME: Use formal numbered headings. Abstract or summary needs to be there and should be descriptive.

TL: In the first sentence of every paragraph the reader must know what the paragraph is talking about.

ME: backs up TL’s claim or advice.

TL & ME give general sentence writing advice.

ME: Does not like direct reference to the previous paragraph.

JZ asks on how to start sentences and makes comments in word report.

MC asks about the paragraph layout.

ME responds and explains do not force yourself to change your writing style based on others pressuring you.

JZ asks about the Materials section.

ME: same methodology as before.

TL & ME says pictures must be there to explain the research proposal.

JZ: can the presentation pictures work?

ME says yes and add MinEx rig picture in introduction section.

ME: avoid the words such as in conclusion and summary.

JZ says he is confused.

TL gives an example of a sentence and clears confusion.

ME: Research aims and objectives can be expanded and number the points.

TL & ME advice it is the most important section and add bearings.

ME: Gaps must align with aims as it is easy to follow and mark.

TL reads the aims out loud and asks point 2.

JZ explains and Tim is convinced.

ME: explains again why aims and gaps should align. Addressing the gaps are important.

TL says computational model can improve increased durability.

ME asks Max about FEA and whether it can address the points.

MC: Explains his findings.

ME says there should be a correlation between gaps and findings.

ME asks about rubric to make amendments to the template.

RJ asks if ME follows the marking rubric.

ME says sometimes WHS must include WHS.

ME and TL says ignore ethics approval.

6. Action Items

Action	*Assigned to*	*Due date*	*Status*
Send gaps and aims, introductionn to ME	JZ, MC, RJ		In progress
Email ME the gantt chart	RJ		In Progress

7. Next Meeting

Date: 26/05/2021		*Time:*	*10am*	*Location:*	*P1-23*

Agenda:

1. Apologies
2. Review Previous Action Items
   a. Review Gantt chart.
   b. Introduction, Gaps, Aims.
   c. Review on research proposal.
3. Discuss the research proposal draft items: WHS & Ethics approval, Logistics & Budget, Project timeline (Appendix or needs volume by adding text).
4. Discuss the revised methodology.

Meeting Minutes

Date of Meeting: 26/05/2021

Location:	**UniSA Mawson Lakes Campus P1-23**
Minutes Prepared By:	John Zhovnyak
Start Time & End Time:	10:00 am to 11:00 am

1. Purpose of Meeting

To discuss the previous action items and draft research proposal.

2. Meeting Agenda

1. Apologies
2. Review Previous Action Items
    a. Review Gantt chart.
    b. Introduction, Gaps, Aims.
    c. Review on research proposal.
3. Discuss the research proposal draft items: WHS & Ethics approval, Logistics & Budget, Project timeline (Appendix or needs volume by adding text).
4. Discuss the revised methodology.

3. Attendance at Meeting

Michael Evans (ME), Tim Lau (TL), Rajveer Jandir (RJ), John Zhovnyak (JZ) and Max Cabato (MC)

4. Apologies

Soren Soe (SS)

5. Current Minutes (Notes, Decisions, Issues)

RJ: review of Gantt chart – ME indicates that we need all the activities to finish the report such as drafting, milestone reports in SP5, VIVA and presentation also are part of the submissions,.

Remove: quizzes, weeks from column A.

Leave: tasks required actually to do our project, coloured bars, make logical connection between activities

Important: Plan for the whole academic year and who does what. Activities to plan are testing, FEA etc…

End of October submission date and plan the project backwards. Don't this about this as a course, but think as a year long project.

Make resolution of weeks.

TL: list of all activities required to complete the project.

Presentation slides in SP5: 3 weeks in advance.

Gantt: in appendix on A3 page.

Timeline: to be done as a WBS with a rough column of weeks. Make a comment "details are presented in the Gantt chart in the appendix".
Aim: focus on designing within the scope. Focus on materials that we need to drill within. Select a combination of materials out of the literature review. Focus more on the design constraints (geometry). Think about how the new design can protect the bearing. If bearing doesn't work, investigate why bearings don't work.
RJ: funding question: Why can't a student spend money on personal equipment upgrade. UniSA provides the funding to MinEx as a small grant. Any purchase to be adhered to UniSA's policy.
Research proposal: show what and how you are going to do it. That's is the most important part. Add section in methodology of what work has been done so far.

6. Action Items

Action	***Assigned to***	***Due date***	***Status***
1. Sunday night to send final draft to ME along with the mintutes	JZ	26/05/2021	
2. Ask SS what "medium hardness is", what is the range. Do we need other infomrtaion from SS?	JZ/RJ/MC		

7. Next Meeting

Date: (02/06/2021)		*Time:*	*10am*	*Location:*	*P1-23*
Agenda:	1. Apologies 2. Review Previous Action Items 3. Review research proposal draft				

Meeting Minutes

Date of Meeting: 02/06/2021	
Location:	**Zoom Meeting**
Minutes Prepared By:	Max Cabato
Start Time & End Time:	10:00 am to 11:00 am

1. Purpose of Meeting

To discuss the previous action items and draft research proposal.

