Tribology study in deep downhole drilling processes: Influence of contact pressure and sliding speed on friction under Newtonian and Non-Newtonian Lubrication.

MSc (50/50) Research Report

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Abstract

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Tribology study in deep downhole drilling processes: Influence of contact pressure and sliding speed on friction under Newtonian and Non-Newtonian Lubrication.

By Siphesihle Mbatha (683396)

Drilling processes are complex and costly processes. Mechanical friction is predominant as the limiting factor in attaining high recovery rate of target recoverable oil resources. As a result it is of essence to reduce the cost incurred as a result of mechanical friction by putting in place the methods to minimise the friction encountered during drill string/casing and drill string/formation contact. However to best perform this, laboratory simulation of the conditions and / understanding of the mechanisms found in downhole, in particular, deep and ultra-deep downhole is a necessity.

The work presented herein simulate the drill string/casing and drill string/formation or rock contact under aqueous and non-Newtonian lubrication. Furthermore contact pressure and drilling speed were varied under the two later mentioned lubricant. Following the running in method, the results depicted a decrease in friction coefficient as load or contact pressure was increased. This was observed both when the steel/steel contact (simulating drill string/casing contact) and when steel/sandstone rock (simulating drill string/formation contact) were simulated. Increasing speed increase perturbations in the coefficients of friction, and has no direct effect on the mechanical friction in comparison to observations in the case when the when load was incremented at low speed ranges. However, as the speed increases the friction coefficient for steel to steel contact reduced significantly. The latter invalidates the universality third law of friction, which state that friction is independent of speed. Offset of

the steel pin, meant that the pin encountered new and fresh/hard asperities and hence increases the vibration. Thus to better control this was concluded that load allowance and measurements thereof is to be made when designing drilling strings for deep downhole drilling. In addition the incorporation of the bentonite particles into the drilling mud increased the friction for steel/steel contact due to two-body abrasion which becomes the prevailing mechanism on the entrainment of the bentonite particles between steel pin and steel disc.

For steel/sandstone contact the friction decreased on the entrainment of bentonite particle. This was attributed to the microstructure and porosity of the sandstone disc. Furthermore and important for lubricant design, the water to bentonite ratio was tested. The result for the latter testing showed that friction increased with increased water concentration in the bentonite mud. This means that the overall performance of pure water lubricant in comparison with bentonite mud was found to be poor. Thus addition of bentonite mud at certain concentration for specific drilling contact, can either increase friction or decrease friction and consequently it was found advantageous to use bentonite particles under drill string/formation contact depending on the hardness of the formation. The porosity seemed to reduce the tribofilm, making it difficult for smooth and good friction reduction since the charged lubricant is lost in filling the pores. Upon visual observation the tribofilm thickness for when sandstone was lubricated with bentonite was slightly thicker than in the case when water as a lubricant was used. Though for different sandstones the rock porosity increased friction, it was assumed that with time the worn material and the bentonite particles quickly works to fill the pores that were initially taken to be gas filled. The microstructures of the contacting materials and their abrasiveness strong influence the drilling friction.

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Declaration of Authorship

I Siphesihle Mbatha would like to declare that this is the product of my intellectual property. I attest that:

- Where it is not the product of my own generation, I have thoroughly given credit to the relevant source in an appropriate manner.
- Where I have quoted the work on another, the ideal source has been clearly indicated.
- The work was done at the University of Witwatersrand and the University of Southampton solely for contribution to scientific knowledge and towards a master's of science (50/50) petroleum engineering hosted by the main university.

Signed:………………………………………………………….

Date: 08 November 2017

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Chapter 1: Introduction

1.1 Background

Exploration/Drilling is one critical, hazardous or risky, complex and costly operation in the oil and gas industry. Oil exploration/extraction process is the process of recovering, from reservoir/well to the surface, target crude oil or gas and/ mixture. During recovery, slurry composition and properties such as viscosity may vary and hence influences many factors essential for realization of target oil product(s). These factors are friction, recovery rate, energy, refining mechanism, and etc. Advances in technologies, including the newly emerged nanotechnology, are aimed at improving extraction/recovery rate by targeting to reduce effects of rate retarding factors such as friction. Mechanical friction is immensely predominant as a limiting factor in inclined wellbore drilling such as extended reach drilling (ERD) and through tubing extended reach drilling (TTERD) *(Ytrehus et al, 2017).* Recent advances in drilling technology have allowed new milestones to be achieved, such as with the drilling and completion of wells which are longer than 10km *(Ismail, 2011).* Demand for oil products continues to increase meanwhile the recoverable oil and gas resources continue to get depleted at an accelerated rate, in particular on the onshore reserves. Consequently the shift in focus is towards drilling in deep downhole and offshore in order to meet the ever-growing demand. The condition presented by these location are harsh and/ comes with risk (such as water contamination in offshore).

Safety and efficiency are top priorities during drilling or exploration processes. Reduction of non-productive (or flat) time serves to be another key player backing demand for improvements in efficiency (*van Oort et al., 2017).* While drilling costs represent nearly half of well expenditures, only 42 percent of drilling operations time is spent on drilling and the other 58 percent is divided between drilling problems, rig movement, defects and waiting periods.

Deeper and harsh condition environments in which these rich reservoirs are located will introduce more hurdles to success of drilling to target recovery rates. Few, but main, amongst many hurdles are high torque and drag (which are tribology problem), controlling fluid circulation and maintaining directional control *(Ismail, 2011).* Much targeted research study, and progress in reducing the effects of the aforementioned is through the development and use of drilling fluids or lubricants and improved material performance through innovation drive. However the basic problems being physics of friction i.e. which is a foundational source of these hurdles remain not fully understood and thus remain unsolved *(Chowdhury et al., 2011).* South Africa amongst many countries has oil deposits in offshore located in Orange basin region. This present a great opportunity for economic success in the country however the main challenge is good infrastructure able to tap into those deeper, difficult to access and harsh environment.

Previously common drilling methods were vertical drilling technique. Complex drilling techniques such as directional drilling are known to have high friction in sliding contacts against rocks, in particular, and in curvatures *(Ismail, 2011).* Key to solving this is improving the performance requirement of drilling equipment's. It is fascinating that friction as a phenomenon that contributes to these hurdles is, and in so many other aspects of our life, still not fully understood despite it being perennially known. According *to Blau and Faulkner (2008)*, friction continues to conceal its subtle origins especially in practical engineering situations where surfaces are exposed to complex and changing environment. There exist no single Mathematical models that can be universally applied to solve and optimize processes through reducing the friction factor. Friction is one of the most researched areas in oil and gas industry. Better understanding of friction and wear rate or tribology in deep downhole drilling provides the opportunity to better optimize the production and reduce the adverse effects (e.g. drag and torque) through best lubricant formulation and equipment design.

1.2 Research motivation

Future hydrocarbon extraction will be from deeper and more difficult to access reservoirs, increasing the performance requirements of drilling materials and equipment. Understanding the effects of friction on drilling performance is key as sliding surfaces in extreme (temperature as high as more than 350˚ F and pressure as high as more than 30 0000 psi) environments can present a unique set of conditions that affect materials and fluid behaviour in ways not fully understood.

This project will study the influence of contact pressure and sliding velocity on the friction and wear behaviour of steel when in sliding contact against Newtonian and non-Newtonian lubricated steel and rock. The tribosystem will be laboratory simulated under aqueous and non-Newtonian lubrication using a pin-on-disc tribometer. The work will aim to establish the influence of running in behaviour on the contact pressure as well as the effect of hydrodynamic forces on the dynamic friction response and wear. This is also aimed to contribute in designing of downhole friction simulator equipment's by n-CATS (UK). n-CATS is the national Centre for Advanced Tribology studies in the UK and currently working with major oilfield companies to investigate the effect of friction in oilfield operations. Laboratory simulated results of oilfield condition will help to better control exploration operations.

Furthermore results are aimed to guide in design of equipment and lubricants for deep downhole operations. This will help to avoid quick reach of saturated oil reproducibility rate (SOR)-i.e. the rate at which no drop of oil is produced which is friction enhanced. Best drill string protection also has driven wide research studies with an object to mitigate friction. A well design or protected drill-string or casing has potential of decreasing the number of drilled wells if the sole purpose of increasing number was to protect the drill string from tribology effect such as wear. It should also be noted and stated that petroleum industries in the near future are to look into using renewable energy sources such as solar to provide energy for drilling, thus loss of energy as a result of frictional drag and high torque should be as low as possible since the sources are intermittent in supply and characterized by low available energy in ratio to conventional energy sources. Friction reduction also contributes positively to CO_2 emission reduction as fuel consumption during drilling, for example in the case of mobile transport engine, rate decreases.

1.3 Aim

The aim of this report is to provide basis for increasing efficiency of drilling process through reduction of friction induced side effects. This incorporate providing guidance for effective design of drilling equipment and the drilling mud. This will assist in designing durable drilling equipment and drilling mud that can survive the possible failure mode under deep drilling process.

1.4 Objectives

- Assessment of influence of contact pressure and sliding speed of a drill string under aqueous lubrication
- Assessment of the tribological behaviour of simulated drill string under non-Newtonian fluid lubrication
- Lubricants concentration correlation to friction coefficient.
- Assessment of the effect of formation porosity to the friction coefficient.

Chapter 2: Literature review

2.0 Introduction

This section is aimed to highlight the background theory around the project scope. In the first section the drilling process is succinctly analysed with objective to identify the need for tribology studies in oil and gas drilling process. Further review proceeds on to the history of tribology. This will cover the main tribology components which are friction and wear. Progressing in that order, a review on tribology parameters/variables will be given. This is targeted to give fundamental understanding about these parameters and their link to the scope of the project. Furthermore the study on lubrication and lubricants will be shortly reviewed.

2.1 Deep drilling process and tribology Problems

Deep petroleum resources are distributed in different geological strata that have different lithology properties such as dolomite, sandstone or commonly classified as sedimentary formations, clastic or hylaclastic, carbonated, volcanic area, etc. Over 1000 oil and gas reserves with tonnes of barrels of petroleum fluids, and at depth of greater than 4000m have been discovered in different basins of the world *(Longde et al., 2013)*. Most, if not all, are characterised by combination of elevated temperature and pressure conditions. High temperature and high pressure (HTHP) in deep downhole drilling processes have transformed rock properties to a certain degree different from the normal wells. HTHP conditions in deep drilling are estimated to be more than 260 ˚C and 20kpsi, respectively and hence necessitating the need for high rheological stable lubricants while enhancing resource percentage upturn a**s** these conditions are more favourable to high friction and wear *(Abdo & Haneef, 2012)*. On the other hand the cost of lubricant formulation i.e. methodology and additives add to the cost incurred from the latter. Thorough understanding of mechanisms or drilling process mechanisms is essential ere the actual drilling. A large volume of scientific research studied the problem associated with drilling process for different drill string technologies *(Ansari et al, 2017; Lafuente et al., 2017, van Oort et al., 2017, Muhsan et al., 2017).* Deep downhole drilling or extended well-reach in particular has been characterised to have such problem as high torque and drag due to high friction, high possibility of differential sticking, slip-stick, buckling, lost circulation, change in lubricant rheology in a manner that can impact on composition of drilled product and environmental hence incurring more cost for conversion and drill string maintenance e.g. formation of acids, loss of stability in drill string, high corrosion zone, etc. These results into consequences such as complete failure of drill string system with high potential of wellbeing abandonment, enhanced non-productive time and high operation and maintenance costs. Furthermore, they also result into reduced profits due to some project operation disturbances. On the other hand the conditions may vary to a great extent when going deep downhole resulting into fluctuations in friction parameters, and thus call for lubricant that can sustain possible wide conditions (temperature and pressure) ranges.

During drilling different excitation including casing contact, weight on bit (WOB), stick-slip, well-borehole contact and drilling fluid interactions create different drill string vibrational response. Vibration of the drill string is one of the major stimulant to propagation of afore mentioned problems, and drilling performance deterioration in deep well drilling *(Khufiel & Al-Sulaiman, 2009)*. Other mechanism taking place within the dynamic drill string include bending, torsional and self-excited drill stick-slip oscillations. Rotary drill string are widely used in industry and their vibration mechanism has called for deep mathematical formulation or modelling together with complementary experiments or field test which serve to validate the model. The rotary drill string is constructed with a number of assemblies in different section, of which one is the drill bit. The bit is a rock-cutting assembly tool that is connected to the rotary table through slanders of pipes called the drill pipes. The drill pipe is the longest assembly amongst all and is subject to different gravitational field forces such as tension and compression field forces. On average most notable failure in drill pipes are result of buckling stimulated by inherent low resistance of the pre-mentioned forces. Furthermore the lowest part of drill string contains drill collars. These are thick walled tubing called bottom hole assemblies (BHA). Drilling assembly is represented by figure 2.1 below.

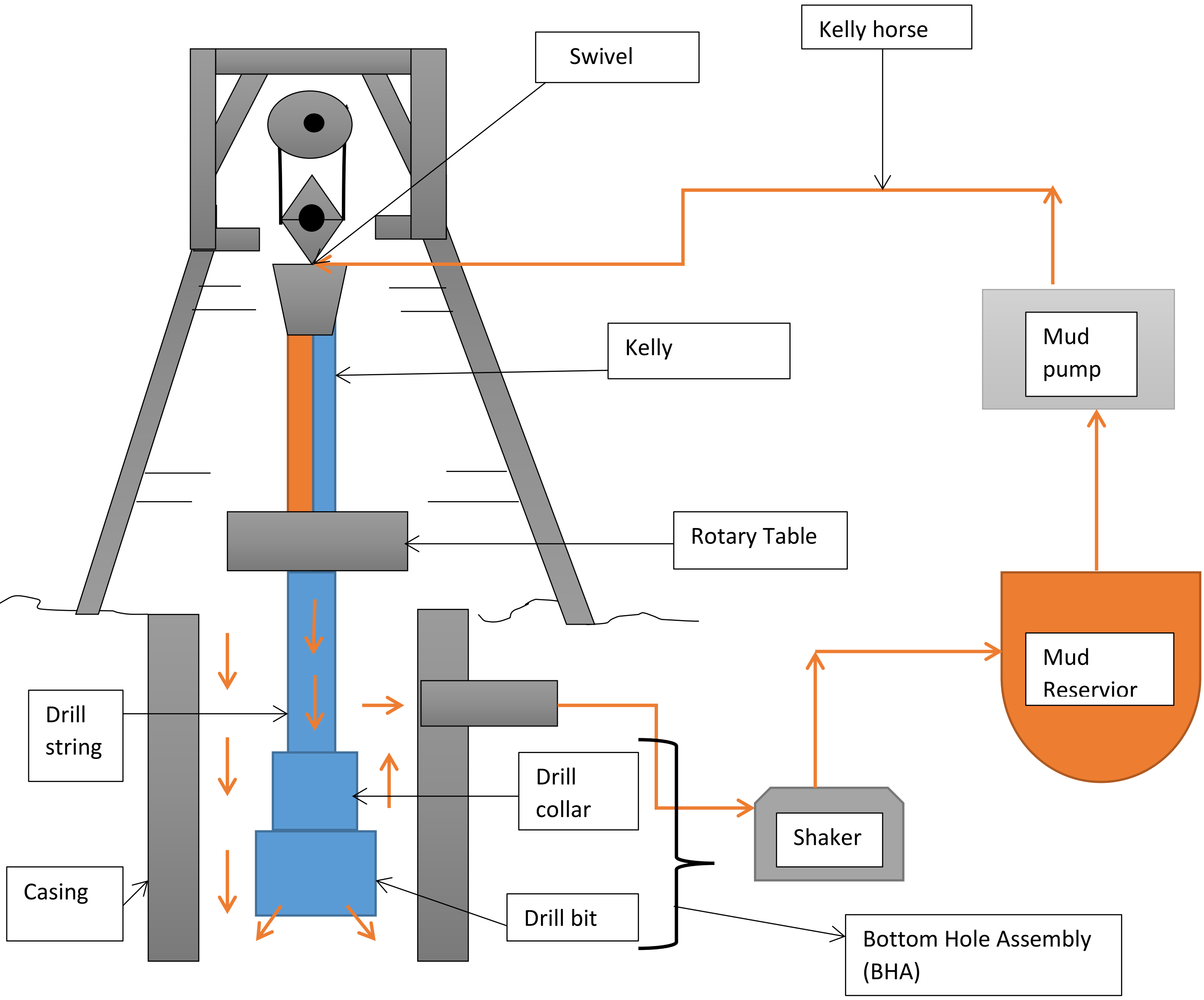


Figure 2. 1 Illustrate drill string assembly with mud circulation (updated from Ismail, 2011)

Abdo & Haneef (2012) attempted to find solution, using nano-particles of Palygorkite (Pal), to reduction of added cost by use of additive and performed the test under HTHP conditions. *Ritto et al. (2009)* argued after wide comparisons of interactions that a source of major uncertainties is found on the bottom hole assembly (BHA), where the drilling collar/bit vibrate in contact with the rock. This has necessitated significant focus on the rate of penetration (ROP) of the bit into rock. Normally during drilling simulation average rate of penetration is assumed together with assumption of fixed bit. *Ritto et al. (2009)* further proposed a computational nonlinear probabilistic model for simulation of dynamic drill string and rock interaction. Deep and superdeep well unstable rock formation is one contributing source of problems associated with rock-string interaction, and this also tend to propagate other vices such as lost circulation. Lost circulation can render some material exposed to hot surfaces that creates fatigue on material or drill string, changes its properties and hence normally enhance friction drag and poses drilling complications. Rock strength is an important factor for consideration in optimization of drilling process such as increasing penetration rate (ROP) *[Zha et al., 2017]*. Laboratory studies together with practical field test provides better understanding of the rock strength and drilling parameters to be optimized. However, field tests are not always easy to perform and can be very expensive and require sophisticated equipment's. On the other hand it is difficult to reach ultra-deep and superdeep wells to better collect data. Geomechanical modelling assist in effective development of wells and in optimizing the drilling processes *(Kreknin et al., 2017).*

One property of high importance is porosity of the rock. Rock porosity affect the lubrication mechanisms and hence can render material susceptible to high rate of frictional drag and wear if not well understood and adjusted with correct lubricants. Better understanding of friction and wear of cladding materials under certain rock with defined properties yields good optimization of entire drilling process, including drilling parameters *(Shirkavand et al., 2009).* Downhole friction reduction is a very essential concept in drilling process and its success has been difficult to achieve in deep drilling processes due to interplay of numerous significant parameters. Reduced friction on the other hand decreases energy requirement and dissipation as result of drag, hence optimize upturn rate of drilled fluid. Wear reduction improves material life, and hence reduce non-operating time (NOP) resulting from need to maintain equipment and drilling safety. It is this minimization of NOP, i.e. maximise production or recovering time at a reasonable cost that drives the better understanding of material performance under deep downhole conditions. Much of the research in the area has put emphasis on studying and formulating stable lubricants that has an extended potential of operating under these volatile environment. On the other hand, little is reported on drill string and rock interaction as one factor which is part or basis of better formulation. The interplay between rock properties (except roughness) and sliding friction under lubricated conditions has not been fully researched. Intensive research effort have been subjected to studying the interplay between sliding friction and rock surface roughness and /hardness with incomplete result to date (Byerlee, 1978). Under deep reservoir the rock properties, are highly influenced by pressure and temperatures. Better understanding of rock property and drillability interplay is core to success of drilling task. For example the correlation between rock hardness and drillability measured by parameters such as the rate of penetration (ROP) has been profoundly accepted to be of inverse relation. This has necessitated drill string operator to increase weight subject to bit in order to increase rate of penetration, however too much weight on bit has a potential of increasing buckling potentials and the point where ineffectiveness of bit weight increase begin has been termed as Founder point. This point occurs when the mechanical specific energy exceed confined compressive strength in deep down hole *(Shi et al., 2015).* Advances in technology has gave birth to number of well performing equipment correlated to mitigate issues arising from rock hardness.

