BIT WEAR ANALYSIS AND OPTIMIZATION FOR VIBRATION ASSISTED ROTARY DRILLING (VARD) USING IMPREGNATED DIAMOND BITS

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Bit Wear Analysis and Optimization for Vibration Assisted Rotary Drilling (VARD) using Impregnated Diamond Bits

By

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Abstract

The effect of vibrations on bit wear and the rate of penetration in rotary drilling was investigated. A laboratory scale drilling rig was used for experiments with capability of controlling important drilling factors such as WOB (Weight On Bit), flow rate, RPM, and vibration. Vibration under different amplitudes was studied using impregnated diamond coring bits. The main goal of this study is to find the optimum drilling conditions considering both ROP (Rate Of Penetration) and wear including the effect of vibration.

Bit profile shape was found to be another important factor affecting ROP and bit wear. In all experiments, three main profile shapes appeared after some drilling in the sequence of: V-grooved, flat end, and rounded edge. The highest ROP results were obtained with V-grooved, decreasing in the order: unused, flat end, and rounded edge. Vibration had more effect on bit wear than profile shape. Profile shapes with sharper edges wore away rapidly.

Wear and bit profile changes should be taken into account in a study to relate ROP to WOB. Otherwise, the relationship observed between these variables may not be correct.

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Table of Contents

List of Figures

List of Tables

List of Symbols

Symbol	Description
ADG	Advance Drilling Group
Agg	Aggregate
ASTM	American Society for Testing and Materials
C	Cement
D	Drill bit diameter
ROP	Rate of penetration
RPM	Revolutions per Minute
UCS	Unconfined compressive strength
VARD	Vibration assisted rotary drilling
W	Water
WC/Co	Tungsten carbide/Cobalt
WOB	Weight on bit

Chapter 1

Introduction

1.1. Background

Drilling productivity, efficiency, and cost effectiveness are important words nowadays for every oil and gas company. Different factors affect drilling time and cost; it is critical to improve the drilling conditions to have lowest elapsed time with less drilling cost. The current research by the advanced drilling group (ADG) at Memorial University of Newfoundland aims to optimize drilling conditions using vibration assisted rotary drilling (VARD). In addition, the main focus of this research was on bit wear, which significantly affects drilling optimization. Experimental investigation was done to find the effect of drilling parameters such as weight on bit, vibration, and RPM on both rate of penetration and bit wear. The analyzed data from experiments will show possible ways to optimize drilling conditions.

1.2. Objectives

- Comprehensive study of bit wear and rate of penetration on impregnated diamond bits
- Analyzing the effect of vibration, specially on wear
- Study of the effect of flow, pressure, and RPM on both ROP and bit wear
- Study of the effect of different matrix profile shapes

1.3. Thesis organization

Chapter 2 is a review of literature of work on conventional rotary drilling systems and vibration drilling systems. The main purpose of using vibration drilling systems is to increase the drilling speed; however, this could affect bit wear. A full review of literature on impregnated diamond coring bits and some analysis on tribological aspect of bit wear was done. The science of surfaces in contact (tribology) could help to better analyze the real bit contact conditions. A study on impregnated diamond bits tribological behavior was done and is presented in this chapter. Diamond impregnated bits were used for all of the experiments.

Chapter 3 is an explanation of the ADG investigation and study on wear measurement techniques and methods. New techniques such as replication and indentation were investigated and improved. Different measurement methods such as weight and length measurements are explained and specifically introduced for each type of bit.

In Chapter 4, experiment runs and tests are explained and discussed. Tables, figures, and plots are used to show completely all of drilling conditions and results for both ROP and wear rate. Comparisons are done to show the effect of vibration drilling on ROP and bit wear. This chapter consists of two main sections on full face impregnated diamond bits and impregnated diamond coring bits. The main focus of experiments is on the impregnated diamond coring bits. Three major groups of experiments were done on coring bits: vibration and non-vibration experiments, experiments on the role of RPM, and pressure and flow experiments. Each one individually focused on rate of penetration and bit wear. Bit wear study can be both qualitative and quantitative. Pictures from real bit teeth and bit weight measurements were used to achieve the best results.