2. Meeting Agenda

1. Apologies
2. Review Previous Action Items
3. Discuss the research proposal draft.

3. Attendance at Meeting

Tim Lau (TL), Rajveer Jandir (RJ), John Zhovnyak (JZ) and Max Cabato (MC)

4. Apologies

Soren Soe (SS), Michael Evans (ME),

5. Current Minutes (Notes, Decisions, Issues)

TL: General Comments on draft,
Formatting is good, Introduction is good, figures good.
Very good to show these drill bits are very different to traditional drill bits. Describe failure modes as either sub section or separate paragraph. Specify where you will talk about the failure modes below
Why low torque? – above in introduction if it does not flow place in 2.0
2.1 Find a figure to break up the paragraphs

2.2 / 2.3 Figures, for materials and bearings, Is it a typical bearing? Or something different.
2.4 GAPS – 2 highlighting “failure analysis” what is it? it could very large or small. It is not clear. Have more clarity on what is the intention? Is it within the timeframe of the project? and communicate it to the reader.
Aim 4 Make sure we know how we are going to do achieve this aim.
Aim 5 – find the requirements for this aim.
4.0 Methods – Key weakness in the report. Should have clear intentions, will it require manual testing. Wil software be enough?
Ex. Concept design. Testing plan, Intentions in mind.
2d or 3d, the how must be clear to achieve the 5 aims.
Provide a description of the procedures with a preliminary design.
Put FEA example in the lit review.
Put emphasis on our choices, broad range lit review, FEA, combine lit review,
Imperial calculations and FEA.

Broad methods in methodologies
More details in research methods
Last sentence must be the strongest – explain it and provide references to other papers.
Model validations – case study or example to follow.
4.2.4 Consider a figure
6.1 in prices, put an indicative value and how much is needed (materials).
Gantt Chart – make sure there is enough time for FEA
FEA will take months and months, start soon
Concepts design into FEA,
Validations – how do we know it is working?
Replicating someone's case study or example to be able to validate.

Start working on model validation.

6. Action Items

Action	***Assigned to***	***Due date***	***Status***
1. Review and Address comments made by TL	MC/JZ/RJ	03/06/21	

7. Next Meeting

Date: (09/06/2021)		*Time:*	*10am*	*Location:*	*P1-23*
Agenda:	1. Apologies 2. Review Previous Action Items 3. Review research proposal draft				

Meeting Minutes

Date of Meeting: (09/06/2021)

Location:	**UniSA Mawson Lakes Campus P1-49**
Minutes Prepared By:	
Start Time & End Time:	2pm to 3pm

1. Purpose of Meeting

Review of proposal draft

2. Meeting Agenda

1. Apologies
2. Review Previous Action Items
3. Draft of research proposal

3. Attendance at Meeting

Michael Evans (ME), John Zhovnyak (JZ) and Max Cabato (MC)

4. Apologies

Soren Soe (SS), Tim Lau (TL), Rajveer Jandir (RJ)

5. Current Minutes (Notes, Decisions, Issues)

ME: More details in Methods, specifics, and intention.

Scope is about range

Conceptual designs are not an aim

Testing samples of hardness or strength of formations??

Large range of medium hardness, need some idea for what medium-hardness strength before getting specifics.

Model verification should have started.

Gantt chart: ME was terrified, needs major changes, bring everything forward as much as possible.

Lose marks due to unrealistic expectations, must work in parallel.

Final draft with all results 1 month before submission

Chat to Soren in obtaining rock samples for possible testing and obtaining real times data.

Tables are best for quantitative data

Text should be legible, no smaller than the figure sizes.

Do not change testing of material just change focus on testing of rock samples. compression testing of brittle formations.

Show WBS as figure in appendix and summary of WBS in a table. Assign roles. Show effective use of each member's time.

Flow chart: Unverified FEA is the easiest way to lose marks.

Need to start with verification then go on to models

What is the verification? Does not need be hand calculations.

Experiments, verifications.

If we have scenarios we can test, use them.

References and equations and figures of verifications.

Use figure to illustrate the range of different hardness rock formations with a range of medium hardness.

Table of properties for materials within medium hardness range. Fracture toughness and UCS etc.

Should have an Abstract.

Risks of lab work should be identified.

No ethics in breaking rocks

Ethics of mineral exploration is different in ethics of mining. Beyond scope.

No worry about patents.

Hybrid – does it need hammering?

When report is done send it to Soren. Have a statement to show where points of interest can be found.

Use the Gantt chart as a Gantt chart not just to as a document to get marks.

Feedback allows for misinterpretations and missing parts to be corrected.

Busy is normal – Needs a level of commitment as a job.

D level shows confidence

HD very good understand of whats out there, why were doing this project with good level of polish

Good level of detail to the best of your knowledge to complete the project on time.