Solberg (2012) conducted a study on improving drilling process through the determination of hardness and lithology boundaries under soft and hard formations. Another challenge arises from the porosity of the rock, which at present has not received full study and act as potential source of lost circulation, has some effect on the rock strength such as its load bearing capacity and , and affect friction in ways not fully understood and hence serves as a contributing factor to increased drilling cost. Understanding the rock porosity has been another key factor in deciding on drillability of reservoir rock. In general porosity is the inverse of differential pressure, and hence tend to decrease as the depth increases. However, according to *PetroWiki*, this occur until depths of at least 3500m are reached. This is to point out the necessity of understanding the effect of this parameter on rock strength and drilling potential. *Shi et al. (2015)* developed a model that considers the effect of porosity and nonlinear characteristics on rock confined compressive strength. *Shi et al. (2015)* applied double stress model which treated porosity at the major factor of formation pore pressure in their study. In supporting the presence of the gap, *Shi et al. (2015)* reviewed different models and pointed out in their writing that most models present in literature lack effective consideration of the influence of porosity on rock strength which closely impact on drilling optimization. One of these is the Terzaghi effective stress theory, which is widely used in engineering and can be said to be limited in application to shallow onshore wells as it is founded on soil mechanics. The model proposed by *Shi et al. (2015)* combines both the mechanical specific energy equation and double effective stress theory to give insight to inefficiency of drilling process and hence provide the estimate of optimum drilling parameters. This approach has some validity since it take into account the non-linear nature of the rock strength properties as opposed to Terzaghi stress theory previously adopted by multitude of researchers. However the efficiency of the method in describing porosity influence is questionable as it present indirect treat of the rock parameter and is founded not only on the porosity factor but on other interplaying factors, and porosity is treated as secondary factor assumed to be main controlling in determining confined compressive strength. However the relation between mechanical specific energy and confined compressive strength provides some reasonable possibility of using porosity to optimize drilling parameters.

Longde et al. (2013) intensively studied deep downhole formation and porosity changes in search of trend in deep and ultra-deep drilling progress in past years and potential for effective regions i.e. regions of notable porosity and permeability. *Longde et al. (2013)* argued a presence of gap in deep downhole theoretical understanding which highlight a call for intensive research due to their complexity, and pointed more notably towards needs for research in areas such as effective drilling direction formulation, exploration targets prediction, prediction of fractures and dissolution pores, accumulation problems caused by deep downhole high temperature and pressure zones, low permeability and low porosity zones etc. *Longde et al. (2013)* deduced five development and preservation mechanism of different reservoir intervals containing different rocks. Stressed out on their research is porosity as the main controlling or core factor for formation research in deep downhole reservoir with each of development factors contributing differently, in different regions, on porosity. These processes or factors include fracturing, diagenetic overgrowths, over-pressure, shrinkage, pressure solutions, cementation, compaction, increased mineral volume, early-stage trapping, dissolution, and oil & gas charging. According to *Longde et al. (2013)* fracturing process in deep reservoir contributes little to porosity but highly rather on permeability and factors such as early stage charging are critical for porosity preservation in deep down hole. *Longde et al (2013)* further commented on complexity and gap in critical understanding or interplay of these fore mentioned factors of formation to yielding effective reservoir.

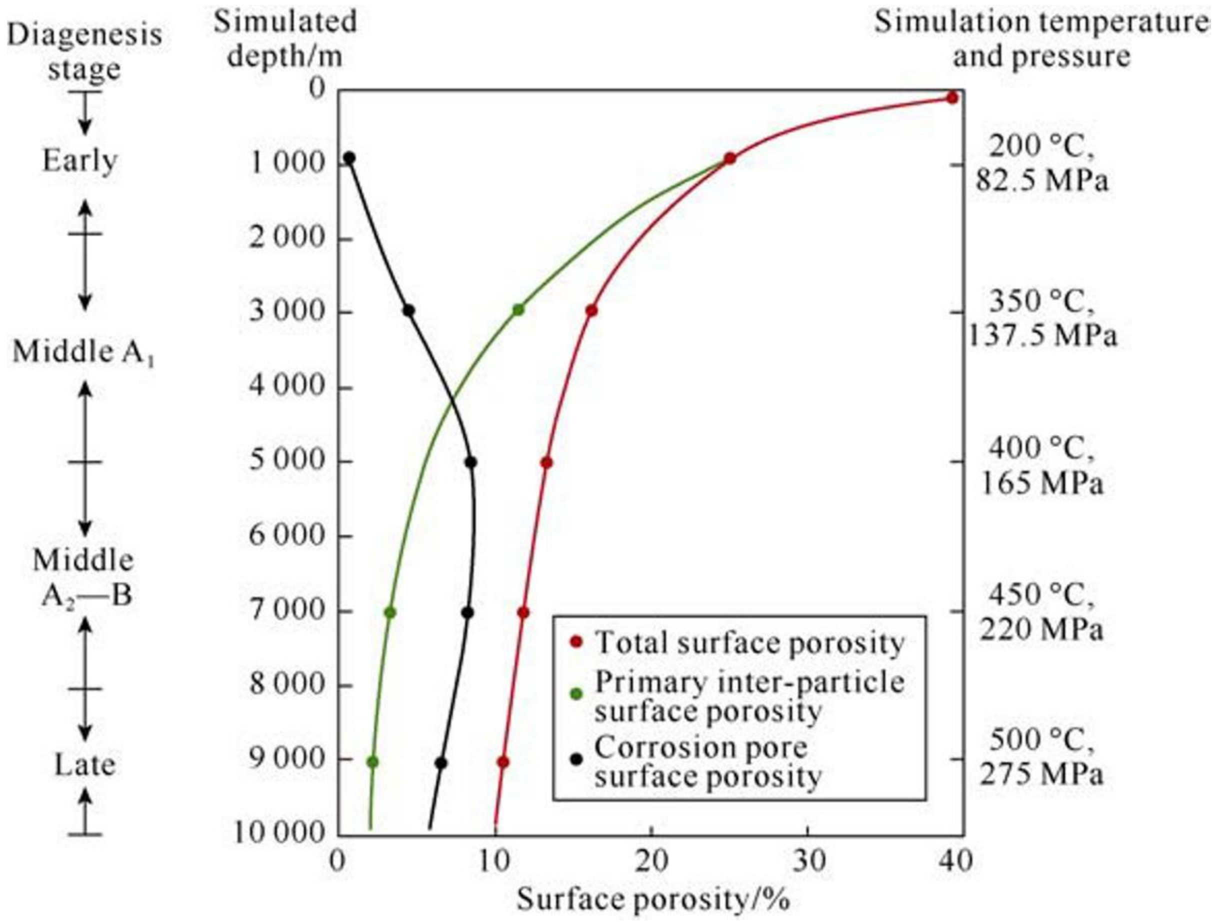


Figure 2. 2 shows the changes in porosity, temperature and pressure with depth due to phenomenon called diagenesis. The trend for corrosion pore surface porosity and primary inter-particle surface porosity are unique, and total surface porosity gives a decreasing trend as the depth increase with increase in temperature. The results are a product of Halogenisis experimental simulation conducted by Longde et al. (2013).

The relation depicted by figure 2.2 gives insight to changes on the applied conditions and depth possibility. They are not actually a true representation of changes in deep downhole porosity changes as it has been difficult at present to get the exact measure of conditions or sometimes core samples at such depths. The trend may not be exact when considering different evolution or development factors in different areas. For example, one study conducted by *Millet et al. (2016)* on the geology of deep offshore basalts sequences depicted contrary values to the ones shown on Figure 2.2. This stresses the importance of understanding rock formation before performing any drilling related operation. *Millet et al. (2016)* viewed the problems found in deep offshore drilling in basaltic components or large igneous province (LIP) volcanic facies with an eye of searching a link between the formation features and drilling complications such as fluid loss, drill bit or string sticking, slow rate of penetration (ROP), over-pressured formations, wellbore collapse and spalling. The latter complications were summarised into four categories i.e. rate of penetration (ROP), drilling fluid losses, swelling volcanic clays and unstable volcanic clays prone to caving washouts. One of the conclusion drawn from the study was the notable difference in trend of compaction, porosity, and permeability reductions between sedimentary and volcanic facies. Conversely the analysed problems have been argued to have strong connection with increased friction, some propagating the phenomenon and some other propagated by it. The pre-risk analysis helps to determine the productivity of drilling operations, and associated costs. Another important point mentioned by *Millet et al. (2016)* highlights on how porosity-depth changes can influence on choice of mud cake thickness design or properties.

On the other hand mud cake thickness is well known to impact on hydrodynamic film formation under lubrication mechanisms, a method of friction reduction. This observation or analysis provided a clear implication that the problems encountered in deep drilling processes are mostly and commonly affected by porosity and tend to either affect or be affected by friction too. However the exact or direct link between friction and rock formation effective porosity is not clearly known and cannot be established from the common problems factor. Nonetheless discussion on how each influence drilling rate retarding vices is crucial for understanding and formulation of this relation. Another notable difference in trend is between porosity and compressive strength in different formation, for example in basaltic formation at ~ 50 MPa compressive strength effective porosity can still be found to be high (e.g. ~50%)

which is contrary to sedimentary facies where the porosity of ~40% are found at very low compressive strength ~0 MPa *(Millet et al., 2016).* On the other hand numerous tribological problems occur as a result of associated deep downhole drilling encountered conditions and perpetrates to other drilling problems. These could be erosion, corrosion, wear, friction, loss lubricant or lubricants contamination or composition change, abrasion etc. However the study on this project will be focused on modelling, in a laboratory experimentation, parameters that affect friction and wear, hence a strong link between porosity, as a rock property, will be examined.

2.1.1 Friction contribution to drilling complexities.

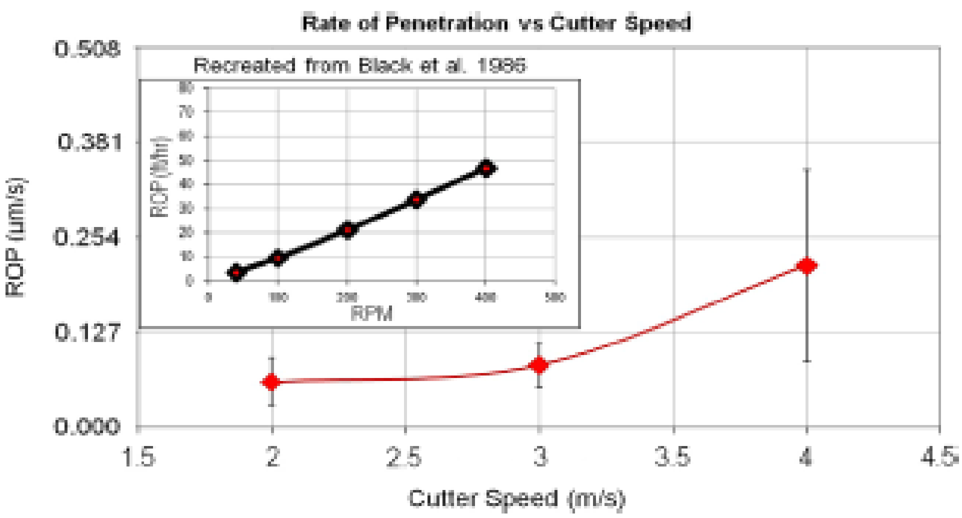
A number of problems encountered in drilling industry has been closely studied by researchers together with their possible sources and linkages to birth and propagation of other relevant drilling complexities. Drilling process, in particular the directional drilling, are known to be associated with high friction. Friction is better defined as rate retarding or efficiency limiting phenomena in drilling operations. Much drilling cost contributions are as a results of effects of high friction in deep drilling processes. Notable influence of friction are seen on propagation of slow rate of penetration (ROP), differential or pipe sticking, lost fluid circulation, excessive torque and drag, non-productive time, etc. The following section will delve in identifying extent friction contribution and reported literature solutions on the four major hurdles encountered during drilling process.

2.1.1.1 Rate of Penetration (ROP)

The rate of penetration (ROP) is defined as the distance travelled by drill bit or string breaking through wellbore rocks per time. Researchers have intensively investigated the rate of penetration as a parameter to optimize the drilling operations against a number of factors to demonstrate clear relations e.g. *Black et al. (1984)* considered parameters such as weight on bit (WOB), torque, and rotational speed for PDC bit test on different rock samples.

Downhole weight on bit (DWOB) is a significant parameter to optimize the rate of penetration (ROP) and overall bit performance *(Wu et al., 2017; Pinckard, 2002).* The study on friction relation to the rate of penetration conducted by *Dougherty et al. (2014)* was directed to studying deep wellbore drilling. *Dougherty et al. (2014)* experimented the parameter using bit cutter- on- rock tribometry (B-CORT) incorporated with a system of sensors to collect, in-situ, data for rate of penetration(ROP) and coefficient of friction as they slide against water–jet fabricated Carthage marble rock disk under dry conditions. Contrary to what most researchers have been pointing towards, *Dougherty et al. (2014)* argued on a direct relationship between friction and rate of penetration (ROP). However, the relationship between cutter speed and rate of penetration (ROP) depicted a direct proportionality similar to the load-ROP relationship. The result for speed and friction arguably correspond to dry sliding test or dry friction. Furthermore there is still a possibility of fitting other polynomials to explain the relationship between friction and cutter speed, and these demands large data collection at very small time intervals since friction is time dependent which has not been thoroughly performed for the COF vs speed correlation. These results are shown on figure 2.3 below.

a



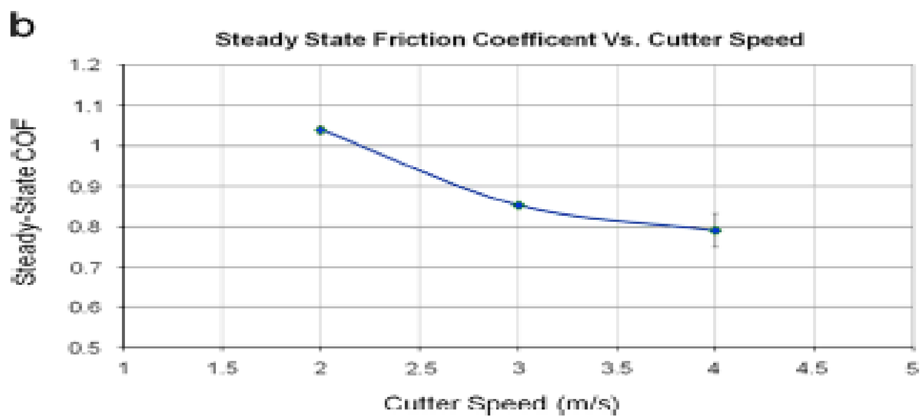


Figure 2. 3 Represent the results obtained by Dougherty et al. (2014) during their bit cutter-on-rock tribometry. a) Plots change of rate of penetration (ROP) with variation of cutter speed. b) Plots the obtained relation between friction coefficient and the cutter speed.

The results for contact pressure and coefficient of friction obtained by them are contrary to the laws of frictions. The results are contrary to what is demonstrated in practical application, a need for increased weight on bit to increase the rate of penetration and in general when friction. These results are not sacrosanct. This implies a retard in rate of penetration at high drag and friction, a contrary to the results obtained by *Dougherty et al. (2014).* In extended reach a faster rate of penetration (ROP) is desirable to minimize energy consumption as a result of high frictions.

2.1.1.2 Differential sticking

Annis et al. (1962) were among the earliest to perform laboratory studies on differential sticking. *Annis et al. (1962)* conducted laboratory test to study the friction between steel and mud filter cake. This friction between mud cake and drill string caused by high difference between drilling mud pressure and formation pressure is a source of differential pressure pipe sticking. Typically during drilling a motor is installed which works to pump the drilling mud to the kelly hose and between the drill bit and formations. Large difference between the mud and formation pressures result in formation of dehydrated mud cake, and severity can cause bit rotation to stop and get stuck downhole. This problem is commonly encompassed with other problems such torque and drag.

2.1.1.3 Torque and Drag

Torque is the force needed to rotate the object about its axis. The relationship between drag and friction is more elaborate compare to the others and can be easily deduced from using Coulomb's friction model. According to *Aarrested et al. (1994)* drag is the difference between the static weight of the drill string and the lowering/pulling weight, and whereas torque represent the difference between the applied torque at the rig floor and the torque at the bit as a result of friction. The higher the friction yield the higher the drag in drilling since drag is determined by friction coefficient and the normal forces exerted by the walls on the drill string, and hence drag act in opposite of drilling motion i.e. as a resisting force.

Normal force is influenced by number of factors such drill string weight, buoyancy (in the presence of drilling fluid, i.e. under viscous friction), well length and well angle or trajectory. High drag and torque have interplay with differential sticking, and stick -slip depending on formation permeability. For torque and drag calculation, friction factor is the most important parameter and hence any reduction in the friction factor will directly reduce the torque and drag *(Brekke, 2016).*

Models of torque and drag have been classified according to drill string stiffness based assumptions ever since *Johancsik et al.(1984)* developed the first model for torque and drag where they assumed soft drill string neglecting the effect of string stiffness. However the soft string assumption was found to underestimate the actual torque and drag, and most models now focuses on stiff drill string in accordance with the current used drilling angles and drilling depths. *Johancsik et al. (1984)* deduced that sliding forces are the main cause of elevated torque and drag. According to Coulomb friction model, a sliding force is a function of coefficient of friction and normal contact force *(Brekke , 2016).*

The choice of the well profile must give minimum possible torque and in addition any uncertainties in torque and drag must be accounted for by improving the design of well bore, drill fluids and continuous monitoring of performance during the actual drilling. Figure 2.4 below demonstrates the typical regions of higher drags and associated forces. On vertical drilling, torque and drag are negligible due to pipe behaving as suspended in the fluid as a result of buoyancy and having no place of contact between the formation and pipe. Furthermore the drill string does not experience any compression as in the case of horizontal or angular drilling. During drilling at an angle, there is local contact between the drill string and the formation or casing in particular at the points of pipe bends due to gravity.