The final chapter, Chapter 5, contains conclusions and recommendations for future work. Optimization of drilling productivity is one the main subjects to be discussed in this chapter. This optimization method uses both ROP and bit wear plots to conclude the best possible drilling conditions for vibration drilling. Not only the drilling conditions, but also some physical features of impregnated drill bits like matrix abrasiveness or matrix profile shape, for better efficiency are discussed. During the experiments some new factors showed an important effect on the results like bit profile shape. In this chapter, conclusions are drawn on the best drilling conditions and bit profile shape.

Chapter 2

Literature Review

2.1. Drilling systems

Drilling systems or drilling rigs are used in different applications such as mining, oil and gas and geosciences research. Different mechanisms are used in different types of drilling systems from a large drill rig to a portable one on the back of a truck. A drill rig is designed to drill bore holes or wells in the Earth's crust. Drill rigs are categorized in different ways: by platform type, by power used, by pipe used, and penetration mechanisms they have. Two main types drill rigs are rotary and rotary percussive. Rotary drill rigs are used predominantly for oil and gas drilling. However, rotary percussive drill rigs have mostly been used in the mining industry. New drilling mechanisms are under development to improve ROP like vibration assisted rotary drilling (VARD).

2.1.1. Rotary drilling systems

A rotary drilling system consists of different subsystems including a rotary system, hoisting system, drill string, bottom hole assembly, power system, circulation and well control system. Figure 1 shows a schematic picture of a rotary drill rig and its standard components.

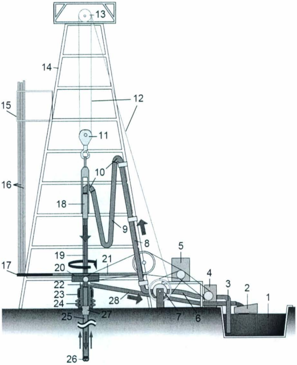

Figure 1. Rotary drill rig (from www.wikipedia.org, 2011)

1. Mud tank
2. Shale shakers
3. Suction line (mud pump) head 4. Mud pump
5. Motor or power source
6. Vibrating hose
7. Draw-works (winch)
8. Standpipe
9. Kelly hose
10. Goose-neck
11. Traveling block
12. Drill line
13. Crown block
14. Derrick
15. Monkey board
16. Stand (of drill pipe)
17. Pipe rack (floor)
18. Swivel
19. Kelly drive
20. Rotary table
21. Drill floor (2011)
22. Bell nipple
23. Blowout preventer- Annular
24. Blowout preventers-rams
25. Drill string
26. Drill bit
27.Casing
28. Flow line

Figure 2 shows a schematic drawing of a rotary drilling system in which torque from the rotary system at the top of the well is transmitted through the drill string to the bit. The drill bit is pushed on the rock contact surface by a force called the weight on bit (WOB). WOB is a balance of different forces on the bit such as the weight of drill string, the buoyancy force generated from drilling fluid in the annulus, the drilling fluid pump off pressure, and the hook load from the hoisting system. The WOB can be easily controlled by varying the hook load.

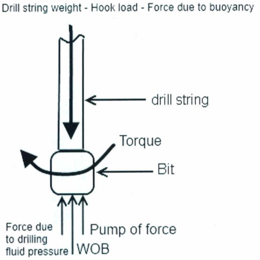

Figure 2. Schematic drawing of rotary drilling system Forces

2.1.2 Vibration assisted rotary drilling (VARD)

It is well known that vibration, as in percussive drilling, increases ROP. The aim in the ADG is to find conditions in which VARD increases ROP without so much increased wear of bits; significant increase of bit wear could make VARD uneconomic due to cost of bit replacement. An investigation has been done in Memorial University to prove the efficiency of that. Li Heng et al. (2010) showed the improvement of using vibration on rotary drilling. Figure 3 from his experimental work shows the higher ROP with vibration drilling.