6. Action Items

Action	***Assigned to***	***Due date***	***Status***
Finish Research Proposal	JZ/RJ/MC	13/06/21	
Send Research Proposal to Soren	JZ/RJ/MC	13/06/21	

7. Next Meeting

Date:(/06/2021)		*Time:*	*10am*	*Location:*	*P1-23*
Agenda:	1. Apologies 2. Review Previous Action Items 3. Next actions.				

Meeting Minutes

Date of Meeting: (16/06/2021)

Location:	**UniSA Mawson Lakes Campus P1-23**
Minutes Prepared By:	
Start Time & End Time:	10-11am

1. Purpose of Meeting

Review of proposal draft

Discuss Gantt

Discuss next steps

2. Meeting Agenda

1. Apologies
2. Review Previous Action Items
3. Exam period meetings discussion
4. Review Gantt, research proposal, next steps

3. Attendance at Meeting

Michael Evans (ME), John Zhovnyak (JZ) and Max Cabato (MC), Rajveer Jandir (RJ), Tim Lau (TL),

4. Apologies

Soren Soe (SS),

5. Current Minutes (Notes, Decisions, Issues)

Soren suggested to ME that the hardness range is from 60 – 100 mpa.
JZ Asks is there any value of testing if data is known?
ME says yes, as it is a component of research project to prove methodology.
Soren will send someone to attend meetings soon.
ME: Fix weeks in the Gantt chart caption
JZ & RZ: Can we meet next on 1st July?
ME: says spend couple hours every two days to keep the project on track.
MC: trying to learn SolidWorks and ANSYS.

ME suggests stick to one, rather than both.
ME says keep working on project to keep the project fresh in mind and asks for dates.
RJ asks about this year's final presentation.
ME says start early to SolidWorks.
ME asks what work is scheduled for next two weeks.
MC suggests verification model.
RJ asks about the cross referencing the tables.
ME demonstrates the method to do it.
ME says do not number to appendix and reference list.
ME gives us the hassling rights to contact him via email.

6. Action Items

Action	***Assigned to***	***Due date***	***Status***
Project team to send a of research proposal to ME	JZ/RJ/MC	17/06/21	
Send ME & TL the availability for SP5	JZ/RJ/MC	17/06/21	
Sen ME availability for exam period meeting	JZ/RJ/MC	17/06/21	
Start formulating the next steps	JZ/RJ/MC	19/06/21	

7. Next Meeting

Date:(/06/2021)		*Time:*	*10am*	*Location:*	*P1-23*
Agenda:	1. Apologies 2. Review Previous Action Items 3. Next actions.				

Meeting Minutes

Date of Meeting: (30/07/2021)

Location:	**UniSA Mawson Lakes Campus P1-23**
Minutes Prepared By:	Rajveer Jandir
Start Time & End Time:	1:00 pm to 2:00 pm

1. Purpose of Meeting

To discuss the previous action items and draft research proposal.

2. Meeting Agenda

1. Apologies
2. Review Previous Action Items
    a. Verification model.
    b. Bearings, UCS values
3. Discuss the research proposal draft items: Verification model, Design concept, next steps, progress report.
4. Review findings..

3. Attendance at Meeting

Michael Evans (ME), Tim Lau (TL), Rajveer Jandir (RJ), John Zhovnyak (JZ) and Max Cabato (MC)

4. Apologies

Soren Soe (SS)

5. Current Minutes (Notes, Decisions, Issues)

ME: Start working in parallel.
MC asks about SolidWorks modelling and verification modelling.
ME: Do not do that, there will be problem with meshing (poor mesh, results will be worse) basically bad practice. As we will have to repair the geometry.
JZ: Simplified geometry?
ME: If it is simple use ANSYS itself.
ME not a pleasant task using SolidWorks as a modelling software if ANSYS is required for simulation.

MC: 128,000 nodes limitation or fine?
ME depends on what you are trying to achieve.
ME finds the verification paper to be rubbish and questions why have they used full depth, scale & Number of nodes?
MC questions the legitimacy of the paper.
ME responds ANSYS is linear, and quadratic and thermals will be an issue due to wrong focus of mesh.
TL suggests use a simpler model to get started with ANSYS.
ME approves and suggest use a coarser mesh. Summarise all the papers in couple lines and outline findings in a single document.
ME says use a clever approach rather than taking a full approach.
ME says signup for Leap Australia.
MC asks if MinEx approval is required for design?
ME says seek approval from ME and TL first for recommendations and changes.
ME says do not worry about cost (ME thinks).
TL asks what we envision in the thesis?
ME says there are quizzes in the course expect that everything is related to project.
MC replies to manufacturing drawings, concepts and FEA

ME says manufacturing drawings is a week's job. Focus on design should be higher and will be more rewarding.
Make tweaks to Gantt chart.

RJ asks about progress report.
ME says 2 pages, does the student know what and why they have done it, demonstrate what needs to be done to successfully finish the project.
ME says email ME as we submit progress report or remind him a week prior.
TL asks about when we must present findings to MinEx.
ME suggests and asks if 2 weeks' time is fine?
Write a progress report for Soren – something (design, bearings, FEA, and where money is spent) that can be read in 10 minutes.