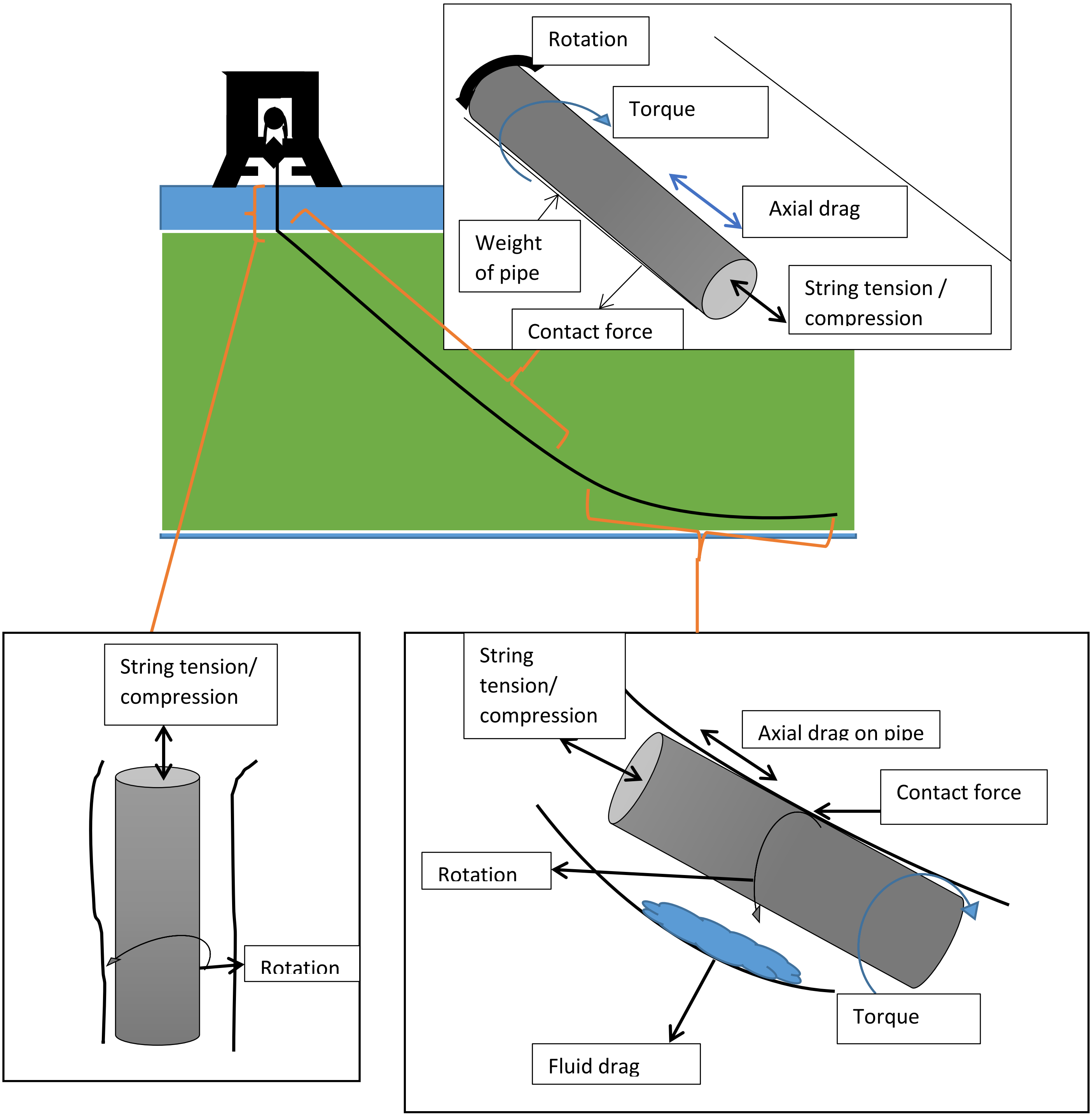


Figure 2. 4 Illustration of different sections where torque and drag are at maximum (Modified from K&M Technology group and Ytrehus et al, 2017)

2.1.1.4 Fluid loss circulation and Porosity

The lubrication in drilling process serves to reduce the effect of loss fluid lubrication. Literature has reported a number of field methods to alter porosity of reservoir formation of interest so as to obtain a productive orientation. Porosity, just as friction, has been linked to propagation and reduction of some of problems encountered in deep drilling process. This identifies indirectly the possibility of link between porosity and friction. In viscous fiction, which is under lubricated conditions, the formation porosity has a tendency to propagate entrainment of undesired fluids to the target well, and further permitting fluid loss circulation as the drilling fluid escape through the formation from the target well during the actual drilling. Fluid loss circulation and the undesirable fluid entrainment increases cost of drilling process and presents situations that may propagate the friction during drilling.

A mathematical equation describing the actual link between friction and porosity is still missing. Hence only empirical link will be approximated through hydrodynamics study by analysing the result from the comparison of rock of different porosities. Intuitively it would be difficult to attain hydrodynamic regime i.e. the regime where the two bodies, drill string/casing or drill string/formations are fully separated by film thickens in such a way that there is no contact between the combinations of the mentioned bodies, when drilling in formations of high porosity. Thus drilling will tend to fall to other regimes where asperity contacts are present. This has tendency to impact on drilling friction, and thus further reducing the effectiveness of the process. In addition, the latter increase the frequency of hole instabilities and excessive costs as a result of need for continued fluid injections.

2.2 Tribology history and Knowledge developments

The term tribology was introduced around in year 1966, but became prominent a few decades ago. Tribology is found in multitude of industrial processes and disciplines. This is because almost every process involves two or more surfaces in contact and motion. Tribology is the study of the overlap of friction, wear and lubrication

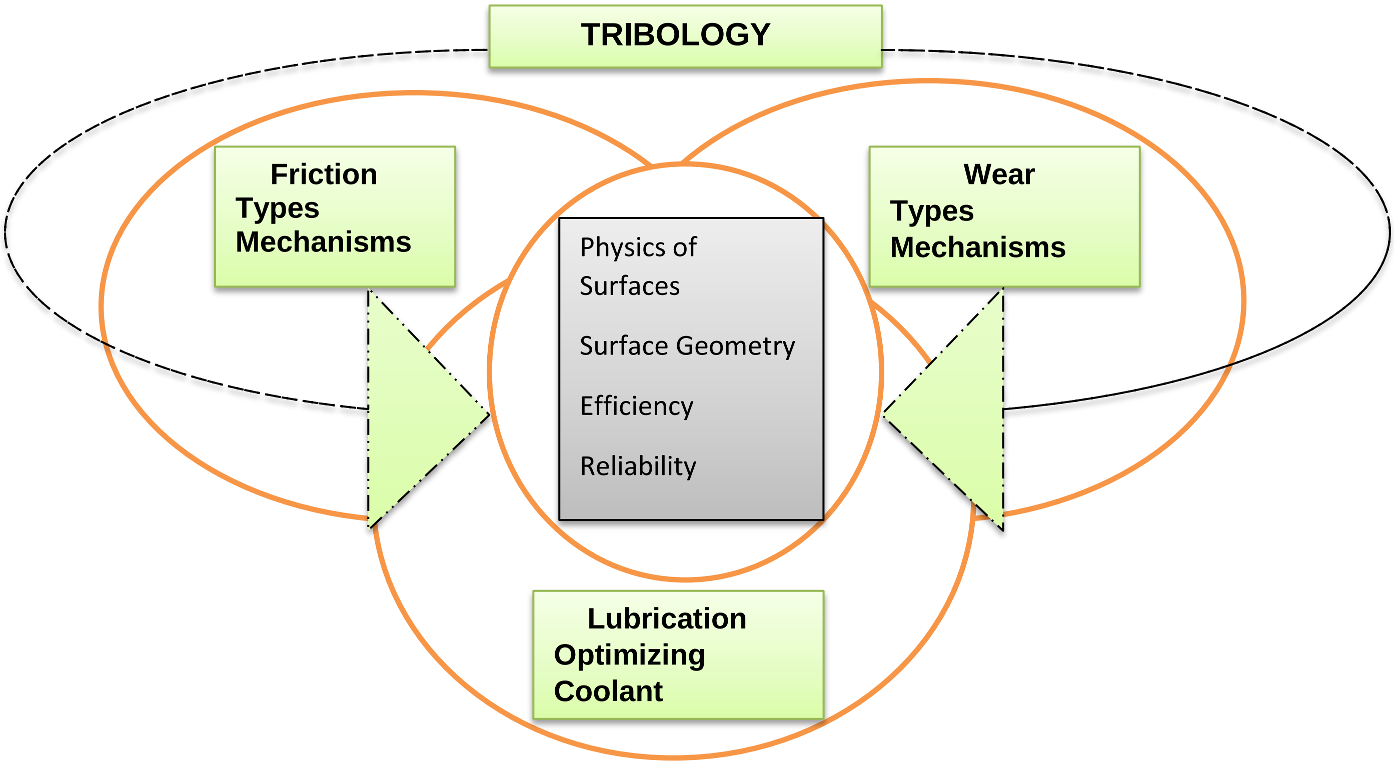


Figure 2. 5 Elements of Tribology

Figure 2.5 above summarizes elements of tribology. Operating variables play bigger role during tribo-simulation. Interplay of different mechanisms poses challenges in analyzing and optimizing the performance of tribo-pairs, particularly under variable auxiliary sub-system and conditions. This paper put focus on both friction and wear which are major components of tribology.

2.2.1 Friction

"For oil and gas operators worldwide, friction has been the major nemesis of downhole drilling since the industry's inception'' *(Farr J., 2015)*. Science of friction is an old-aged or perennially unsolved and succinctly understood phenomenon. "More than 10 years ago the word tribology was foreign to many, even though it was long developed and researched'' *(Blau and Faulkner, 2008).* Introduction to tribology has brought more focus on friction and wear as the major components. The science of tribology (Greek tribos: rubbing) focuses on contact mechanics between moving interfaces and generally involve energy dissipation. Its scientific components encompass adhesion, friction, lubrication and wear. Friction and wear are present in almost all part of life including animal/human skeletal system (e.g. body-joints such as hip-joints). During oil well drilling, tribology occurs due to sliding conditions either on actual drilling process itself or on the tools *(Ismail, 2011).* Friction is a major source of tribology and the primary factor to control input energy to the system, and the production rate *(Ramalho and Miranda, 2006).* The greater the friction drag the lower the flow rate and the higher the energy used, higher torque, and hence cost of production also increases. This science has forced development of nanotechnology materials and advances in material/ surface engineering/sciences.

Leonardo Da Vinci (1452-1519) was the first scholar to study friction systematically. He realized the importance of friction phenomena in machine performance. He focused mainly on two kinds of friction and drew a distinction between sliding and rolling friction. Da Vinci conducted experiments using two solid bodies, sliding and rolling on each other. From his study, Leonardo da Vinci deduced two famous observations on the phenomena:

i) Friction is independent of the area of the surfaces of contact.

ii) Friction force is proportional to the applied load.

Da Vinci later realized the beneficial effect of lubrications on frictional force reduction. However, the first mathematical relations describing dry friction of solid bodies were advanced later by a French physicist Guillaume Amontons (1663-1705) *(Courtel and Tichvinsky, 1963).* Amontons documented Leonardo's observations in the form of friction laws in 1693. Amontons deduced that: (i)-friction is approximately one third of normal pressure, (ii)-friction depends on a complex relationship between normal pressure, time, and sliding velocity, (iii)-And that frictional coefficients for copper, wood, lead and iron is nearly the same regardless of the combination when lubricated with lard oil. Another novel contribution made was that by Antoine Parent (1666-1716) who was the first to relate the tangent of equilibrium angle -which is the maximum angle of inclination that describe the reaction of sliding surface, and observed it's not equal to the reaction of normal to the surface but numerically equal to the coefficient of friction. Seeing the importance of the study, Coulomb (1736-1806) went further, in 1781, and made his remarkable contribution on the distinction between static friction-used to start motions and dynamic friction-which is associated with moving objects and needed to maintain friction force. Coulomb made wide contribution on the science of friction. During his study on this subject, birth of Amontons-Coulomb's laws was realized. The theory gained wide applications in machine development during the 17^{th} -18^{th} century. Mathematically presented, Amontons-Coulomb's laws of friction states relationship between friction force, F, and the load L as follows:

$$F = A + \mu L \qquad \text{eqn. 2.1}$$

Where μ denotes the coefficient of friction which differs with materials, statics (static friction, μ_0) and motions (kinetic friction, $\mu_{k)}$ of the body, A is the grippage parameter and L is the load or rarely called normal force (N). However this theory can only be applied to study friction at macroscale and does entail direct applicability or any connotation about friction at microscopic level. Despite its many limitations it serves as a powerful tool for the general description of dry and boundary friction *(Courtel and Tichvinsky, 1963).* Coulombs theory failed because it claimed that friction is encountered merely as a result of surface roughness and did not explain very well the dissipative nature of the phenomena. Amongst many novel contributions real breakthrough was witnessed during World War II, in 1943, in Austria as result of study by two scientists from Austrian region i.e. Bowdon and Tabor. They made two main conclusions that friction is due, taken in nowadays as one of the friction laws, to the following:

i) Adhesion between surfaces in contact.

ii) The contact between softer and the harder surface through forceful methods.

Their practical explanation of the observations was that the true area of contact is of a smaller fraction of the apparent area of contact and this true contact area is due to asperities. And this true contact area is proportional to the normal force. Rabinowicz added two more observations to those developed by Bowden and Tabor. Rabinowicz's concluded with roughness (which is the same observations that Coulomb made), and electrical components as other factors. Numerous other great scientists and mathematicians studies friction and made notable contributions, these include (to highlight few) Hore, Hook, Newton and Euler. These great thinkers mainly focused on dry friction with less contribution to boundary friction. With advances in technology, much work has been done on attempt to understand the phenomena and attempts to incorporate to the basic equation given above the other factors that are known to have influence. Inversion of atomic force microscope (AFM) sophisticated the study of friction at microscopic level. Tribology researchers of the 19th century, equipped with state of art facilities, investigated continuously the viscoelastic relationship of lubricants in the boundary region, such as that encountered in rolling contact, and as when quasi-solid lubricants are subjected to a high pressure and high rate of shear *(Courtel and Tichvinsky, 1963).* To date there is no universal mathematical equation of friction that incorporates all the factors and which can be applied to any frictional situations. There is no deep scientific explanation but only empirical analysis and explanation of science friction. However the improvements in the past 100 years is notable enough and has transformed early understanding which was based on Amanton's theoretical formulations. For example it has now been well accepted that the wear and friction are not solely due to adhesion, as previously assumed. One recent novelty study on friction is that conducted by *Ismail (2011)* where reduction of friction was achieved through the use of potential difference or electrochemical methods. *Ismail (2011)* designed on a pin-on- disc with three electrode electrochemical cell, and used this setup to conduct study on voltage as a potential method to minimize friction drag and wear loss. The method worked to reduce friction by 11% and proved to be robust with limited error on current density measurement. However there exist some of challenges to this method such as complete grasp of open circuit potential during sliding test.

Huang and Zhu (2016) performed an experimental study on friction and wear between drill collar and casing. They studied the relationship between wear resistance and hardness of drill collar and casing. *Huang and Zhu (2016)* observed that the hardness can be improved through altering the heat treatment to improve wear resistance, and that increasing hardness increases the wear rate for both materials. *Kuang et al. (2016)* studied the effect of friction on buckling of drilling string during the horizontal drilling process. Buckling is a collection of instabilities that leads to catastrophic deformation as the load increase beyond the critical load. The increase in the load result in increase in compressive stress hence sideway equipment failure. Buckling behaviour of drill string restrain the extension of weight on bit (WOB) , increase wear rate of drill string and can result into ''lock up'', making the drilling process difficult *(Kuang et al., 2016). Kuang et al. (2016)* observed that buckling increases with increase in friction coefficient. This hinders axial load transfer or axial load flow and hence reduces the rate of recovery. Thus friction as a contributor to buckling at critical load must be reduced. One recent concept of friction drag reduction in drilling process associated with drilling non-circular wellbores proved to be effective in achieving this by reducing drill string and side walls contact area. The disadvantage of this methodology is the increase in the contact pressure between the drill string and rock formations due to reduction in contact/apparent area. *Taghipour et al. (2015)* studied friction and wear characteristic of steel on rock under water and oil based lubricated sliding conditions using steel pin-on-disc.

They *(Taghipour et al., 2015)* documented a decrease in friction coefficient with an increase of contact pressure when either water or oil based lubricants is used under wet condition. This was observed from wear scars that propagated with increase in contact pressure. *Taghipour et al., (2015)* plotted their finding as depicted by figure 2.6 below.

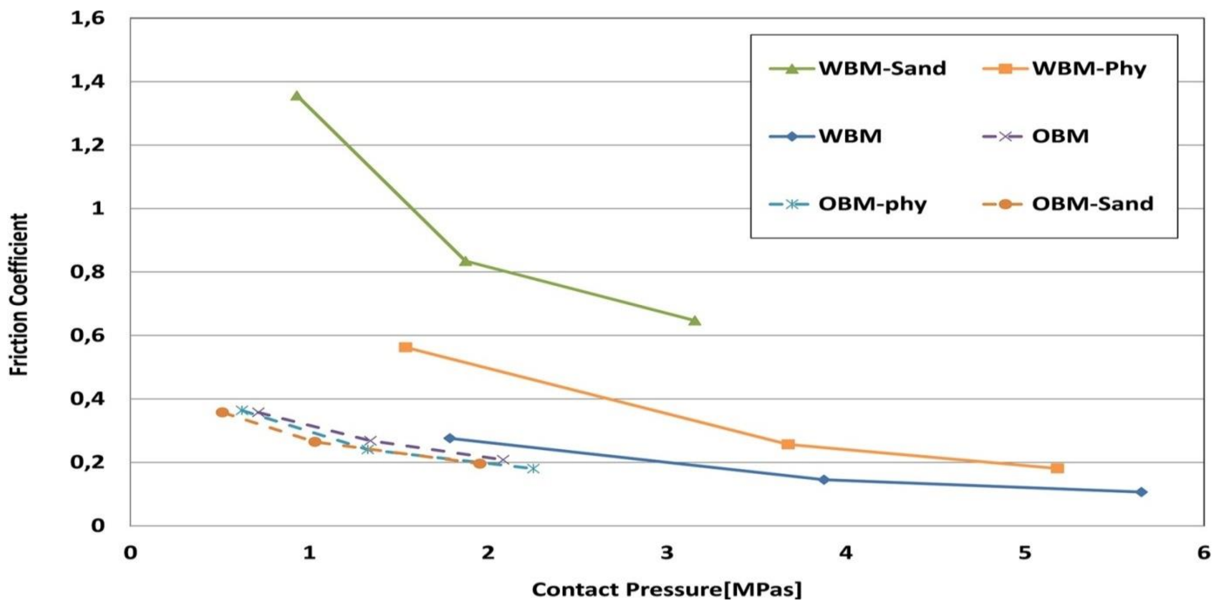


Figure 2. 6 Plots friction coefficient against contact pressure for different (Source: Taghipour et al., 2015).

The main graphs that relates to the scope of the project proposed are OBM and WBM. These graphs point a decrease in friction coefficient as the contact pressure increases, with the slope of OBM graph being a bit steeper than that of WBM graph. This implies better performance of the oil based mud (OBM) than water based mud (WBM). *Taghipour et al. (2015)* discussed their results to be in support of hypothesis about reduction in friction as a result of reduction in contact area (by increasing contact pressure, i.e. defined by P= F/A). It is also important to note that addition of sand particles increased the friction coefficient for WBM, but not the case for case of OBM.

Another, now old, method of studying friction factors in wellbores is the inversion method. Typically the wellbore is divided into two sections, case hole and open hole. Hence this introduces only two friction factors in drag calculations. However this does not provide best drag estimate for highly deviated and extended reach wellbore (ERW) due to their complexity. *Chen et al. (2015)* added a novel contribution to improve these methods by proposing multi-segments friction factor method. The method makes considerations of multiple friction factor typically found in extended wellbores. *Chen et al (2015)* applied the method in shale gas wellbore and obtained higher and best drag estimate. This method improves the accuracy of friction factor estimation and hence drags estimation. But it still gives estimated data and its accuracy is not guaranteed. Other methods uses finite element and they are typically computer based. One other method of friction or torque reduction is the back reaming method which is applied during the start of the drilling and helps to clean the drilling hole. The method includes lubricating the well and removing the spoils.

The other prominent method to measure friction factor and mitigate friction effects is the energy method. The methodology is profound fact that whenever there is friction there is system energy changes or energy dissipation. This is a very broad method and ranges from medium complex to more complex depending on number of factors incorporated. The energy generated or a system energy change on the surface is calculated using the ‘’approximated’’ friction factor. This is usually termed energy aspect for tribology-system analysis. The method analyses the exchange and transformation between mechanical and thermal or internal energy. The frictional energy losses also include strain energy and fracture energy. Entropy is an ideal tool incorporated into the methodology due to irreversible nature in the phenomena. But this poses complications in mathematical model which renders ease application limited. Even so, the method has not been mathematically generalized to achieve universal application or cater for all tribology-system.

Rymuza (1996) considered the study of friction using the energy approach. *Rymuza (1996)* proposed a new coefficient derived from inseparable energy dissipative nature of friction and termed it coefficient of friction losses (CFL). CFL is used in calculating the averaged energy losses in tribosystems. CFL is defined as the ratio of energy losses caused by friction to product of input referenced energy represented by load (IREL) and sliding speed.

$$\text{CFL} = \frac{\text{Friction caused energy losses}}{\text{IREL} \times \text{Sliding Speed}} \qquad \text{eqn. 2.2}$$

CFL has inherent dependency on environmental condition sourced from its relation to frictional energy. However *Rymuza (1996)* pointed the over simplification by this approach which renders nor universality or complete adequacy of it, as it mainly adequately describe friction process only in macroscale. *Rymuza (1996)* study was further extended to incorporate the microscale nature of friction by *Chen and Li (2005). Chen and Li (2005)* investigated the thermal aspect of friction putting much priority on heat generation as a result of friction and its relation to plastic deformation. *Chen and Li (2005)* based their study on sliding contact and concluded remarkably that during sliding contact, a certain fraction of mechanical energy is converted to heat and the remainder is shared by plastic deformation, micro-cracks, and change in surface roughness.