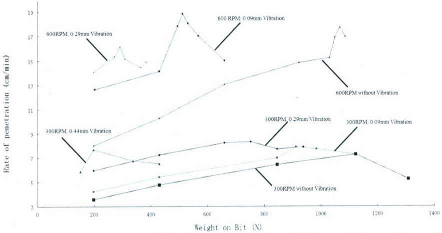

Figure 3. Experimental results of vibration rotary drilling at 300 and 600 RPM, 2-3 levels of amplitude (Heng, et al. 2010)

These experiments were done at 60 Hz vibration but with different vibration amplitudes. The result shows: "a significant increase in ROP at low levels of WOB and also increase of ROP in relation to increase of vibration amplitude" (Heng et al. 2010). He recommended further experiments to investigate to show the efficiency of higher ROP considering bit wear rate.

2.1.3. Rotary, Percussive Rotary, and Vibration Rotary forces

Static WOB is used for Rotary drilling, but dynamic WOB is used for both percussion and vibration rotary drilling. In percussive rotary drilling, high velocity force applies to the bit, causing elastic waves to be generated. This high velocity force usually results from dynamic impact or hammering which is normally produced by pneumatic or hydraulic mechanisms.

2.2. Tribology and Wear

Tribology is the branch of science and technology that concerns about surfaces in relative motion, as in bearings. For this, tribologists suggest the tribosystem for considering the volume including two bodies and the environment around the two bodies with their interaction. Tribology can help to understand and analyze better the parameters affecting wear rate.

In order to develop a convenient framework for the description of systems, it needs some simplification; it could be applying the methods of "black-box cutting" or "systems tearing". In black-box cutting a model is cut down to smaller boxes until first principles can be applied. Systems tearing can be achieved by locating the hypothetical systems envelope in a convenient way. Next, the envelope should be as narrow as possible to be around the central parts of the mechanical system as "interacting surfaces in relative motion". With this information in mind, a detailed system description should involve the following steps: (Czichos, 1978).

"A detailed system description must involve the following steps:

1- System's function

1-1- Separate the system from its environment,

1-2- Compile all inputs and outputs,

1-3- Describe the functional input-output relations,

2- System's structure

2-1- Identify the elements of the system,

2-2- Characterize the interrelations and interactions between the elements,

2-3- Specify the relevant properties of the elements" (Czichos, 1978).

Based on this system (Czichos's framework) analytical procedure, it is necessary to consider the influencing factors and mechanisms relevant to the function and structure of mechanical systems in which friction and wear processes occur.

2.2.1. Tribo-system

For describing tribological processes we need to define tribo-system. The purpose or function of technological systems is the transformation and/or transmission of "inputs" into "outputs" which are used technologically. Figure 4 shows a functional description of tribological systems in general:

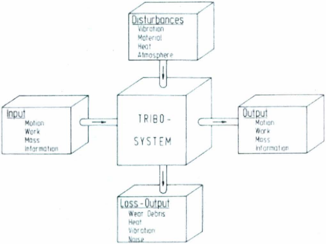

Figure 4. Tribo-system (Zum Gahr, 1987)

The relationship between a useful input and a useful output may be considered as the technical function of a tribo-system. Friction and wear results in undesirable outputs such as wear debris, heat, vibration and noise. Useful inputs and outputs may be classified in motion, work, materials or mass, and information. In general, we have four categories, 2 inputs and 2 outputs as we can see from Figure 4. The first major input is the motion, mass, and work which are the consumption of energy for doing some work. The other major section of system is output as work, mass, or motion which is the desirable results of our first input energy; while on the other hand, we have two other parts which are related to these sections as some disturbances as vibration, material, heat, etc. that cause some loss during the work of system as wear debris, heat, vibration and/or noise (Zum Gahr, 1987).

The Structure of the system is determined by the elements, their properties and the interactions between them. Figure 5 shows a basic tribo-system:

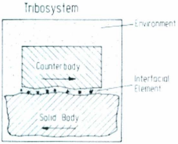

Figure 5. Typical tribo-system environment (Zum Gahr, 1987)

Usually the system consists of four elements:

1- Solid body

2- Counter body

3- Interfacial element

4- Environment

The tribo-mechanical systems are usually considered under two major categories as functional and structural.

2.2.1.1. Function of Tribo-mechanical systems

The tribo-mechanical system is defined as an entity whose functional behavior is connected with interacting surfaces in relative motion. The functional cause-and-effect relations between inputs and outputs are accompanied by loss-outputs of mechanical energy and of materials, denoted summarily by the terms friction and wear losses. In relating a system to its function, we are concerned with operational variables which can be controlled by a designer or an operator (Czichos, 1978).