JZ asks comprehensive verification questions.
ME says try modelling and importing into ANSYS if it works or not.
Step or Parasolid may work without issues. Basically, we may get away.
Keep minimum number of complexities (demonstrates on white board).

ME is happy to setup consulting time.

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6. Action Items

Action	*Assigned to*	*Due date*	*Status*
Summarise papers in couple lines outlining our findings and email Michael.	RJ/MC/JZ		Completed
Signup for Leap AU and discuss models with ME about our model.	RJ/MC/JZ		Completed
Update Gantt chart	RJ		Completed
Remind ME about room booking for FEA meerting	JZ		Completed
Send Email to ME when we submit progress reports.	RJ/MC/JZ		TBD
Write a progress report summarizing it for Soren.	RJ/MC/JZ	14/08/2021	In progress

7. Next Meeting

Date: (6/08/2021)		*Time:*	*1:00 to 2:00 pm*	*Location:*	*P1-23*

Agenda:

1. Apologies
2. Review Previous Action Items
   a. Gantt chart
   b. Verification modelling
   c. CAD Package – ANSYS, SolidWorks progress
3.
4.

Meeting Minutes

Date of Meeting: (13/08/2021)	
Location:	**UniSA Mawson Lakes Campus MM3-20A**
Minutes Prepared By:	John Zhovnyak
Start Time & End Time:	1:00 pm to 2:00 pm

1. Purpose of Meeting

To discuss the previous action items and draft research proposal.

2. Meeting Agenda

1. Apologies
2. Review previous action items
3. Review of research proposal
4. Review final project template
5. Next steps with verification models
6. Minex engagement
7. Design constrains – complete missing data
8. Progress report
9. Review concepts & design constraints (with MinEx) – if possible narrow down concepts
10. CAD modelling

3. Attendance at Meeting

Michael Evans (ME), Tim Lau (TL), Rajveer Jandir (RJ), John Zhovnyak (JZ) and Max Cabato (MC)

4. Apologies

Soren Soe (SS)

5. Current Minutes (Notes, Decisions, Issues)

Project template: Methodofly secyion is a waste of time/space. Use the same as used in research proposal. Use the research proposal file and continue working on it.

Verifictionm model has been covered.

MinEx stakeholder engagement.
Moving forward: concepts in order that we want to do. Send to MinEx to review the concepts to 4 MinEx stakeholders to get a quick feedback. ACTION.
Send meeting minutes before 4pm.
Send concepts early Monday morning. Ask for a feedback by a certain date.
Finish with "please let me know if they need extra time".
If an email doesn't come up until Monday and send another reminder on the following Monday.

Connection diameter aim for around 50mm smooth cylinder.
Send an email to Shane or Luca ask about missing data such as RPM.

Don't worry about the flow of the cooling.

For presentation, take images from a video or FEA to describe.

Modify progress report ACTION

Look for papers published by Soren or Minex to get an idea about technical specs related to the project. ACTION.
ME states that speed should be 6000 RPM.

First full draft 8th of October – looking at results and discussion. Continue RP.

Concepts: summarise top three and ignore the high torque.
Explain which design features are causing high torque, and back it up with simulation or literature.
Expand to add other features and on the existing pros and cons.

6. Action Items

Action	***Assigned to***	***Due date***	***Status***
Summarise top three concepts and send MinEx for review and email to SS	JZ/RJ/MC	16/08/21	
Modify progres report and notify ME on submission	JZ/RJ/MC	14/08/21	
Search for papers published by SS or MinEx which are related to this project	RJ	15/08/21	

7. Next Meeting

Date: (20/08/2021)		*Time:*	*1:00 to 2:00 pm*	*Location:*	*MM3-20A*
Agenda:	1. Apologies 2. Review previous action items 3. Review validation models 4. Review selected concepts 5. Review meshing in ANSYS				

Meeting Minutes

Date of Meeting: (20/08/2021)	
Location:	**UniSA Mawson Lakes Campus MM3-20A**
Minutes Prepared By:	Max Cabato
Start Time & End Time:	1:00 pm to 2:00 pm

1. Purpose of Meeting

Review validation model and discussion of upcoming VIVA

2. Meeting Agenda

1. Apologies
2. Review previous action items
3. Review validation model - meshing & contact regions
4. Review of shortlisted concepts
5. Discussion of upcoming VIVA

3. Attendance at Meeting

Michael Evans (ME), Tim Lau (TL), Rajveer Jandir (RJ), John Zhovnyak (JZ) and Max Cabato (MC)

4. Apologies

Soren Soe (SS)

5. Current Minutes (Notes, Decisions, Issues)

VIVA: ME is the marker for all Mech Eng VIVAS. Craig will be the independent marker for us
ME: Have a response for all 16 question
ME: 5min explanation of our project.
JZ: Shares VIVA format
ME: Address all points, within 5 minutes, Craig will ask the questions, practice together, expect to not say the same thing, what you have found, what you're focusing on. Show good understand of the project. Stand out.
Next stages of the project are this, this & this. I will be doing this etc. It will happen in zoom room going into a breakout room. Supervisor will make the appointment, within these four weeks, ME will not be available four days within those four weeks.