2.2.2 Wear

Wear studies have been fairly a complex project in previous years due to unknown interactions between surfaces. Wear is the progressive loss of material from the operating surface of a body, caused by relative motion at the surface and it may be broadly classified as mild or severe. Wear is an irreversible degradation process and the main characteristic of friction. While friction mainly induces energy losses, wear induces material loss. However both friction and wear are interdependent. This means that as friction propagates to be higher so does wear and the reverse is scientifically valid. However the rate of propagation may not necessarily be the same, resulting into different duration to steady state. Both friction and wear promotes multiplication (or enhancement) of both drag and torque. This is also validated by a known fact that dissipation of energy as a result of surface contact gives rise to wear. Implied by the latter is a direct proportionality between wear and dissipated energy as a result of friction, hence the relation is the same with friction. This linearity between wear and dissipated energy is affected by surrounding humidity. In comparison with multitudes of approaches to study wear, frictional energy dissipation is credited as a promising method for characterizing wear in tribosystems analysis. It is so because the linearity finds wide application for both sliding and non-sliding contact conditions. The beauty of the approach is also seen in multiple factors that it incorporates. These factors include effect of load, environmental conditions, velocity, contact pressure, etc. Reduction in the wear resistance propagates due to incessant transformations of metallurgical properties and mechanical properties of the material. Again this is also as a result of material oxidation owed to rise in surface temperature between materials in contact. Propagation of wear due to surface transformation or metallurgical properties transformation as result of temperature rise (increase in temperature gradient) can be theoretically supported by direct relation between entropy and temperature gradient. Entropy increases, i.e. molecules arranges randomly to different forms, as temperature gradient increase. The trade-off between wear types is due to energy dissipation giving rise to surface temperature. For steel-52100 transformations from mild to severe wear rate occur at around 200 ˚ C. Using energy dissipation, i.e. heat partitioning (Q) at steady state (equation 4), method, Archard's law (used to calculate wear rate (W), represented by equation 3 below) and linearity of temperature gradient (to equation 5 introduced by *Amiri et al (2010))* one can create basic relation between temperature gradient and the coefficient of friction.

$$W = k\frac{SN}{H} \qquad \text{eqn. 2.3}$$

$$Q = \mu \times \eta \times u \times N \qquad \text{eqn. 2.4}$$

$$\Delta T = \Psi \times Q \qquad \text{eqn. 2.5}$$

Simultaneously substituting (2.4) into (2.5) and further substituting the result into (2.3) by eliminating the normal load in (2.3) yield equation 2. 6 below.

$$k = (\mu \times \eta \times u \times H \times A \times \Psi)\frac{\dot{W}}{\Delta T} \qquad \text{eqn. 2.6}$$

Where μ represent friction coefficient, η is a partition number or factor, u represent sliding velocity, N is a normal load, Ψ represent the slope or linearity factor, $\dot{W}$ is a wear rate, ΔT represent temperature gradient, S is the sliding distance, H is the hardness of material, Q is the heat partitioned at steady state and k represents the wear coefficient. It is important to incorporate the partitioning factor, since in tribosystems energy is partitioned differently. For soft materials wear can also be measured using a linear variable differential transformer sensor (LVDT). Some other researchers prefer to use the Archard's specific wear rate to measure calculate wear rate. This equation is given by equation 2.7 below:

$$k = \frac{V}{NL} \qquad \text{eqn. 2.7}$$

Where V is volume loss, N is a symbol representing the normal load, L is a sliding distance. But using (7) the main challenge is to estimate wear volume or volume loss (V). A number of assumptions must be made such neglecting the volume chance on the off- wear track area and finally calculating the mean area which is not the exact area but average. Thus in practical situations some data may be lost when assumptions are to be made. But in certain scenarios , others are accurate and seem to give good estimates.

2.2.3 Wear Mechanisms

A number of wear mechanisms can exist between steel and rock contact. Typically the most common in hard formations are abrasive, surface fatigue, adhesion and tribochemical reactions. Abrasive wear and surface fatigue are produced largely from mechanical action. Whereas tribochemical and adhesion are more related to chemistry or chemical nature or charge nature of the system or components taking part of the tribology system. A brief highlight of mechanical dominated wear mechanisms sums section 2.2.3.

2.2.3.1 Abrasive wear

Abrasive wear occur as a result of presence of protruding hard materials called asperities that get in contact and wear by mechanical action the moving softer material. Abrasion is on its own divided into four sub mechanisms: microfatigue, microploughing, microcutting and microcracking. Abrasive wear mechanism is predominantly linked to the microstructure of the contacting surfaces.

2.2.3.2 Surface fatigue

The initiation of cracks in the specific surface position followed by their rapid propagation throughout the considered surface occur as a result of surface fatigue. This result into severe structural or material failures and potentially high friction and wear volumes as a results of new pore formations or cracks acting as sharp surfaces and quickly wear the softer material surface.

2.3 Tribology parameters

Numerous parameters aid in tribology phenomena. These include amongst many sliding velocity, contact pressure and load. The theory around these parameters will be succinctly discussed.

2.3.1 Sliding Velocity

Sliding velocity is mathematically defined as the slid distance per unit time. The introductory study on effect of sliding velocity on friction appeared in late 1850s and was performed by *Bochet (1861).* Bochet's interest was on action of brakes and railway wagon wheel *(Blau and*

Faulkner, 2008). Bochet developed a semi-empirical correlation of friction coefficient to sliding velocity. One of the limitations of *Bochet (1981)* correlation is its lack of common basis to achieve universal application/generalization. Effect of sliding velocity is theoretically proportional to the surface energy of the contacting bodies. This observation can be well proved as soon as one begins to rub both hands together or as fire is produced when one quickly rubs the match stick on cemented floor.

However the relation between sliding velocity and friction differs for different metals and under certain conditions (such as duration of contact). Predominantly there are two most important conditions, lubricated and unlubricated, where different behaviour on steel has been reported. Under boundary lubrication the coefficient of friction can demonstrate either a rise or decrease as speed is increases, and neither of the behaviours is observed during unlubricated conditions of which friction appears to be independent of sliding speed. This introduces complexity and it is one of the hindrances to development of a single universal applicable velocity-friction coefficient correlation or equation. An early study on rifle and artillery gun high speed which was laboratory conducted by *Kragelskii and Alisin (1981)* reported a decrease in friction as the sliding velocity increases. However other studies proves quite the opposite of the latter. These findings are in contrast with the third law of friction which state that friction is independent of sliding speed *(Chowdhury et al., 2011). Blau and Faulkner (2008)* attributes this to factors such as temperature rise, oxidation formation, surface softening (which tend to occur as temperature get close to material melting point, and tend to reduce friction), non- periodic/steady nature of velocity etc. that which can come into play at different conditions and introduce instabilities. At low velocities friction coefficient has been found to increase as the velocity slowly increases for certain conditions. Thus the correlation can be said to be material and situational or system specific. Similarly opposite trends between wear and sliding velocity exist. In engineering design, sliding velocity is usually combined with other factor or a product of two factors such as sliding velocity-nominal pressure (PV) is plotted against energy/friction coefficient to find the correlation necessary to design to optimum. This is not always effective and may produce further complication on correlation at certain conditions which can be difficult to interpret or use in design/operations optimization.

2.3.2 Contact Pressure

Contact pressure does not only directly impact friction and wear but can impact it indirectly too, by influencing other parameters such as initial surface finish. This interrelatedness of affecting friction parameters/variables renders singling out of each factor during laboratory measurement complex and hence results become difficult to interpret. According to *Blau and Faulkner (2008)* the effect of contact pressure and load are important to measure the probability and rate at which material galls. Contact pressure is typically reported as the apparent contact pressure, which is defined as a ratio of applied load to apparent contact area. It is typically ideal to keep load or normal force (if in direction of gravity) constant while varying the contact area. A challenge to this variable is determining the true contact area. More than 10 methods are documented on literature to perform this, but they are situationally specific. The effect of contact pressure initially targets microstructure.

2.3.3 Load

Similarly to behaviour of friction response with velocity variation under lubricated conditions is the friction-load relationship. However, this is elaborate and has reasonable explanation to buckling behaviour is typically the most severe hazard associated with increase in load. However, load effect on friction factor may be different and contrary to our intuitive or even scientific expectations. This is backed up by the finding of *Budinski (1981)*. *Budinski (1981)* conducted a study using different metals looking at their tendency to gall using standard ASTM and G98 method. The results showed an increase in friction factor or coefficient as loads increased, say to a range of 2000N-4000N, but higher load about 18000-25000N produced decreasing trend of friction coefficient. Under higher loads surface films (yielding an additional triboformed film/layer) or roughness can be altered in favourable manner in such a way that friction factor decreases as the wear rate propagates. The subject of surface conformity, which is attained through running-in behaviour plays a significant role in explanation of load and friction response. Again different formations such in deep drilling formation rock composition or grain sizes and their cluster plays a role in friction response at different load. The other factors include debris accumulation which has a tendency to affect the shear strength on the interface.

The relationship between load and wear has been studied and documented as proportional according to wear volume equation 2.8 below:

$$V = k\frac{SN}{H} \qquad \text{eqn. 2.8}$$

Where V represents wear volume, N is the normal load, S is the sliding distance, and H is the hardness of material. k represents the wear coefficient, which measures material wear behaviour. This equation can be generated from the energy dissipation method, in its description which can also be mathematically attested connotes the proportionality relationship between wear volume and friction, and hence energy dissipated by friction. Load effect is one perennial (dated to have begun during Amanton’s time) intensively studied friction influencing factor that ‘appears’ by now to have been ‘better’ correlated, though the correlation is practically not general or does not apply to all situations. Early researchers such as Amanton’s used crude instruments to conduct their studies and this made their data more produce able hence yielded them to reach conclusion on equations correlation quick with incomplete data. But modern instruments have proved some of the correlation to be situationally specific and not generally applicable to well articulate the behaviour of all tribosituations. This is attributed to physical factors that were previously neglected in early scientific studies such as elastic deformation of asperities to plastic deformation and fracture *(Blau and Faulkner, 2008).*

2.4 Lubrication

2.4.0 Introduction

Lubrication is an old method of friction reduction. Its appearance can be dated to time of Leonardo Da Vinci. To date multitude of researcher and companies have put effort on developing better performing, and efficient lubricants to reduce friction, reduce viscosity and enhance flow or productivity per time/per pump energy use. Lubrication is currently the best method available for friction, and wear reduction compared to others like welding (or surface finish-used to even the surface) to name the few.

According to *Farr J. (2015)*, a quick summary for operators is that the lubricant is the time-proven solution to more than a dozen major drilling challenges. The solutions offered by lubrication according *to Farr J. (2015)* include faster setting of casing, enhanced liner sliding by personnel, increased rate of penetration (ROP), substantial reduction of pump wear, improved drilling or production time (to about half the typical drilling time) for curve/directional drilling, substantial reduction of torque and hook load, and allow for reduced corkscrewing in straight vertical drilling. With lubrication cost savings (of the cost that would have been incurred without them during drilling) can go above $1 million.

The biggest challenge on lubrication study is to develop lubricants with strong positive charged molecular structures, capable of working under extreme heat and pressure, which can bond to all metals. Lubricants that produce more ordered adsorption layer are needed. Other challenges include lubricant contamination, separation, costs and loss *(Muhsan et al., 2017)*. Green tribology is the new tribology component that aim to contribute in producing environmentally friendly lubricants to reduce effect such as toxic contamination of ground water. For hydrocarbon lubricants, carbon chain or content plays a very important role in lubricant selection, typically oleate (e.g. Sodium oleate) as they better reduces friction but small chain or lighter hydrocarbons can also be used where the fluid mobility is paramount. These also serve to justify the effect of temperature on lubricant viscosity and composition is so foundational to understanding the chemistry of lubricants. Lubrication chemistry is termed tribochemisty. Tribochemistry is one of the prominent studies in tribology. Tribochemistry focuses of factors such as lubricant's relative humidity, surface reactivity/catalysis, composition at present or induced environmental condition, cleanliness, oxides formation ability, friction polymer formation, tribopolymerization, and tarnish films. However, particularly in petroleum industry, other factors such as supply of lubricant, aging etc. plays significant role and are considered as part of rheology study.

Control of performance and equipment life is fundamentally performed using lubricants and the process is called Lubrication. Different lubricants are valid for applications in different lubrication process or regimes. Lubrication regimes are best studied using Stribeck curve developed in 1902 by Richard Stribeck. The term Stribeck is used to describe the plot of coefficient of friction (COF) against a dimensionless bearing number i.e. $\mu V/P$. Where μ is the dynamic viscosity, V is the relative velocity, and P is the nominal pressure. Nominal pressure is the ratio of load to nominal or projected bearing area. The section will introduce the stribeck curve development, proceed to elucidating on the lubrication regime, then wear mechanisms and contact mechanism. On contact mechanism section the emphasis will be put into Hertzain contact stress and this will be the concluding.   Figure 2.7 below introduces a typical diagram used to model the dynamic behaviour of lubricants introduced in annulus (thickness =h) between the drill string and well-bore.

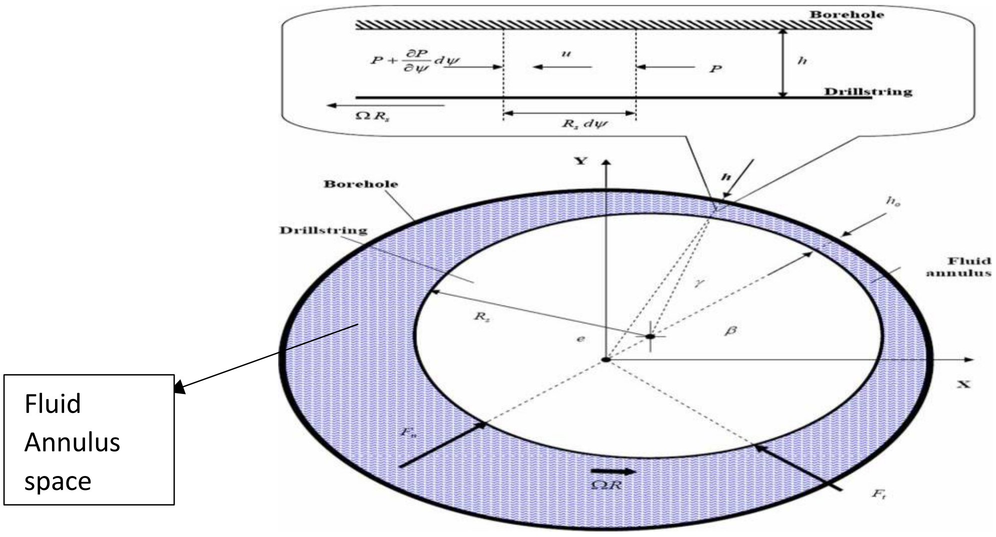


Figure 2. 7 showing typical section where lubricants are introduced in drill string and borehole. This diagram shows some of the important parameters considered in lubrication process (Khufiel & Al-Saliaman, 2009).

According to *Khufiel & Al-Saliaman (2009)* the fluid effects are of high practical importance drill string vibrations, associated resonances and instabilities. This necessitates the deep understanding of lubrication phenomenon.

2.4.1 Lubricants classifications

Lubricants are generally classified according to the two measure category: Newtonian or Aqueous Lubricants and Non- Newtonian Lubricants. The differences between the two lubricants lies in the properties. Generally the mixtures of the two classes of lubricants are utilised. This necessitates the important establishments of their functioning in terms of friction reduction at different lubricants. Fluid rheology is an important factor in friction reduction. Determining the optimal concentration is a target in deep drilling process, however this is performed experimental wise in laboratory and there exist no single method for determining the concentration of the drilling fluid mixture. This necessitates the study of the rheology of friction. One of the greatest challenge is the dehydration of drilling fluid in deep drilling process a results of exposure to high temperature and pressure conditions. This accelerate the mud cake formation. The need to study effective concentration, which can possibly account for sustained and long term performance of drilling fluid appears to be most demanded for deep downhole drilling.

2.4.1.1 Aqueous Lubrication

Typically in onshore drilling water is used as a cheaper and readily available lubricant. An important factor for lubricant effectiveness is its composition which makes up its viscosity. Many have attempted to formulate different lubricants with several commercially available additives in the market, and other researchers have worked to vary particle size a source for aid of nanoparticles or rather nanotechnology in lubricants. However the effectiveness of the lubricants in reducing friction happens to be a function of numerous factors. Even with continued decades attempts to define and find linkage between concept of friction and lubricant compositions there is still no exact correlation between a specific lubricant compositions and friction coefficient. For aqueous lubricants such as water, viscosity is a gradient of the straight line curve formed by direct proportionality between the shear stress and shear rate model which is a behaviour similar to Newtonian fluids and thus water is sometimes referred to as the Newtonian lubricant.

2.4.1.2 Non-Newtonian Lubrication

Non-Newtonian fluids such as bentonite mud have been a subject of interest for centuries due to their non-linear behaviour making their rheology not easy to interpret. The most basic unique point about these fluids is that they do not follow the same behaviour of shear stress and shear rate as that of their counterpart i.e. Newtonian fluids. Thus the shear stress is not linearly dependent to the shear rate and viscosity varies with changes in shear rate. Thus non-Newtonian fluids can also be classified as thixotropic fluids due to thinning of viscosity with shear rate and changes in viscosity influences the carrying capacity of the drilling mud *(Ismail, 2011)*.

2.4.1.3 Measuring lubricant lubricity or quality.

Lubrication process is targeted to perform whole or one of the following functions i.e. cooling, reductions of torque and drag between bore-hole and drill strings, cleaning of the hole/well, maintaining effective pressure during drilling i.e. weight on bit control etc. Friction and drag is one of the major problem in drilling industry and other fluid transportation section pipe lines. Torque is the frictional resistance to rotation of the drill string, whereas drag is the resistance to hoisting and lowering of it *(Abdo & Danish, 2013).* Hence to determine the lubricity of the lubricant one needs to calculate the reduction in torque. Equation 2.9 below is used to calculate the %torque reduction.

$$\%\text{Torque reduction} = [(A-B)/A] * 100\% \qquad \text{eqn. } 2.9$$

Where A represent the water coefficient of friction (COF) and B represent COF of the lubricant to tested. To generate the two COF similar conditions are tested using same set up by introducing to surface the two different lubricants.

2.4.2 Generation of Stribeck Curve

Primary to the generation of Stribeck curve are the lubricant properties. The lubricant must have a potential of creating a converging gap geometry, which implicate possible creation of pressure increase to support the load. This make it possible to distinguish from the regimes, or combination of, occurring in between the surfaces of interest. Each regime is defined by the ratio of film thickness to composite surface roughness symbolised as λ. This service parameter according to *Williams (1994)* is comparable to the dimensionless group called Sommerfeld number (S). Further analysis of Sommerfeld number will follow in section 2.4.2.1.

To generate different regime, typically a lubricant is introduced in between the sliding surfaces which yield different geometries essential for different lubrication regimes.

Practically speaking a single regime is rarely possible. At this point it is essential to understand another dimension that play a significant role to distinguishing between regimes which can be termed surface finish between the sliding surfaces. Typically in reality there exist rarely a complete smooth surface; surfaces usually on different ranges have some hills and peaks which can be of different heights even on same surface. These peaks and hills are called Asperities. They typically enhance wear depending on their strength (Hardness and elasticity), they can penetrate though the fluid film (this sometimes depends on the size of the applied normal load). Thus not only lubricant properties are crucial but surface properties are important too. It is also important to note the contribution by operating conditions. Temperature affect lubricant viscosity by decreasing it while pressure tend to increase the viscosity of the lubricant. Most lubricants tend to thermally decompose, polymerize, and oxidize due to thermally catalysis of chemical reactions. Thus this can change the regime and also impact on dimension less group. Needless to say that for some other contact or lubrication bearings bulk lubricant properties such as density, viscosity etc. are the only essential for the analysis of identified regimes.