JZ & RJ have a presentation next Friday

ME: Advises to send email of availability times. ME will not be able to attend next weeks meeting.

ACTION: Send times we cannot do and when we're available to any times between 9am-5pm

TL: don't over prepare, don't have a script, "pretend your going out with friend setting"
ME: Get action items done, Time is running out. Be very conscious of the time.
ME: Doesn't understand the suggested improvements column
ACTION: Change suggested improvements column – modifications on concepts

ME: Reputable source is what matters with regards to materials.

RJ: Review of validation model

ME: Look into thermal-transient videos/tutorial.
Validation model: investigate element death based on strain.
Try 1/6 model for element death
Check boundary conditions

Action: Send Soren concepts and inform him about our start date for design.

6. Action Items

Action	***Assigned to***	***Due date***	***Status***
~~Send MinEx concepts for review and email to SS about~~	JZ	27/08/21	
~~Send availablity times between 9am-5pm for VIVA within Wk5-7~~	JZ/RJ/MC	27/08/21	
Look into thermal-transient videos/tutorials/ - element death and create 1/6 model	MC	27/08/21	
Materials Investigation	RJ	27/08/21	

7. Next Meeting					
Date: (27/08/2021)		*Time:*	*1:00 to 2:00 pm*	*Location:*	*MM3-20A*
Agenda:	1. Apologies 2. Review previous action items 3. Review validation models updates 4. Review selected concepts with response from Soren				

Meeting Minutes

Date of Meeting: (3/09/2021)	
Location:	**UniSA Mawson Lakes Campus MM3-20A**
Minutes Prepared By:	Rajveer Jandir
Start Time & End Time:	1:00 pm to 2:00 pm

1. Purpose of Meeting

To discuss the previous action items and draft research proposal.

2. Meeting Agenda

1. Apologies
2. Review previous action items
3. Review validation models updates
4. Review selected concepts with the response from Soren
5. Validation model.
6. CAD Model
7. Materials
8. VIVA - Can we have notes in form of bullet points?
9. Proving design by research papers or FEA?
10. FEA on the roller and PDC blades enough?

3. Attendance at Meeting

Michael Evans (ME), Tim Lau (TL), Rajveer Jandir (RJ), John Zhovnyak (JZ) and Max Cabato (MC)

4. Apologies

Soren Soe (SS)

5. Current Minutes (Notes, Decisions, Issues)

MC: FEA Model transient analysis code
ME carefully reviews the code and questions if it works.
MC could run the simulation only for a few minutes.
ME recommends Nset.
TL recommends reducing the tolerance to kill it.
ME recommends making changes in line 17 & 19 of the code to kill it.

JZ asks what if we cannot validate the models.
ME responds then we will have to reassess. If one parameter of the validation cannot be assessed, move to the next one.
TL recommends try to understand the reasons behind validation not working.
ME says start thinking about contingencies and he expects all three of us to do FEA in parallel.
Look at side loads for bearings.

In terms of final presentation, the first guy gives a bigger picture and the other two will follow up.
Try to implement codes (element kill), verification model.
JZ asks about the Michael's contradicting statement.
ME says try to do a bit of everything and play with words (basically be careful that you are not in a supportive role).
Be careful with marking as it is careful.

TL asks about holes in the rollers.
JZ answers rollers and assembly will be made to one part.
ME says rollers to be separate part. Have a three-body assembly. Why is the angle v shape in concept drill bit?
JZ says V shape for evacuation and cooling.

ME says second design will fail due to no fillets, high stress, and snag. Worry is always sharp geometries.

Start with bar graphs, sensitivity analysis (formulas with differential equations), moisture content,
Look at three worst conditions for the drill bit (mostly dry bit). Glass temperature is important.

Q9 Both, use literature and FEA. Explain why it has not been done.

Q8 We can have notes but elaborate and have extra details. What went wrong = What have you learnt? Therefore, now we will try abc/xyz.
Q10 info from FEA and papers to justify with proper considerations.

6. Action Items

Action	*Assigned to*	*Due date*	*Status*
Verification Models	RJ/MC/JZ		
CAD Model	RJ/MC/JZ		
Materials	RJ		
Review Research Proposal and give feedback	ME		

7. Next Meeting						
Date: (10/09/2021)			*Time:*	*1:00 to 2:00 pm*	*Location:*	*MM3-20A*
Agenda:	Will send one day before next meeting					

Meeting Minutes

Date of Meeting: (10/09/2021)

Location:	**UniSA Mawson Lakes Campus MM3-20A**
Minutes Prepared By:	John Z.
Start Time & End Time:	1:00 pm to 2:00 pm

1. Purpose of Meeting

To discuss the previous action items and draft research proposal.

2. Meeting Agenda

1. Apologies
2. Review previous action items
3. Validation model
4. Material specs range + bearings findings review
5. CAD model and PDC buttons review
6. VIVA feedback
7. Spending budget (MinEx + Hons)
8. Review new action items

3. Attendance at Meeting

Michael Evans (ME), Tim Lau (TL), Rajveer Jandir (RJ), John Zhovnyak (JZ) and Max Cabato (MC)

4. Apologies

Soren Soe (SS)

5. Current Minutes (Notes, Decisions, Issues)

CAD: Try changes with small increments, such as different PDCs and angle changes
ME: Defeature curvatures for models
TL: Comparing models change only 1 factor
ME: We want to see what is most effective.
Create a criterion of what is success.
ME: Due to external CAD package lots of work to change parameters and continuous variations
TL & ME: Likes the buttons and angles. What happens when the buttons are changed first?
ME: Doesn't have to be best design for the transient case.
ME: Designs have enough FEA for two people to work on.

FEA validation model: MC to send the archived file to ME. MC to send a follow up email o arrange a time to catch up on Monday.

Materials and bearings: Put only values that required. RJ to modify.

Progress report: Put images and discuss it throughout the report. Use as an evidence to support the progress. Bullet points with short sentences. Details to show what we are doing. Show what we are planning to do between now and the next report. Plan dates with contingency. For example, verification takes 1 month. What have you tried, what have succeeded with.
Example 2: This FEA, this is what we tried, we tried to add element death, didn't work, further consultation is needed.
Use the findings and the attempts made to solve it.
Put references to images.

VIVA: ME – level of explanation was varied. Introduction is important.
Presentation: Target to a someone with an engineering knowledge. Impress people who are not aware of this project and people from MinEx CRC.
Regarding MinEx involvement: Make educated assumptions and convince ME.
When something doesn't work, don't spill negatives, but try to describe how you spin out of that.

Spending budget: make a list and send the list to ME.

6. Action Items

Action	*Assigned to*	*Due date*	*Status*
MC to send ME archived file	MC	10/9/21	
MC to send a reminder on Monday for a catch up meeting	MC	13/9/21	
JZ to continue with design refinement and angles with importing to ANSYS	JZ	7/9/21	
Review Research Proposal and provide feedback	ME	17/09/21	
Maje a list of budegt spending and send to ME	MC/RJ	13/9/21	

7. Next Meeting						
Date: (17/09/2021)			*Time:*	*1:00 to 2:00 pm*	*Location:*	*MM3-20A*
Agenda:	Will send one day before next meeting					

Meeting Minutes

Date of Meeting: (17/09/2021)

Location:	**UniSA Mawson Lakes Campus MM3-20A**
Minutes Prepared By:	Max Cabato.
Start Time & End Time:	1:00 pm to 2:00 pm

1. Purpose of Meeting

To discuss the previous action items, budget spending, presentations and plans for outcomes.

2. Meeting Agenda

1. Apologies
2. Review of previous weeks action items
3. Summary of work to date (students to "present")
4. Plan for next six weeks
5. Spending Budget Discussion
6. Validation Model
7. CAD Model Review
8. Teaching Break Meetings
9. Thesis Discussion
10. Seminars
11. Research Proposal - Feedback

3. Attendance at Meeting

Michael Evans (ME), Tim Lau (TL), Rajveer Jandir (RJ), John Zhovnyak (JZ) and Max Cabato (MC)

4. Apologies

Soren Soe (SS)

5. Current Minutes (Notes, Decisions, Issues)

RJ: Apologies
RJ: Summary of work to date.
ME: Something tangible, stuff that will be put into the thesis,
In about a fortnight makes slides to show ME and TL, its practice for the seminar
Provide a narrative to construct the presentation
Essentially a figure list to date of results.
Have a think of the results to be put in the slides.
It is an Internal presentation
Tell a story…

TL: Ways to layout the slides - Presentation of figures to present the work to date,
Have figures with arrows.
Figures with a box of dot points.

ME: 2 weeks before the final presentation, draft slides should be completed
1 week before presentation, practice presentation.
RJ: Presentation on 15th of October
ME: Allocated time, Independent but don't repeat things.
Significance of the project to the Australian economy and MinEx motivation,
"These are our team aims, I will discuss this, this and this…"
Acknowledge what our team has said.
TL: All presentations from 9am onwards back-to-back with a lunch break
Presenting sequential
ME: Marking presentations all day with Craig
RJ: Discussing the shortlisted concepts in thesis
ME: Provide depth on the shortlisted concepts.
TL: Asks about bearing connection in its effect on the other parts (FEA/Design)
JZ: Bearing's selection is dependent on the results in static-structural analysis of the model.
ME: Factor of Safety 3

ME: Static Analysis to maximise the stress of the rock and without exceeding the stress on the bit.
TL: Every stresses of the on the bit
ME: Number and size, 5 evenly spaced PDC.
ME: 5 full model for stress distributions looking a sweep angle, static, Verification: stress on a cantilever
ME: Static of the CAD models (each 4) which one applies the loads better on the rock, get rid of the other three.
PDC optimisation (restricted to small scale due to meshing).
ME: Stress concentrations can be explained.
ME: If there's room, discuss that there needs to be room for water flow.
ME: Break it down from calculations to smaller parts.
ME: Narrow down the amount of FEA, to reduce workload. I.e. pick the best model and continue on from that.