Further on generating Stribeck curves different techniques have been devised depending on the direction of contact. Typical contact direction/motion are reciprocating and unidirectional motions. Uni-direction is easily modelled in the laboratory using a pin-on-disc rig flooded with lubricant. According *Shaffer (2014)* the pin end contact geometry serves to create also a converging gap. The simplest method to obtaining a stribeck curve is to vary one parameter amongst those constituting the dimensionless group while fixing the other two. The choice of parameter values are such that the range is able to cover all regimes. However as simple as it is, not all motions are uni-direction and most tend to be reciprocal. Example of this is found in simulating lubrication conditions on the cylinder piston ring found in the automobile engines *(Shaffer, 2014).*

Reciprocal motion test find have been intensively researched and sometimes called high frequency reciprocating rig (HFRR). However, there are challenges associated with using a reciprocal motion which commonly are the prevailing motion in most industrial drilling equipment's such as pumps in oil wells. These include developing enough velocity over a wide range of stroke length ere the reversal process begins. This is to build up required pressure necessary to encompass all the regimes. The challenge doubles when the regime targeted has no clear correlation theory between the parameters. This challenge remains a significant gap as one cannot laboratory model all the prevailing conditions in the practical industrial process, hence a correlation pave a way to mathematical modelling which better give substantial replicable results. Even so with laboratory techniques there exist no well know and establish standard method of generating a stribeck curve. The importance of stribeck curve is top study the lubricant rheology, analyse separating regime, an enables analysis of additive performance on friction.

2.4.2.1 Dimensionless parameter

Normally a lubricant is introduced on the clearance space, with journal bearing in particular, between bearing and rotating shaft. Loading conditions are designed, and either a test is conducted under isothermal conditions or varying temperature. Under isothermal condition the complexity in formulation of the dimensionless number is reduced as viscosity and other parameters are fixed as result of constant temperature. This simplifies the complexity in the dimensionless group as would otherwise be when temperature is set to vary. Hence permit ease for analysis of the relation between the dimensionless number with other parameters forming its equations. One typical such dimensionless group is called the Sommerfeld number (S). The Sommerfeld number is applicable under isothermal condition and represented in the expression on equation 2.10 below:

$$S = \frac{\mu V}{P} \left(\frac{R}{C}\right)^2 \quad \text{eqn. 2.10}$$

Where S is the dimensionless quantity called Sommerfeld number; V is the rotational velocity of shaft; R is the radius of the shaft; μ is the lubricant viscosity; C is the clearance between the shaft and bearing radii's; P is the specific load represented by equation 2.11 below.

$$P = \frac{W}{LD} \quad \text{eqn. 2.11}$$

Where L and D are bearing length and diameters, respectively.

Few important points to draw from equation 2.11 above:

- When shaft is unloaded, i.e. P=0, the S value goes to infinity. Hence concentric run of shaft on the bearing occurs.
- Considering a Journal bearing, when load is increased or reduction of speed i.e. decreasing S then the shaft will move away from its concentric position. Resultant Journal trajectories will approximate a semi-circular arc.
- When shaft is extremely loaded or speed severely decreased the value of S turn to zero. Thus metal-to-metal contact occur at the point where the load line cut the bearing section.

The points noted above contribute in the design of equipment by approximating the possible regimes of lubrication. Hence they help to best explain the prevailing geometry through mathematical observation of relations between the parameters and the dimensionless number. Sommerfeld number is equivalent to that used in American standards called the Hersey number.

Another representation of the dimensionless quantity is that which represent surface roughness as square root of root mean squares roughness's of both surfaces i.e. R1 is the root mean square roughness of surface 1 and R2 is the root mean square roughness of surface 2. Where hmin is the minimum film thickness. It is important to note that this equation normally assume Gaussian distribution of asperity heights which practical surfaces do not conform to.

$$\lambda = \frac{h_{min}}{\sqrt{R1^2 + R2^2}} \qquad \text{eqn. 2.12}$$

2.4.3 Stribeck Curve Regimes

Numerous lubricants commercially available are associated with few regimes. Each regime is differentiated from the other by the occurring geometry, dominating properties and film thickness. The liquid lubricant frictional characteristics are plotted on the stribeck curve over the condition encompassing the four main regimes: Boundary lubrication (BL), Mixed lubrication (ML), Elasto-hydrodynamic lubrication (EHL) and Hydrodynamic lubrication (HD) regime. The ratio of film thickness to surface roughness i.e. service parameter λ has been assigned different figures or ranges to differentiate the three regimes. It should however be re-iterated that in practical system a single regime is rarely possible. Succinct discussion will be given on each of the regimes. But it is important at this point to introduce a schematic of Stribeck curve, and figure 2.8 demonstrate this. It should be noted that on practical system the curve may not be too smooth as there exist many factor that influence friction but not considered leading to some possible outliers.

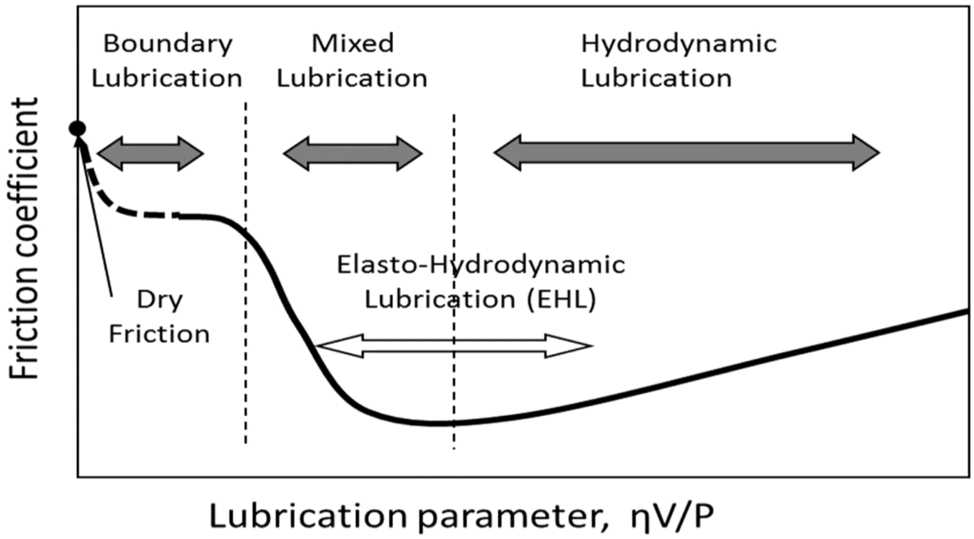


Figure 2. 8 Plot of logarithmic of friction (COF) vs logarithmic of Lubrication parameter (Hersey or Sommerfeld number) demonstrating different regimes. This is called a Stribeck curve. (Kondo et al, 2013)

From figure 2.8, the regimes location are approximated to exist over a given drawn range. It is important to analyse the local minimum point found on the Stribeck curve. At this point viscous shear losses in the lubricant are at lower value and the forces of friction are at low development stage and /influence. This can occur as a result application of low sliding speed. This is a very sensitive point in the curve. It is typically said to be short lived and unpredictable. This can be viewed as a string mounted with a ring of which any vibrations on the string causes a shift in the position of the ring on string. in a similar manner and more sophisticated engineering language; any little change in the condition shift the local minima point. It is also difficult to predict this point and perhaps if it can be predicted one may gain more ease insight to separation of some regime. Hence for these prevailing reasons one should not be misled in design to attempt to operate at this point. On the other hand this point seems to have important bearings and thus further research is needed in particular with regard to ensuring ways to its stability.

2.4.3.1 Hydrodynamic lubrication

Theory associated with this regime is the only well understood and established amongst other regimes. Consider two surfaces of different roughness in parallel contact motion with each other and completely separated by wedged fluid lubricant. The fluid in between the parallel plate must be naturally at rest according to the laws of fluid dynamics to allow continuation of parallel motions. Thus this is termed hydrostatic lubrication. Hydrostatic lubrication study the fluid lubrication at rest in between two parallel surface. The opposite of hydrostatic fluid lubrication is termed hydrodynamic lubrication.

Hydrodynamic lubrication regime represent fluid lubrication between non-parallel motions of surfaces completely separated by fluid of certain thickness. It is important to emphasize the complete separation of the two surfaces by the film fluid thickness as fundamental to character of the hydrodynamic regime. Fluid film thickness is certainly the basic distinguishing factor between the lubrication regimes. However there exist scientific values that have widely been accepted as ranges representing the existence of each regime. For hydrodynamic regimes the fluid film thickness is estimated to be in a range of $\lambda > 3$. This value can be interpreted to mean that to a unit of surface roughness the film thickness must always be three times greater. Unit surface roughness is interpreted as the average surface roughness of the surfaces. Figure 2.9 below represent the clear schemata which is believed to be visible enough to maintain the afore-estimation for consideration.

However, in practical situations film fluid thickness cannot, by any means so possible, be solely used to distinguish between the prevailing regimes unless the analysis of applied parameters attest sufficiently to span the conditions for lubricant viscosity. This then necessitate the evaluation of other factors that can be used to distinguish one regime from the other. Pre-mentioned are other important factors of reigning geometry and bulk fluid properties.

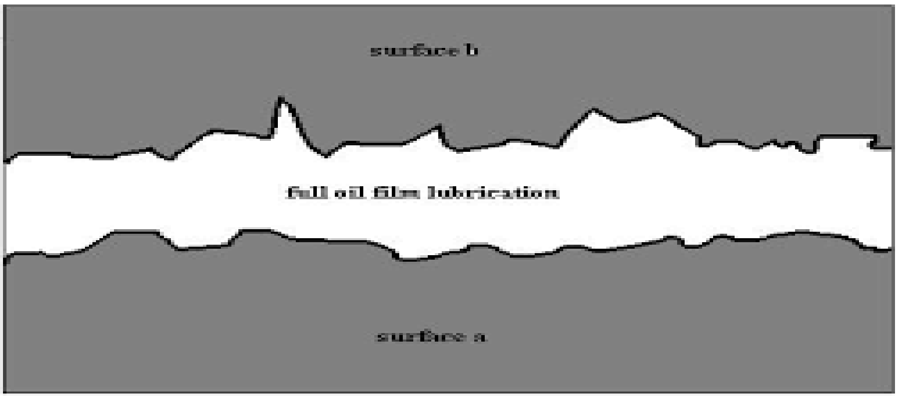


Figure 2. 9 Demonstrating lubricant film thickness occurring under hydrodynamic lubrication regime between the two surfaces a and b. (Adapted from: Nehal &Amal, 2013)

For Newtonian fluids under hydrodynamic regime the coefficient of friction (COF) is dependent on the square root of Hersey number, and tangential force (or Friction) increase with sliding velocity provided specific load is kept at moderately minimum or average value *(Williams, 1994).* However for non-Newtonian fluid, of which lubricant's viscous nature changes are a result of shearing, the coefficient of friction has strong bearing relation to lubricant viscous changes. This point to the dependence on fluid bulk properties by coefficient of friction under the hydrodynamic regime. It is thus for this reason that pressure necessary to support the load can be manipulated positively when fluid film is convergent in the direction of relative motion. Convergence is then therefore the geometry that fluid must take. This geometry allows film to run continuously throughout the clearance space, and film raptures which occur predominantly at the divergent section are negligible. This typically occurs when two surfaces fit conformal contact. Hence no outside load support by virtue of external equipment or even asperities is needed if these criteria are met. Without neglect, one of the challenges associated with this regime is its association with high drag in particular under high sliding velocity.

2.4.3.2 Elasto-hydrodynamic lubrication

Elasto-hydrodynamic lubrication (EHL) usually occurs in non-conforming contact geometries or surfaces. In general, it is slightly difficult to build a perfectly uniform thick film which completely and almost equally separate the two surfaces in motion. Hence the lubricant-carrying surface area may not be constant, and is very small compared with conformal surface geometries though it is known to increase with load. As a result some mechanical contacts occur by asperities between two surfaces. This then demands forth the understanding of surface properties. This mechanical contact yield some heat developments on the surface of which results into elastic deformation or flattening. Reduction in film thickness is a source allowing this contact but not solely. For very high load or low speeds the fluid hydrodynamic pressure is typically not sufficient enough to support the subjected load, thus yielding again peak to peak or peak to bearing surface contact. Stresses developed from non-conformal contact are detrimental to surfaces. Thus the extent to which the regime extends depends on both surface properties and partial lubricant properties. Figure 2.10 shows a demonstration of how this may look.

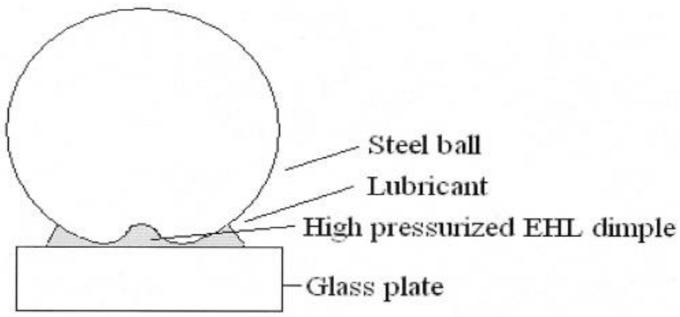


Figure 2. 10 Demonstrating non –conformal contact between the two surfaces separated by lubrication. The ball undergo elastic deformation and forms a dimple (Adapted from: Chi Lok Wong et al, 2005)

The hardness and elasticity of the surfaces distinguishes between hard and soft EHL. Hard EHL is common with metal-to-metal contact as these are hard and characterised by high elastic modulus value. The soft therefore are as a result of low elastic modulus and typically occur on rubber. The latter tends to be a common target in bio-tribology. This regime tend to neglect any possible chemical reactions or plastic deformations.

2.4.3.3 Boundary Lubrication

Under boundary lubrication the film thickness is so thin as to allow neglect for effect of bulk properties of the lubricants. Wedged lubricant thickness falls far below root mean square or relative average surfaced roughness. This thinning of the film allows for more surface to surface contacts, as the force of penetration through thickness by asperities is close to negligible. This force of penetration of asperities is in view close in relation to load applied in as much as the fluid bulk properties affect it. Some asperities penetrate the surface so easy and this can be for a longer contact area. As a result of contact between the two surfaces heat may be produced. Usually surfaces are designed with some oxides or protection layer on their surface. It is widely accepted that frictional heating yield rise in temperature, and that temperature is inversely proportional to viscosity. Another factor with strong bearing in this regime is introduce by the latter and termed environmental/surface conditions. This therefore has either negative or positive connotation to the already thin fluid thickness. Due to effect of temperature on microscale of film, chemistry (in particular thermochemistry or chemical thermodynamic) of the lubricant becomes important to study. Thermo-catalysed reaction may occur, producing product that may either be beneficial or detrimental to the surface. Furthermore these mechanical interaction also produce scuffing, adhesion, abrasion and fatigue; making these typically common in the regime. Thus according to *Williams (1994)* load sharing by asperities together with chemical reaction constituents are the main basic characterisation of boundary regime.

Furthermore during these mechanical interactions plastic deformation and collapse of the asperities occur. The collapsed metallic product may further open the surface for propagation of the reaction and in essence yielding organometallic/inorganic metallic and/ oxidative products. Static oxidative conditions are necessary for the formation these product. These products can form, as previously mentioned, a tribofilm which may either be detrimental (prowear) or beneficial (antiwear) or rather inactive to surfaces. Another possible benefit or vice is the possible transition from non-conformal to conformal contact can change the contact area. According to *Bhushan (2000)* detailed physical and chemical properties occurring on contact section are still missing; making the theory of boundary regime incomplete and rendered less understood. Literature assigned estimated value for boundary lubrication occurrence $\lambda<1.2$. Both mechanisms of wear i.e. wear by mechanical interaction and wear by chemical behaviour of materials are important in analysing surfaces under boundary lubrication. However, foundational are mechanisms under boundary lubrication. Different mechanisms are associated with different rate of reactivity or deformation which better linked to prevailing surface layer. According to *Williams (1994)* there are several known mechanisms by which the boundary mechanism tend to occur classified according to layers; these are: Sacrificial layer, low shear interlayer, friction modifying layer, shear resistant layer, and load bearing glasses. In overall the boundary film formation and propagation is through these different mechanisms, and it controlled by three main factors: surface elements, lubricants and the environment.

(a) Sacrificial layer

This is based on the principle that there is originally a layer of oxide designed on the surface which will tend to be quickly removed instead of actual surfaces being worn out. This layer is termed sacrificial layer. It usually open up to the low shear inter-facial layer. There lies in this mechanism the possibility of protecting the surfaces as the layer can again form and get adhered to the surface. However this demands rate of formation to exceed rate of removal of the layer.

(b) Low shear layer

The source of this mechanism is the presence of weak interlattice between the shear planes of the solid molecules of surfaces. This weak interlattice allows ease sliding of lubricant between the planes; hence both shearing and motion occurs in between the layers.

(c) Friction modifying layers

This mechanism is strongly controlled by chemical reactions product. In general the weak multilayer adsorption of the products occurs on surfaces they formed. This creates another ordered layer of which the two surfaces move along between each other.

(d) Shear resistant layer

Typically this layer is formed by strong bonding of organometallic reaction products onto the surface in motion. This strongly bonded layer certainly exhibit solid or semi solid like behaviour or shearing strength. The layer is by itself shear resistant; hence reduces shearing.

2.4.3.4 Mixed Lubrication

As pre-mention it is rarely possible unless purely in hydrodynamic regime to classify a system as having one regime. Typically two or more regimes may be at work in keeping the load supported and separated. Thus therefore mixed lubrication is a sum of different mechanism to support the subject load or surfaces. For a certain section in lubricated system a boundary regime may prevail for example. This therefore implicate that there exist non-uniformity in thickness length across the lubricated surfaces. Hence allowing for load support by asperities. Normally in a mixed regime both boundary lubrication and elasto-hydrodynamic lubrication exist. The need therefore arises for one to understand the interplay between these two lubrication regimes so as to explain the mechanism of mixed regime. Mixed lubrication is as a result of non-uniform distribution of surface asperities. The lack of comprehensive theory associated with boundary lubrication makes it difficult to separate it from EHL. Thus mixed lubrication serve as a transition, interchange or interplay between EHL and BL, and in some cases hydrodynamic mode (HL). Again some elastic deformation can occur in the boundary regime.

2.5. Contact Mechanisms

Two typical mechanisms of solid contact are Hertzian and non-Hertzain contacts. Generally the principle of classical mechanics assumes deforming materials to be isotropic and homogeneous. Non-Hertzain contact mechanism is directed towards un-curved surfaces. In this section a brief description of Hertzain contact mechanism is presented.

2.5.1 Hertzian Contact stress

The birth of notable studies in stress analysis is dated to have begun as old as in the 18th century when Heinrich Hertz first introduced the concepts model. Consider figure 2.4 in section above again, heavily loaded ball rolling on flat surface. The rolling ball deforms, its surface is altered whether by elastic or plastic deformation. This will occur also out of visibility to the eye i.e. only in microscopic scale. To some extent this can go to as far as changing the entire surface. According to Hertzain model the degree of deformation can be expressed as a proportional to the radii's i.e. at microscopic scale. These radii's represent the true contact areas. According to *Bhushan (2000)* these areas provide room for stress generation whose effort is to balance the applied load by transforming it into pressure in microscale. Hertzian developed his theory of contact area using following assumption:

- Surfaces are assumed to be non-conforming, continuous, smooth and frictionless
- Strain associated with deformation are small as a result of assumed small areas of contact relative to entire body.
- In contact zone, each solid behaves as an elastic half-space.

- Parabolic expression of un-deformed area.

Hertzian contact is of central focus because they analyse in particular heavy loaded surfaces failures and thus leading to better understanding of the material plastic deformation which begin occur at few distance from the surface. Thus due to distribution of maximum tensile stress at r= a deformation propagates greatly at the edge of loaded surface, yielding to visible surface deformation. The difference in stress formulation is a function of sub-contacts i.e. Nominal point contact, Nominal line contact, elliptical contacts etc. The area of contact in m^2 is given by equation 2.13 below:

$$\pi a^2 \approx 0.83\pi \left(\frac{W_r}{E}\right)^{\frac{2}{3}} \quad \text{eqn. 2.13}$$

Where E is the elastic modulus and Wr is the radial applied load on sphere. Equation 2.13 is used to compute contact pressure between the contacting surfaces by dividing normal load with the area calculated from the equation. The elastic modulus is a function of Young moduli (E_1 and E_1) and Poisson's ratio (v_1 and v_2) given by equation 2.14 below:

$$\frac{1}{E} = \frac{1-{v_1}^2}{E_1} + \frac{1-{v_2}^2}{E_2} \quad \text{eqn. 2.14}$$

Hertzain contact theory best explain the mechanism in curved surfaces. Hertz theory was later used as a basis for development of contact area theory. If two surfaces are brought to contact, the initial contact will occur by asperities. The load on surfaces plays a big role in allowing surfaces to come more close to each other and deformation to occur. Surfaces will move close to each other till the area is sufficient enough to support the load. The conclusion from this was thus that the contact area is proportional to the load (W) and inversely proportional to the yield stress of the material (p_m) as given by equation 2.15 below.

$$A=W/p_m \qquad \text{eqn. 2.15}$$

Equation 2.15 provided the basis of friction or tribology analysis. The first mathematical expressions and analysis of friction or friction coefficient were founded from the above contact area equation. This has also served as `the basis of Archard's theory of wear and Bowden and Tabor expression or analysis of friction.

2.5.2 Line contact: A mechanism for drill strings

The contact mechanism demonstrated by drill-string and rock interaction is the linear contact mechanism. This is because drill string are usually designed as cylinders. In basic terms, this means that the drill string axes of symmetry are typically the y-axis. Hence a specific formula or modification (given by Bhushan, 2000) of the stress equation should account for this. Contrary to line contact is point contact, a contact mechanism for spheres. Contact mechanism affect the stress distribution between the two bodies.

2.6 Friction data analysis methods: Regression analysis.

To analyse the collected friction data regression is used to analyse the best fit to results. Table 2.1 below looks at the parameters important for regression analysis. Polynomial of 2nd and 3rd degree are normally used as these are very readily comparable to linear model and can be easy to interpret than other polynomials and the choice of the polynomial can be influenced by data points. The best model must have the best explanatory power and give minimum deviations or have reduced number of outliers. Hence the higher the R^2 the best the model fit the data.

Table 2. 1 Regression parameters definitions

Nomenclature	Definition
R	Measures how two variables move in relation to each other
R2	Proxies how much variation in Y is explained by X in percentage
Adjusted R2	Improved reliable statistics. It takes into account the number of variables in the regression. When you increase the number of variables it takes into account for the real increase in the explanatory power.
Standard error	Measures the variability of actual Y values from the predicted Y values
N	Sample size or population.
Line formula	Used to predict what is going to happen with the change in the X variable: in this case the temperature. The line formula will equal the change in the friction factor.

Chapter 3: Materials and Methods

3.0 Introduction

This chapter presents materials and methods used to conduct the tests in this project. A pin on disc set up is explained, followed by sample preparations, calibrations and in test methodology used to conduct the actual test.

3.1 Experimental Setup and Sample fabrication

The pin-on-disc set up is as shown in figure 3.1 above. The different loads were placed on the load holder. The inherent load of the load holder was calculated and found to be about 15N. The disc holder allows the sample disc to be placed and rotate the disc at variable speed. LVDT sensors were mounted to the part where the pin was placed in order to best collect the results and allow reduce vibration collections. The safety switch allows for quick shutdown of the system.

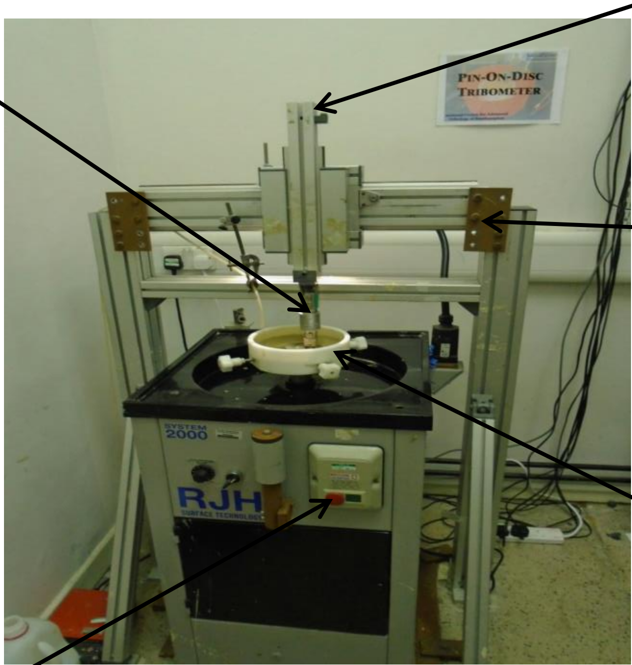


Figure 3. 1 Experimental setup

The pin-on-disc rig used and shown in figure 3.1 above permitted unidirectional (either clockwise or anticlockwise) sliding of disc holder mounted in the shaft. The rig consisted a static pin mounted on a rigid frame that was fixed to the ground. The pin was fixated at on a rotating disc and pressed against this disc to allow modelling of desired stress. The load holder consisted of a removable plate used to place various load sizes. The load holding system combined resulted to the inherent load of 15N as described above. This load was factored as base load and all load were incremented from this value to account for its effect on friction. The unloading process meant that the load holder be continuously lifted up.

Table 3.1 below show the sample morphology. Figure 3.2 illustrate the dimension and geometry of the steel pin, steel sample, and sandstone rock sample. The steel pin sample were fabricated with spherical tip and hand polished. Whereas the steel disc were polished using magnetic diamond polishing plate which was subsequently followed by 1200 grit. The steel pin and steel disc had the similar Vickers hardness of about 241 HV.

Table 3.1 shows the properties of the rock and steel samples. Figure 3.1 shows the sample design and dimensioning.

Table 3. 1 Sample properties.

Properties	**Pin**	**Sandstone disc**	**Steel disc**
Type	ASI 4340 Steel	Larsen B Sandstone	AISI 4340 Steel
Diameter (mm)	8mm	83 mm	60mm
Width	-	35mm	25mm
Silica content (%)	-	*Approx. 91.22	-
Ultimate compressive strength	-	*Approx. 37.45	-
Mohs hardness	-	* Approx. 6.44	-
Roughness	0.05µm	-	0.04µm

*****the values were adapted from Ersoy and Waller (1995).

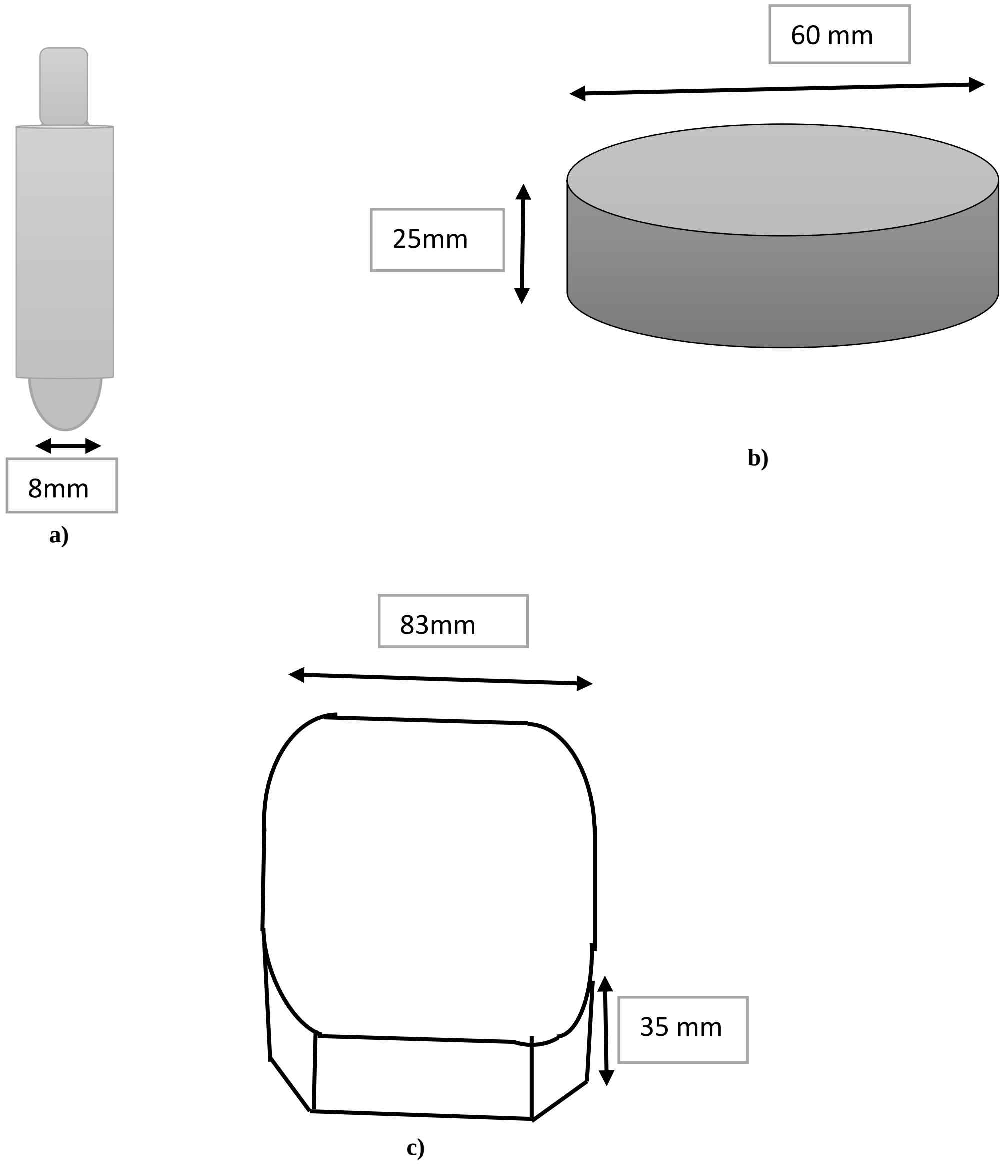


Figure 3. 2 Sample design. a) Pin and b) Steel disc. c) Sandstone disc

For mud preparation, 60 g. L^{-1} of bentonite particles were mixed distilled water. The pH was further increased by adding a drop of NaOH to 9. The mud concentration was prepared in conjunction with industrial bentonite lubricant. All sandstone samples and steel pin and steel samples were fabricated at the University of Southampton, United Kingdom. The sandstone discs were cut using the water jet cutting.

3.2 Preliminary Test or Wear Volume Calibration

The preliminary test was conducted at a speed of 30RPM (0.053407m/s), with sliding distance of 192.265 m in 3600s. To calculate wear volume for each time progressive diameter of wear scar, the spherical cap equations 3.1 and 3.2 were used.

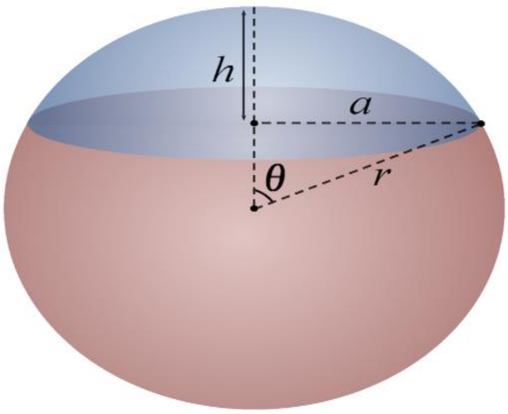


Figure 3. 3 Express dimensions of spherical cap as measured on Steel pin used in project

$$V = \frac{\pi h(3a^2+h^2)}{6} \qquad \text{eqn. 3.1}$$

$$r = \frac{a^2+h^2}{2h} \qquad \text{eqn. 3.2}$$

Where V is the wear volume or volume removed due to steel- rock contact, h is the height of removed surface on cap, a is the radius of the cap, and r = 3mm is the radius of spherical steel pin. The data was collected when experiment was run for 1800s and plotted in figure 3.4 below. The wear calibration depicted acceptable accuracy of the pin-on disc.

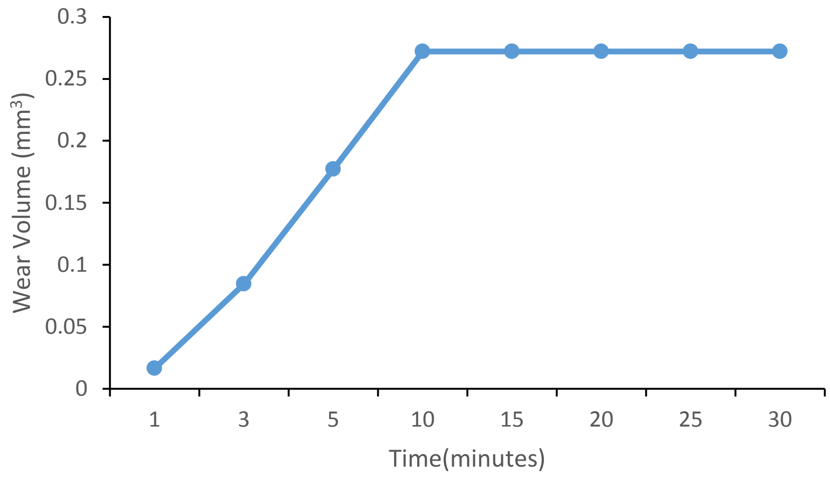


Figure 3. 4 Plots wear volume calibration curve against time for steel spherical pin sliding against the sandstone under water lubrication, to mimic the drill string found in deep downhole, under the conditions of T= 25 C and P= 1 atm . This is performed at speed of 30 RPM and Load of 15 N.

3.2 Direct test methodology

The steel used is the typical drill steel or equivalent with typical roughness and makes contact with a rock sample to allow true tribo-contact simulation. Thus the rig makes a point or area contact mimicking string/Rock contact whilst open drilling into rock. The lubricant will be aqueous drilling fluid and the Rock is porous and this limits lubrication by hydrodynamic fluid film separation under some conditions. Friction measurements as a function of load, speed and drilling fluid cake thickness, porosity and contact pressure. The mechanisms of contact are investigated post-test. The method to be presented will be performed for both Steel/Rock sample (sand stone) contact. Sensors are mounted on the rig to digitally collect the data for friction and wear as a function of time for the varied parameters. The focus will be on running-in in particular as follows:

Stage 1: Load variation test

- The test will first be conducted at different loads on a pin at constant sliding velocity and temperature, with and without bentonite mud run on the steel disc. The area of contact will be kept constant.
- Pin will slide on the face of a disc rotating in a horizontal plane, with provision for controlling load, and speed.
- The applied load is directly varied by scaling of the weight placed on the weight holder; the exact procedure is as described below:
- Set up rig, digital functions, and samples.
- Clean the sample holder to ensure no existence of substance that might impact on equal sit of the sample placed.
- Turn on system plug switch mounted on the wall and the motor on/off switch on the machine, making sure the emergency stop button is not depressed.
- Place the rubber seal and sample rock (on top) on sample holder
- Slowly clamp the placed sample to ensure it's tightened on its position, Caution not to break the rock.
- Adjust the mounted pin holder as according to designed track length.
- Before making contact of rig with rock sample, first pour lubricants to a certain constant volume to be marked on rig- ensure that this is above the rock sample.
- Then as to adjusted position allow contact between the rig and rock sample.
- Place the selected load on top of load holder, ensure that this is gently done and sensor is well connected

- Once completed the above procedure, start the entire system using digital control switch.
- Extract recorded data after every 10 minutes.
- Repeat the above procedure, changing load by stepwise increase.
- Collect the lubricant from the surface to sealable container after every run.

Stage 2: Sliding velocity test

- Sliding distance is kept contact but the rock sample is changed. For the very same procedure as that of load variation, keeping the load constant now vary the speed.
- Sliding speed (in similar manner/range to that of existing drill strings) will also be varied while keeping the load constant.
- Different lubricants will then be tested at elevated temperatures when both load and speed are varied in a separate manner. The lubricant volume introduced to surface will be kept constant and the collection of lubricant after a period of running-in will be conducted. This will compare lubricant loss, friction reduction and wear on the surface as the temperature varies. This should be carefully conducted to avoid any spill over or side loss of lubricants.

Stage 3: Contact Pressure test

- In this case the contact area will be varied, repeating some procedure in the first two stages. This will be performed at constant load and speed. This is performed by adjusting position of the pin holder to new position

Stage 4: Mud Thickness

- Mud thickness will be varied while in similar fashion keeping the other parameters constant. This procedure is also performed simultaneously with variation of each parameters as per above procedure. This demands change of rock sample.
- First water test will be performed and all other parameters varied as according to above explanations.
- Then bentonite mud will be used in a similar manner. Care must be taken that the rock sample must be changed.

Chapter 4: Steel To Steel contact

4.0 Introduction

The results and analysis of steel to steel contact simulation representing drill-string to casing contact are presented in this chapter. The running in was performed between the ASI 4340 steel pin and ASI 4340 steel disc using pin on disc with a mounted LVDT sensors. The sliding was performed at speed range of 30 to 190 rpm and different contact pressures of 32N and 44N. The lubricants used are bentonite mud (non-Newtonian fluid) and pure distilled water (aqueous). This chapter is aimed at understanding the friction response, from using modern equipment with robust data collection system, with variation of load, and speed under aqueous and non-Newtonian lubricants. The discussion will incorporate mechanisms involved during steel to steel contact and make performance comparisons of the two distinct lubricants.

4.1 Steel/ Steel contact under aqueous (water) lubricant

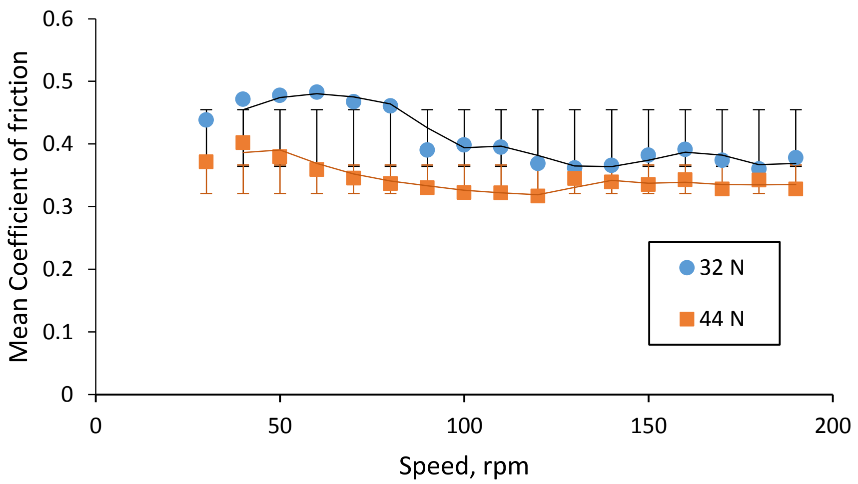


Figure 4. 1 Mean coefficient of friction for steel to steel contact under water lubrication

The results were captured using Labview software. Fig. 4.1 above plots the data collected for water run. Data was best fitted using the polynomial of second degree and depicts an overall decreasing trend of mean friction coefficient as the speed is increased. The fitting polynomial was used to fundamentally understand the coefficient of friction behaviour when the speed was increased. These findings are in agreement to the study of effect of load and sliding speed for aluminum done by *Chowdhury et al. (2011),* and deductions of *Fridman and Levesque (1959).* In general, this is in contrast to the adopted third law of friction which state that friction is independent of sliding speed. This trend proves that friction coefficient has a negative relationship to the speed. This is because when the speed increases, the contact area between the two surfaces decreases following the increase in momentum with speed *(Chowdhury et al., 2011)*. Thus as the area of contact decreases, the coefficient of friction decreases. Additionally, the decrease in friction coefficient of steel may be due to changes in shear rate which results into lower contact area and hence lower coefficient of friction. The latter concept was also observed by *Chowdhury et al. (2011)*. Furthermore the effect of change in contact pressure under water lubrication significantly lowers the mean coefficient of frictions. Thus for increased load from 32 N to 44 N, i.e. increase in contact pressure as load increase (44N> 32N), the average friction coefficient decreases as depicted in the plots on figure 4.1. This trend is similar to that found by Taghipour et al. (2015) and Chowdhury et al. (2011). The effect of abrasive material is readily observable by looking at the fluctuation in the trend. As the speed increases at fixed contact pressure the abrasive appears to add more contribution in raising the coefficients of friction. This is so because at high speed, a slight elevation of surface asperities can quickly deviate or off set the pin from the wear track/sliding distance whereas the behavior under low speed is similar to grinding of the asperities. However at low speeds the area of contact is greater causing more oscillations in the friction as the two material contact almost every asperity present in their respective surfaces *(Kakaš et al., 2009)*.