ME: Two reasons to run explicit on ME's computer: Limitless licence and time consuming
ACTION: Send ME a meeting invite for 2pm-4pm aim to capture for 1hour.
ME: Will be on leave on Thursday and Friday next week
TL: Meeting next week is up to us.
ME: The figures on our slides can be used in the presentation
ME: Regarding spending, get prices and make list to send Michael to send Soren:
ME: Wants us to spend it all
ME: Suggests ram and storage are the most plausible.

6. Action Items

Action	*Assigned to*	*Due date*	*Status*
Send ME a meeting invite for 2pm-4pm Monday on campus	MC	18/09/21	
ME to read research proposal by Monday	ME	20/09/21	
Send ME a list of prices for SSD storage and ram	MC/RJ	19/08/21	

7. Next Meeting

Date: (24/09/2021)		*Time:*	*1:00 to 2:00 pm*	*Location:*	*Zoom*
Agenda:	Will send one day before next meeting				

Meeting Minutes

Date of Meeting: (01/10/2021)	
Location:	**UniSA Mawson Lakes Campus MM3-20A**
Minutes Prepared By:	Rajveer Jandir
Start Time & End Time:	1:00 pm to 2:00 pm

1. Purpose of Meeting

To discuss the previous action items and draft research proposal.

2. Meeting Agenda

1. Draft skeleton of presentation
2. Thesis outline with subsection headings
3. Referencing images in tables - is it required?
4. Discuss timeline to receive feedback on draft thesis.

3. Attendance at Meeting

Michael Evans (ME), Tim Lau (TL), Rajveer Jandir (RJ), John Zhovnyak (JZ) and Max Cabato (MC)

4. Apologies

Soren Soe (SS)

5. Current Minutes (Notes, Decisions, Issues)

it would raise alarm bell as a reader if not using same package
Could be considered lack of planning – should Segway.
Comparative cases in ANSYS or else it could be perceived at our detriment. Not everything. ANSYS

Import a plane from Solidworks to allow for angle changes, before jumping into ANSYS consider how you're going tell the reader/ listener tell why you're using two different packages
Scattergun approach, make sure there's consistent narrative. The solvers in ANSYS and Solid works are different. Its not worth the time and effort to explains.
If it takes more than a day or two don't waste your time on it.
FEA: don't use two packages - use ansys for all
Solvers are different, explain both if we use both

JZ shares his slides
Start with Mining industry
Why low torque drilling tools
CTD taken from oil and gas industry
Start with footnotes
Aim for 7 mins and use the rule of thumb 1 slide per min
aim for 3 sentences and 5 maximum (if necessary)
put ticks next in the highest score of selection matrix.
Stat with explaining drill bits rathe than a selection matrix.
explain the differences between drill bits.
Rank the content according to importance and give a take home message.
90% of talk must be understood by 1st and 2nd year students.

1-2 max slides with extremem depth.
Make it visually appealing by having background
ME says centre page number and footnotes of right.
22nd Oct 3 practice presentations
15th oct send slides for detailed feedback.
metion safety factor/ loads on PDC.
Dont present arbitrary numbers.
Convey message by quantitave assements for FEA.
conclusion 2nd last slide
last slide acknowledgement (thank SS, ME, TL)
Use callouts for PDC inserts
Marking is done by bunch of academics (whoever is in the room).

WHY VON MISES - assumes elastic material? Directional strength - isotrpic material - von misies inapproppriate.
If mineral plasticag vivaly deform and fails, von mises is appropriate, if it fractures, we are interestedin directional stress.
Listening for keywords during question time, can take a bit f time to think, if unsure say unsure, but practice is key.
Dont risk animations.
Make extra slides for questions after acknowledgement section.
ME says thesis feedback timeline before 22nd October.
4.1 should be heading 2
6.1 should be heading 2
No brackets in headings
future work - 6.5
Section 6 on FEA
Section 7 on final design
Conclusions over conclusion
hand calculations in FEA section or 5.4 on preliminary hand calculations.

6. Action Items

Action	***Assigned to***	***Due date***	***Status***
Thesis draft	RJ/MC/JZ	8/10/2021	Ongoing
Presnetation slides	RJ/MC/JZ	15/10/2021	Ongoing
Redo Static analysis on ANSYS	RJ/MC/JZ	8/10/2021	Finished

Review Research Proposal and give feedback ME

7. Next Meeting

Date: (1/10/2021)		*Time:*	*1:00 to 2:00 pm*	*Location:*	*MM3-20A*
Agenda:	Will send one day before next meeting				

Meeting Minutes

Date of Meeting: (08/10/2021)	
Location:	**UniSA Mawson Lakes Campus MM3-20A**
Minutes Prepared By:	John Z.
Start Time & End Time:	1:00 pm to 2:00 pm

1. Purpose of Meeting

To discuss the previous action items and draft research proposal.