In addition, under low speed the removed asperities (wear debris) can be carried by the pin until they either can be further re-grinded or carried away with fluid. Thus in simple terms more deviation is expected in the drill string at high speed than at low speed. The increments in the load further plays a very crucial role as the speed seems to induce less influence on the coefficient of frictions and thus it can be concluded that abrasive particles are responsible for deviation in the case, but their effect too is quite less as each removed asperity can also have the opportunity to be re-grinded to smaller elements since the contact force is large enough to do so even at very high speed. It was observed, in particular for water lubrication, that centrifugal forces played a very big part in reducing the lubricant film thickness between the steel disc and the pin in particular when the speed was increased under 32 N as the lubricant was quickly drawn from the surface center to the walls of the disk holder. Fluid gets bent into circular shape and pushed away from the center where tribosystem was simulated to the side walls of the disc holder rendering the thickness of tribofilm on the sliding position reduced. This further separate particles in the drilling fluid depending on their density and speed of rotation. At high speed centrifugation is very prevalent. The film thickness was also observed to be bigger for 44N than for 32 N under water lubrication. Perhaps this can be attributed to the fact that for 44N the disc penetration rate or indenting of surface by pin will be higher allowing for large wear track depth which consequently allows fluid to sit well and assume a larger space and further reduce the effect of centrifugation. However for 32N the penetration force is lower and much energy is spent in cracking the asperities than inducing surface cutting in particular at higher speeds. This further explain the contradictory link between the effect of centrifugation resulting into reduced film thickness and the observed reduction in friction as the speed increases since therefore the low reduction in penetration rate means less new asperities are contacted or created hence low friction coefficient value. Furthermore this was expected for aqueous lubricants as they have very low viscosity. It was observed that as you increase the speed of rotation, more fluid moves from the center to the walls by centrifugation reducing the fluid lubricant film thickness between the steel disc and pin.

Thus the trend in the graph is similar to that of dry run since the film gets significantly reduced. This further support the occurrence of more contact between per asperities and steel pin as film reduces and explains the bumps in trends as observed in fig. 4.1 above. In addition, for 32 N loads, the indentation mark left depicted some slight off track from grooved area on the worn surface. Whereas for 44 N the indentation mark was restricted to the worn surface.

4.2 Steel to steel contact under Non- Newtonian (bentonite mud) lubricant

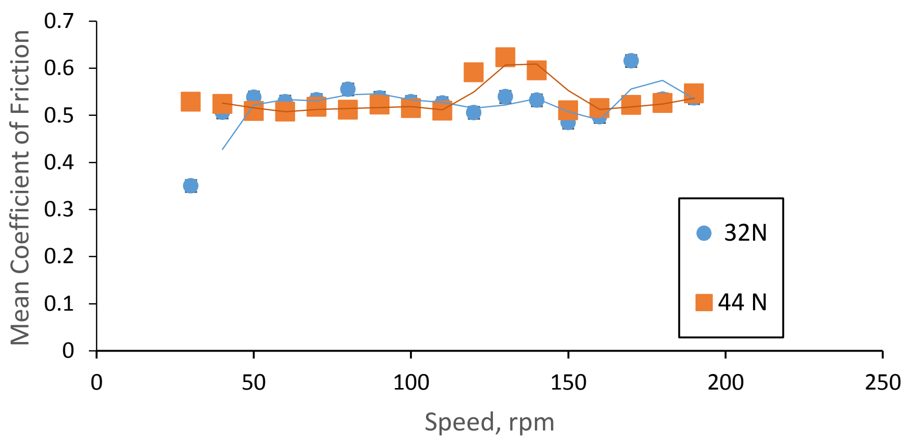


Figure 4. 2 Plots the average coefficients of friction for steel pin and steel disc contact under Bentonite lubrication.

Bentonite mud was input on the surface of the steel disc till the disc was fully lubricated with drilling mud at constant pump rate similar to the water testing above. The results were processed to give a plot in fig. 4.2 above. The second order polynomial was again fitted in the curve and proved to be best fit. When bentonite mud was used as a lubricant a trend opposite to figure 4.1 was observed as shown in figure 4.2. The effect of speed on friction coefficient was observed to be insignificant as the coefficient of friction increases with time. The curve could be very well fitted with the linear graph. None the less a significant increase in the coefficient of friction is a crucial factor calling for scrupulous analysis. The mean coefficients are in a range of 0.4 to 0.6, and higher than when system was lubricated with water in section 4.1. This is so since the particles further acts as asperities. Thus the shift to two-body abrasion occurred as a result of the entrainment of bentonite particles between the steel disc and pin contact area. This can be explained by the formation of interface between the steel pin and the steel disc. In addition the effect of centrifugation in removing the water from the surface of the disc to the periphery was seen to be negligible and thus the film thickness variation was not much different as the speed was increased. This is so due to the high viscosity of the bentonite mud compared to pure water lubrication. Bentonite particles act as viscosity enhancer. Furthermore the formation of the mud cake was observed and has added effect on increase in friction coefficient. The findings are in agreement with findings and deductions made by Ismail (2011). The mud cake formation is owed to filtering, as result of centrifugation, of fluid leaving the solid particle on the surface of the steel disc to agglomerate. The mud cake formation thickness increased with increase in rotation speed up to a point where the effect of particle density was overcome and the particles further went to the sides leaving very less viscous fluid on the surface. This coincided with increases of particle entrainment into the wear track. In addition the vibrations were also observed and could be used to further explain the high values of mean friction coefficient for 120 rpm, 130 rpm and 140 rpm when a load of 44 N was applied. The differences between runs under 32 N and 44 N were very small as seen from figure 4.2 but not so insignificant, as most values in particular at low speeds readily decreased when load was changed from 32 N to 44 N.

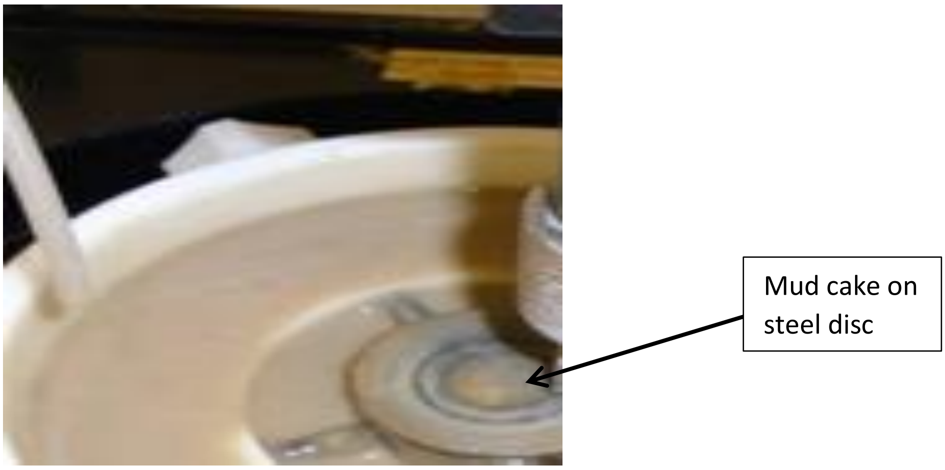


Figure 4. 3Mud cake formation on steel disc

In addition the error bars under bentonite lubrication were larger compared to water lubrication under steel to steel contact, which depicted less stability when bentonite particles were entrained. Upon touching and visual observation, the mud cake particle size reduced and became soft. This explains the concept of regrinding or multiple crushing per particle which has an effect of decreasing the rate of penetration or surface cuttings as mentioned above and this was further attested by the formation of depressed layer near the sliding distance or wear track depicting reduction in size for particles that got entrained. The indentation on wear track was also observed to be significantly lower compared to that under water lubrication i.e. the width and depth of the wear track were found to be smaller in comparison with those observed when water as lubricant was used. This can be further supported by the well-known fact that the bentonite particles were harder than the steel disc.

Chapter 5: Steel to Rock contact

4.0 Introduction

This chapter analyses the results obtained when the drill string to formation contact was simulated in the lab using the pin –on –disc tribometer. The rock used is Larsen B sandstone. The rock is readily rough and contains lot of silica clays. The data was further collected using LVDT's sensors mounted following the similar test methods. The water lubricants and bentonite mud lubricant performance was then compared. Sandstone is made up mostly of silica grains.

5.1 Steel pin/ Rock disc contact under aqueous lubricant

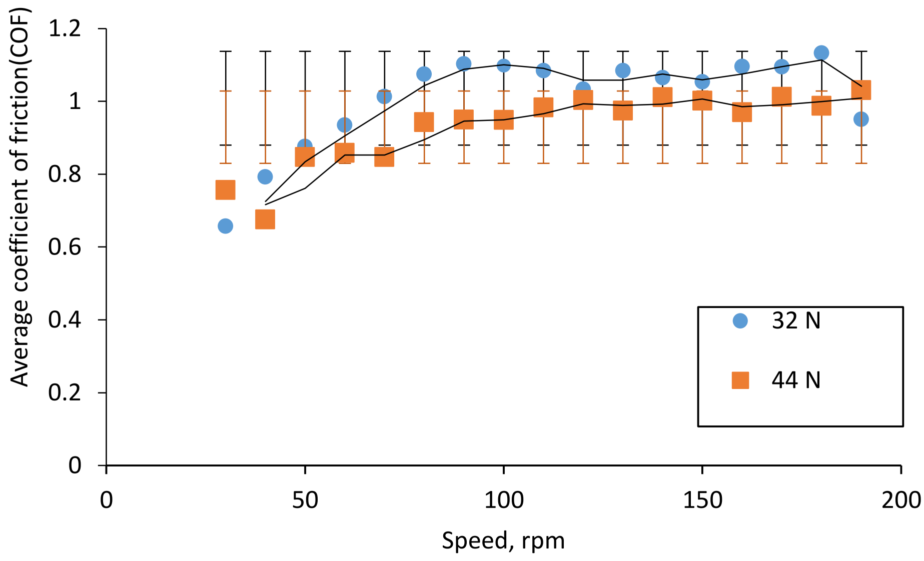
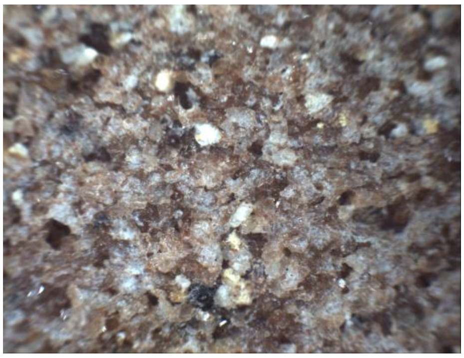
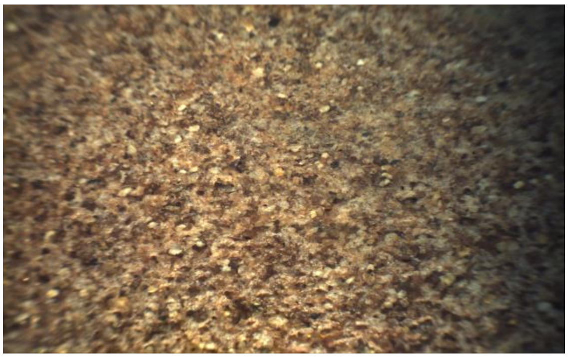


Figure 5. 1 Plots the mean coefficients of friction at various speeds when steel pin is in contact with sandstone rock. The sandstone was lubricated with water.

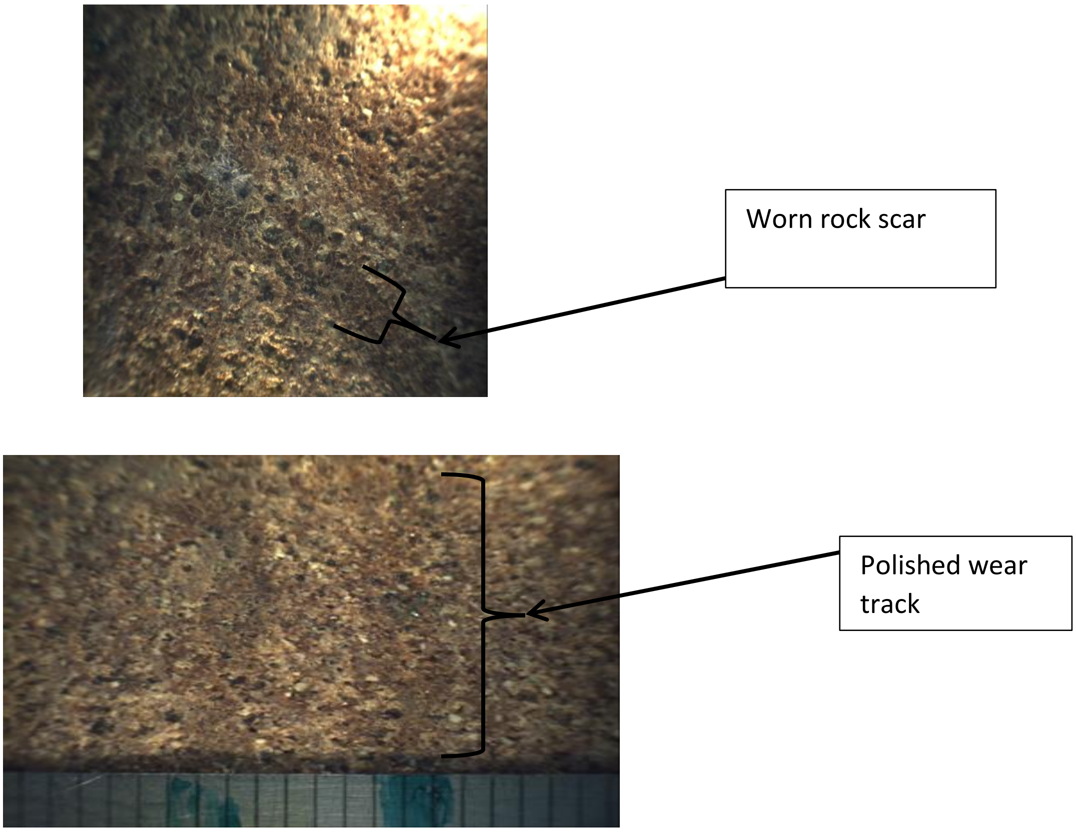
Following the same procedure as with steel/steel contact simulation, the results plotted in fig. 5.1 represent friction coefficient variations with speed under water lubrication for drill string/rock or formation contact simulation. Friction coefficient values ranges from 0.65 to 1.3. These values are extremely high compared to data obtained in Chapter 4. However the obtained high coefficient values were anticipated for steel/formation contact. In analyzing figure 5.1 it can be deduced that friction coefficients increased as the speed was increased for steel/ rock (sandstone contact). However, the coefficient of friction values seem to stabilize around 1.0. This is expected as the maximum coefficient of friction for steel is close to 1.0. A similar response to that obtained for steel/steel contact under water lubrication was also observed in this case when load was increased. For 44N load the friction values are way observably below those obtained when a load of 32 N was applied. To best explain the finding two important rock properties played a significant role in increasing the friction. That is the microstructure of the sandstone rock and its porosity. The effect of porosity will be further discussed in chapter 4. The microstructure of sandstone differs to a larger extent when compared to the steel in chapter 6. Due to the fact that sandstone is composed of very harder particles than the steel such as silica grains, hence the number of asperities in the surface is expected to be higher than the ones found in the steel sample; this can be also said for sandstone porosity and roughness.

Figure 5.2 below gives a rough overview of sandstone microstructure; images were taken on surface of sandstone disc and clearly show the different grain sizes (images not scaled). Thus the increase in friction was attributed to larger surface roughness and occurrences of numerous asperities. The contained a mixture of removed silica or sandstone materials, and the steel debris. In addition the vibrations were also higher for this test. Multiple contacts of steel per asperity are highly expected to have been another contributing factor to increase in the friction. Furthermore, upon visual analysis of the wear scar (refer to figure 5.2c) the material worn from the steel was seen to have been transferred into the wear scar or track on the rock, and with continued running in the surface appears to get polished contrary to the expected increase in cutting depth. This is due to resistance of the sandstone disc to shearing and wear. This simply explains the attempt of stabilization of the coefficient from about 90 rpm to 200 rpm. However the entrainment of the removed grain particles in the wear track continued to create two-body abrasion. The particle entrainment, since it may not be uniform, in nature best explains the fluctuation in the friction values to high values such as at 180 rpm.





a) **b)**



c)

Figure 5. 2 Surface images of the sandstone used in this experiment. a) Gives a closer view on the surface of rock and show the cementing of various clays, quartz and feldspars. b) General surface observation and composition forming the surface of the sandstone. c) Worn rock scar; position where pin was slide (the section marked with blue).

The effect of porosity was difficult to separate from the other properties, however was observed that upon pouring the same quantity of water on the surface of the sandstone rock, the level reduced compared to when steel is used. Thus this has implication that the surface tribofilm will definitely be less than that of steel/steel contact due to difference in porosity between the rock and steel disc, however the re-arrangement of removed grain cutting eventually was assumed to have closed the pores and this could not be further verified due to time constraint. It was assumed that with time the water will fill the gaseous occupied pores, and the effect of porosity on the tribofilm will become negligible once again.

5.2 Steel/ Rock contact under Non-Newtonian lubricant

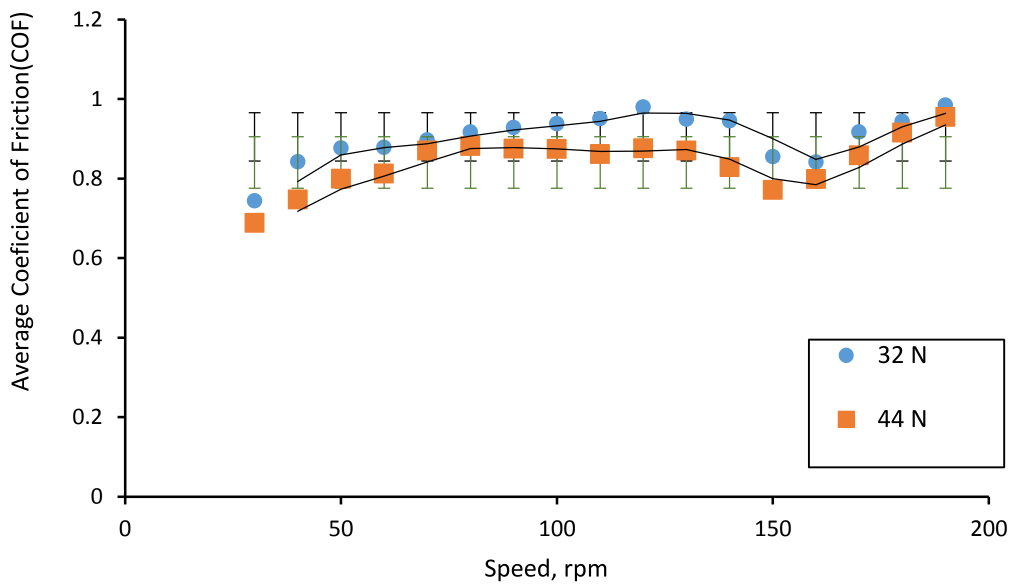


Figure 5. 3 Plots the data obtained when the steel/sandstone tribosystem was lubricated with bentonite mud.