2. Meeting Agenda

1. Review previous action items: Redo static analysis in ANSYS, Progress with thesis, Work on presentation slides
2. Discuss thesis
3. Results of the modelling

3. Attendance at Meeting

Michael Evans (ME), Tim Lau (TL), Rajveer Jandir (RJ), John Zhovnyak (JZ) and Max Cabato (MC)

4. Apologies

Soren Soe (SS)

5. Current Minutes (Notes, Decisions, Issues)

Review previous action items:

- Setup PDC evaluation: PDC was made in SpaceClaim symmetrical. Parameters failing for some reason. Do it manually and refresh the geometric model.
- ME: One way to solve is by clicking updating project to update everything. Remeshing is required.
- Results that were sent to ME seems reasonable. Anything with strong crystal structure needs to be normal stress. Create a coordinate system with a PDC at that point for normal stresses.
- Mesh convergence: Tabular data window can be exported as copy-paste. The last value will change, but other than first two cells, it should follow the same trend. We are not interested on the PDC, but more on the rock. Evaluate the diameter or the depth of the stress on the rock.
- TL: why are we looking at the vertical line. MC: comparing the best angle for the PDC and where the contact point comes with the rock. Research papers indicate the 0-5 degrees are the best positions. Need to justify why we are not doing 25 degrees. That also relevant for the presentation. Particularly if we find stresses peaked at 3 or 5. Do we have an idea of the shape of the curve, why not 40 degrees? Justify that.
- TL: How do you know which angle is the best? MC: we compare with limestone and evaluate the stresses of the PDC and the limestone. MC: at 1 degree a certain amount applying on the limestone and other amount on the PDC. ME: Does the stress on the PDC matter? MC: yes, we want to design for lifetime. ME: what's more important ROP of drill bit life? Therefore, focus on the limestone. ME: Put in some figures with the stress on the PDC. The limestone is the area of concern and the more important tis the cutting and the ROP.
- Divide by the number of PDC and by half. Make sure it isn't the entire WOB.
- TL: Do you care about the limestone stresses? Do we care about the peak stress on the limestone, or we care about the average? ME: We only need to care about the rock, it needs to be brittle compressive failure. It is going to crush and shear, move along fracture lines, but we care about how many elements above the failure threshold. In all cases, we should be looking at the radius of a number of element and a volume of element above that threshold.
- TL: Once it fails, if that failed once micro point, that results in increase in ROP. That is a criterion to evaluate which angle is better.
- TL: For given input, that's the amount of material removed depends on shape and angle.

Discuss Thesis:

- Failure modes of a PDC: Word count don't include tables and captions. For PDC failure: should be as paragraphs. If that is common, say some of them are common.
- TL: he writes documents without worrying about word count. Cut table 7 pics and put them in the table.
- Put a statement that the text in tables includes the table, but does not include references etc.
- Numbers in tables also counted in word count. Comment: word count doesn't include tables for example 7 and 8, provide a note an be transparent.
- TL: likes the table with the current structure.
- Structure: sections after 5 discussion: Matrix is a figure, not a table. Label it as matrix. Tables and figures should be cross-referenced. Before exporting to PDF, lock the document.
- Formatting of table of contents shouldn't be bold. Numbers also should not be bold.
- Section 6.4.4 doesn't make sense grammatically. Does not have the "FEA" in those headings.
- Future work should be after section 7.
- Section 7 to be broken up for several headings: Model of the final design, are we doing transient analysis of the final design, ae we comparing with verification model? Add ROP performance as a second point.
- Introduction, abstract and conclusion does not need to be broken down into sections.
- In the table of contents, aim to show two levels. Remove the third level headings.
- Do not throw info in appendix if we rely on. Cross reference, and if that is not mentioned, do not put it there.
- ME: for the verification, the numbers are the results for the process we describe. Provide a brief introduction for the verification. Aim for two sentence thing and state that it is elaborated in relevant section.
- Comparison between verification model: couldn't get results. ME: send it by email with ANSYS file and calculations. Expect to have discrepancies.

Results of the modelling:

- Next week to be in top agenda items.
- Put slides to discuss on the screen. Aim to have draft slides for the seminar including results.

6. Action Items

Action	*Assigned to*	*Due date*	*Status*
- Prepare darft slides for next meeting	JZ/MC/RJ	15/10/21	
- Modify thesis according to comments in the minutes and	JZ/MC/RJ	13/10/21	
- Send ME the verification calculatiosn and the ANSYS files for evaluation	JZ/MC/RJ	08/10/21	complete
- Aim to have results for dicussion for the next meeting	JZ/MC/RJ	15/10/21	
- Work on thesis and submit ASAP	JZ/MC/RJ	13/10/21	

7. Next Meeting

Date: (15/10/2021)		*Time:*	*1:00 to 2:00 pm*	*Location:*	*MM3-20A*
Agenda:	Will send one day before next meeting - Results for discussion - Review draft presentations				