Steel/ sandstone run under bentonite lubrication depicted interesting results. The friction coefficient when bentonite mud was used was found to be in a range of 0.65 to 0.96. This is lower than when water was used as the lubricant in section 5.1 above for the same system. However the trend remained similar to figure 5.1. Similarly to figure 4.2 the error bars are smaller in this case, indicating that perturbations were minimal. Increasing the load further reduced the friction but to a smaller extent and comparable to findings in figure 4.2. The decrease in friction range was attributed to the fact that bentonite particles are softer than the particles in the rock surface. When the entrainment of the soft (with high shear strength compared to sandstone rock) bentonite particles occur in between the steel and rock contact the friction becomes smaller than in the case of using water as the lubricant. The particles serve to protect the hard asperities from getting contact with the steel pin and instead the cutting occurs on the soft bentonite particles that assumes the surface of the rock. Furthermore the bentonite particles were also anticipated to have closed the pores of the sandstone rock resulting to a larger tribofilm. The tribofilm containing the bentonite particles then formed a separation layer; prohibiting the contact between steel pin and the rock. The effect of microstructure then comes into play again when comparing the steel/ steel contact results under bentonite lubrication and steel/rock contact when the bentonite was used. The high mean coefficients values for steel/rock contact than steel/steel contact was attributed to the potential occurrence of contact between the harder asperities forming the surface of the rock and the steel pin. However it can be said that this was not frequent and the tribofilm really did well to ensure this as seen when comparing with the values of mean coefficients under water lubrication. Thus the use of bentonite particle for drill string/ formation contact will be advantageous for deep hole drilling under normal condition since the particles are relatively soft and can deform plastically contrary to the formation or sandstone particles. Under conditions similar to the ones tested in this study, speed of 150 rpm for both 32N and 44 N applied can be used in drilling, since it represent the lowest friction.

This is clearly depicted in figure 5.4 below, which compares the coefficient of friction under bentonite and water lubrication environment.

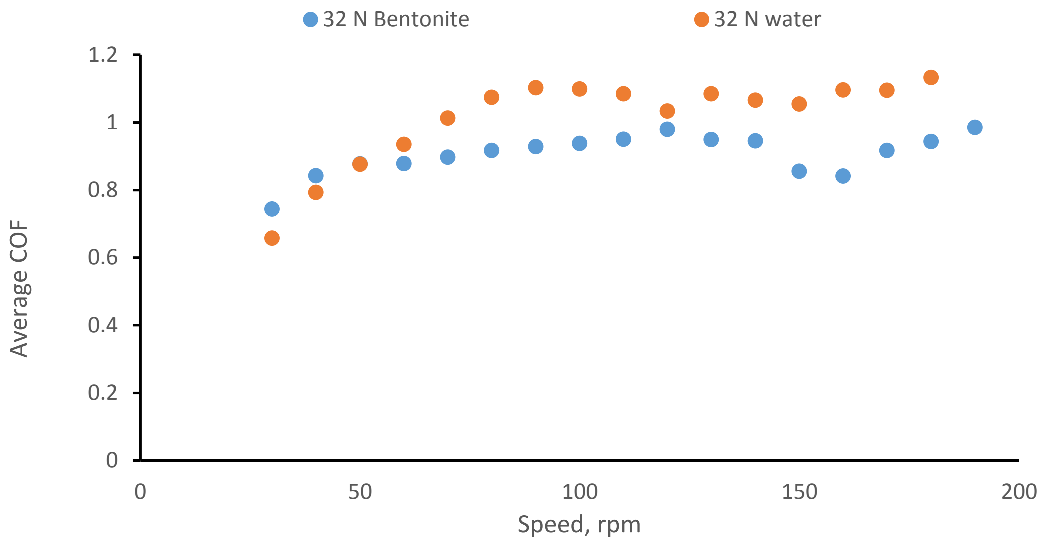


Figure 5. 4 Illustrate the coefficient of friction variation with speed under the water and bentonite lubrication environment

Future work should focus on simulation under elevated temperature as this could not be performed in this thesis due to time constraints and limitations of the equipment's. The testing of polymer lubricants and other additive under elevated temperatures and high speeds is limited in literature and demands focus as future drilling will be moving to ultra-deep drilling depths characterized by high temperatures and pressures and polymer drilling muds possess more potential.

Chapter 6: Effect of Mud Concentration and Rock Porosity on Friction Response

6.0 Introduction

This chapter focuses on mud design by looking at the variation of friction coefficient with concentration, and the effect of porosity on friction. Similar procedure used in the above tests was adopted in collecting the data discussed in this chapter. For porosity variation the microstructure of the two sandstones was assumed to be invariant, whereas only porosity different for the two rock. All pores were assumed to be filled rather with gas as the samples were kept in dry place after fabrication. This chapter is an attempt to support the findings in the latter chapters.

6.1 Analysis of friction vs Mud Concentration

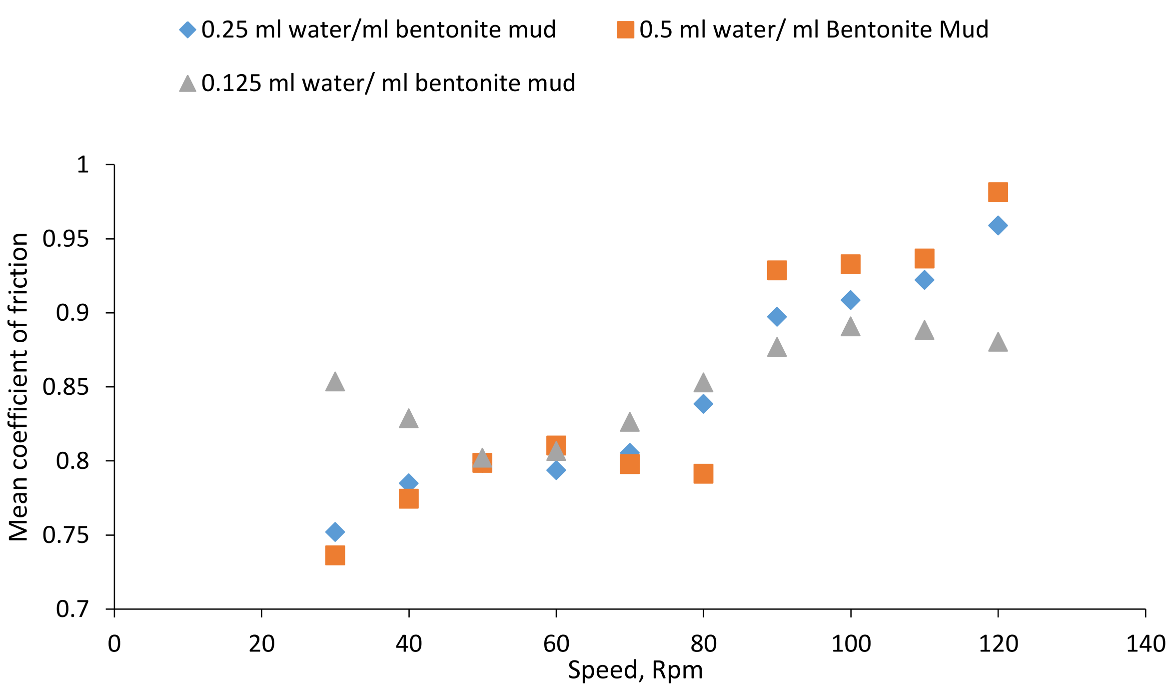


Figure 6. 1 Effects of varying water concentration in the bentonite mud at constant load.

Variation of the concentration was performed to select the best performing ratio of water to bentonite particle mix on friction coefficient. From figure 6.1, the coefficient of friction decreases as the water concentration increases at lower speeds. At higher speed, it is visible that the coefficient of friction increases as the concentration of water increases. However it can be observed from figure 6.1 that when water concentration in the mud was increased at higher speeds the friction becomes very high. Furthermore in observing the trend in the graphs plotted in figure 6.1 it can be deduced that the friction coefficient increases due to dispersion of the bentonite particles in the mud and reduction in the mud thickness; which implies that the surface of the mud can be easily sheared and/penetrated i.e. the tribofilm becomes less thick. Thus it can be recommended to use lower ratio of water to mud, but this should not be made very lower than 0.125ml as, in particular for deep downhole, this can quicken filter cake formation/mud drying due to water evaporation caused by the high temperatures in deep downhole. At 60 rpm, the coefficient of friction is minimum for 0.125 ml water/ml bentonite. This could be the point of operation of drill string since friction is low. Thus it can be said that a right mix should account for the two factors: allowance for water to evaporate and still leave mud wet enough, and prevention of excessive addition of water which can further increase the drilling friction. This is very important for mud formulation. Thus future work should also consider performing the study under elevated temperature and pressures. It is however expected that in ultra-deep hydrogen evolution may occur but this necessitate thorough investigation to confirm.

6.2 Analysis of friction response vs Rock porosity.

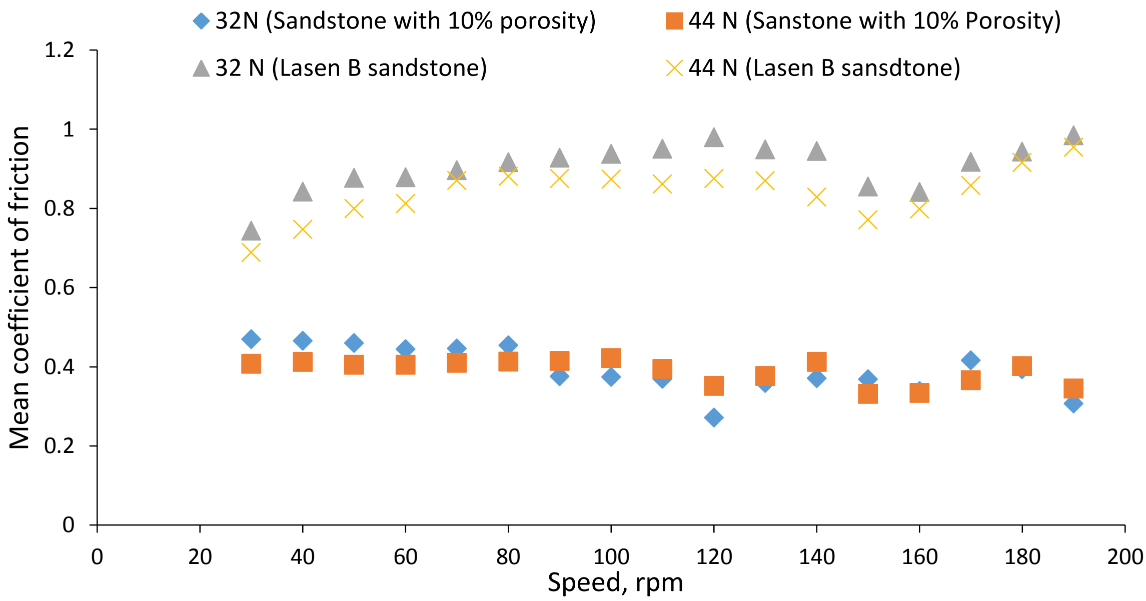
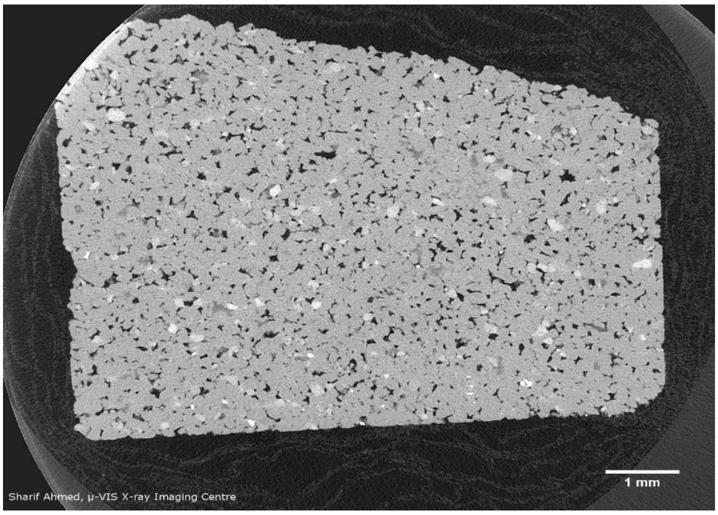
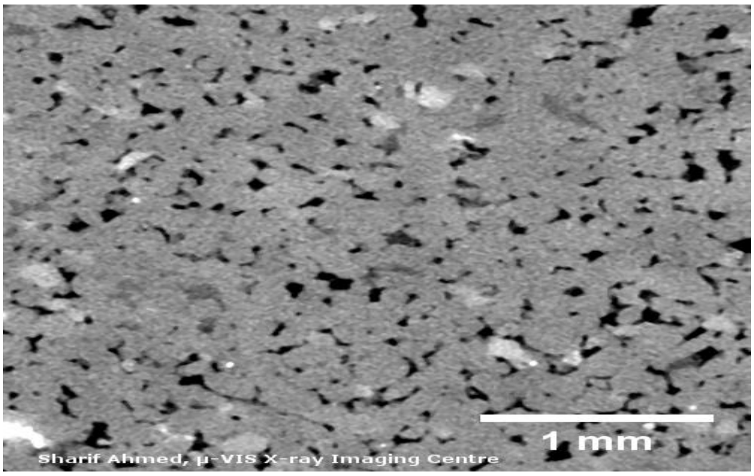


Figure 6. 2 Graphical comparison of friction coefficient for sandstone with different porosities. This was plotted to graphically analyze the effect of porosity on the friction coefficient. Larsen B sandstone has a porosity of about 12 %.

Two sandstone materials of different porosities (sandstone 1 has 10 % porosity and sandstone 2 i.e. Larsen B has a porosity of about 12 %) were tested and assumptions of negligible microstructural variation were made. From the graphical comparison above, the sandstone of lower porosity have lower mean coefficients of friction values under bentonite lubrication than Larsen B sandstone of larger porosity. This was anticipated since the porosity strongly influences the tribofilm thickness between the string and formation, which has necessitated the wells development techniques such as well-bore cementation. However the large differences are a clear demonstration that perhaps the microstructure rather than the porosity played a bigger role in inducing more friction. Thus it was deduced from visual observation of tribofilm which did not differed to a large extent between the two types of rocks that the effect of porosity in reducing the hydrodynamic operations potentials will decrease with time provided the micro arrangement of particles occurs and due to time constraints the porosity analysis on the rock structure could not be performed. Future research should focus on conducting porosity correlation to friction coefficients to better analyses the particle sizes that may need to be added into the lubricants to prevent drilling fluid losses and increased friction. Figure 6.3 below shows different rock porosities for the two sandstone.



a)



b)

Figure 6. 3 Showing different rock porosities. a) 10 % sandstone and b) 12 % Larsen B sandstone

Chapter 7: Conclusion and Recommendations

Knowledge of interplaying mechanisms is crucial to understand and best select potential measures to reduce friction, thus avoiding the use of trial and errors method to find robust solution which is time consuming and can be costly. In this study the performance of aqueous and non-Newtonian lubricants has been tested using a pin-on disc tribometer under variable speed and different contact pressures. From the results it can be concluded that the friction decrease with increase in contact pressure, however the weight on bit should be well calculated to avoid buckling effect. In addition, increasing the load also decrease the vibrations that can off-set the drill string from selected drilling direction. When water was used as a lubricant the friction coefficient was found to be higher than when bentonite mud was used lubrication. Frequent vibration occurred for steel/steel contact (simulating the drill string/ casing contact) when bentonite mud was used and this was attributed to occurrence of two body abrasion as a result of entrained bentonite particles which were harder than the steel materials. The indentation on the wear scar for steel/steel contact under water lubrication was clearly visible upon visual observation and showed a bigger width, but had less deep depth. This was attributed to the fact that the tip of the pin got worn faster under water lubrication forming a flat scar that could not cut deeper to the steel disc with time progression. On the other hand the indentation on the wear scar for bentonite mud appeared to be deeper and less wide. This was attributed to presence of bentonite mud providing a protective tribofilm between the steel pin and the steel disc, yielding the pin tip less worn and able penetrate deeper to the steel disc. Thus though the friction rate increases when bentonite mud is used for casing simulation, deeper cutting can be achieved. However incrementing the contact pressure proved to be very robust. In designing the drilling mud the condition of use must be clearly articulated as the mud can potentially increase the friction such as in the case of using bentonite under drill string/ casing contact.

The results for steel/rock simulation showed that the effect of microstructure largely affect the friction. Coefficient of friction for steel to sandstone contacts were higher under water lubrication than when bentonite mud was used as a lubricant. This behaviour, contrary to steel/steel contact, was attributed to be as a result of influence of hard particles or asperities constituents in the rock structure which cause an increase the friction. This was furthermore supported by the fact that the bentonite particle used are much softer than the particles in the rock structure and hence reduced the friction for steel/sandstone contact as a result. Similarly to steel/steel contact findings, increasing load decreased the friction coefficient. Whereas the increasing speed in this case did not have much effect at low speed ranges up 100 rpm for load of 32 N, other than to increase vibrations and off-sets of the pin from its sliding distance thereby rendering the friction coefficient increasing. This explained the fluctuation in the coefficient of friction values as the speed was increased, since during offset a new harder or softer asperity is contacted that can either increase the friction or decrease it, causing fluctuation to the friction coefficients instead of attaining its stability. Nonetheless, at very high speed the coefficient of friction decreased. This renders the third law of friction, which state that friction is independent of sliding speed invalid. It was concluded that abrasive wear mechanism was the dominant mechanism upon observing the pin at the start of running in for steel/steel contact under bentonite lubrication and for steel/sandstone contact under water lubrication in particular. The steel pin deformed plastically for the latter systems.

Furthermore the porosity of the sandstone rock, upon visual observation did reduce the tribo-film thickness which resulted to higher friction under water lubrication than under bentonite lubrication. In addition, the running in was performed in two rocks of different porosities. The findings support the above, the bigger the porosity the less the tribo-film thickness and hence the higher the friction due to frequent occurrence of contacts between the surface asperities and the pin. To assess concentration ratio, that represented best performing mud, between water and the bentonite, the concentration of water was varied in the mud. The results depicted that increasing the water concentration in the bentonite mud increases the friction at higher speeds due to reduced mud thickness that allows bentonite particle to easily disperse. The findings provide significant conclusion and could very well assist in mud design and selection of the best performing mud to be used in each contact so as to achieve friction reduction. The results presented in this report can help in detecting the possible friction range in deep drilling process. However, it is recommended that the following be performed in addition to improve the findings from this research and broaden the understanding of tribology in deep drilling processes:

- Perform study at elevated temperatures: The simulation of both scenarios be performed under elevated temperatures to best simulate the high temperature condition found in particular under ultra-deep downhole since this could not be performed in this study due to time constraints and complexity in incorporating heating system in the pin-on-disc used. The allowable concentration of water in the bentonite mud preparation must be tested under elevated temperature since the rate of evaporation of water in the mud is strongly influenced by downhole thermal condition. The porosity and microstructural changes under elevated temperature during drilling must be simulated. Furthermore, the drilling mud additives and other viscosity enhancers are ought to be tested at elevated temperatures following the running in procedure utilised in the study.
- The present wear mechanisms for the above scenarios must be elucidated.
- Surface analysis: Furthermore the analysis of the wear mechanisms using microscopic analysis such as SEM. This requires improving the compatibility of tools such as SEM to accommodate the sandstone disc materials for analysis.

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