2.2.1.2. Structure of Tribo-Mechanical systems

The structure of a system is characterized by the elements or components of the system, their relevant properties and their interrelations. For a simple case we can consider the motion of two solids, for example elements in a machine in contact with each other. In this case we have 3 elements as (Czichos, 1978):

Element 1: first machine element

Element 2: second machine element

Element 3: the interfacial volume

Figure 6 shows the tribo-process diagram. In general, in any tribo-system we can analyze the system in different ways, as on different planes, in which each one considers a different aspect of system such as work plane, thermal plane, material, and functional plane. These planes will be discussed more in the following chapter for a drilling kind of tribo-system.

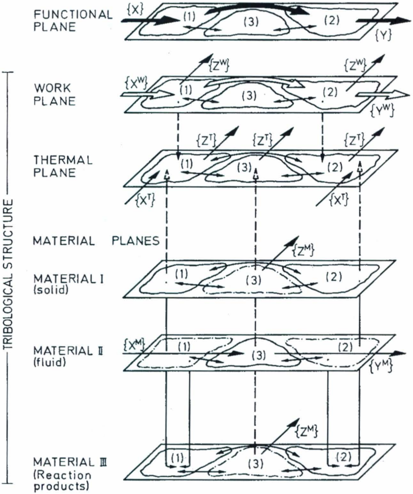

Figure 6. Tribo process diagram (Czichos, 1978)

In this diagram, {X} and {Y} are the inputs and outputs and {Z} is output loss.

2.2.2. Classification of wear

There are some different ways for classification of wear; the first one is classification of wear processes by wear modes as below:

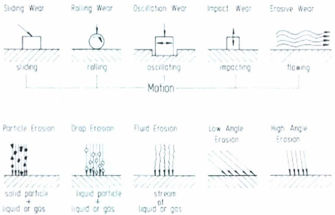

Figure 7. Classification of wear processes by wear modes (Zum Gahr, 1987)

Wear processes here are classified as different type of motion and physical state of counter body or second element of tribo-system. Related to the interfacial element, wear processes are called dry or lubricated, for example lubricated rolling wear, or 2-body and 3-body wear as we can see below:

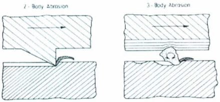

Figure 8. 2-body and 3-body wear (Zum Gahr, 1987)

There are different ways of classification by different institutes and people, the list below shows some of the important ones (Zum Gahr, 1987):

Burwell and Strang (1952): abrasive wear, adhesive wear, corrosive wear, surface fatigue wear, fretting, erosion and cavitation.

Jahanmir (1980): adhesion, delamination, fretting, abrasion, erosion, impact wear, surface fatigue, corrosive wear, diffusive wear and electrical contact wear.

Godfrey (1980): mild adhesive, severe adhesive, fretting, abrasion, erosion, fatigue, delamination, corrosive, electro-corrosive, fretting corrosion, cavitation damage, electrical discharge and polishing.

Rice (1978): adhesion, abrasion, fatigue, corrosion or oxidation, and electrical.

DIN 50320 (1979): adhesion, abrasion, surface fatigue, and tribo-chemical reaction.

The DIN classification is the most widely used classification system and it has been used by other researchers. The schematic description of the four main wear mechanisms is shown in Figure 9.

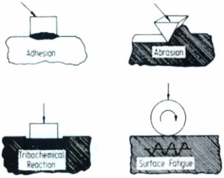

Figure 9. Four main wear mechanisms (Zum Gahr, 1987)

DIN 50320 used the four basic wear mechanisms were defined by ZumGahr (1987):

Adhesion: formation and breaking of interfacial adhesive bonds
Abrasion: removal of material due to scratching
Surface fatigue: fatigue and formation of cracks in surface regions due to tribological stress cycles that result in the separation of material
Tribo-chemical reaction: formation of chemical reaction products as a result of chemical interactions between the elements of a tribo-system initiated by tribological action.

2.2.3. Tribo-System analysis

A tribo-system defines the portion of the equipment and work in which we want to check the surface interactions and the results of that as wear. A systems analysis starts with the construction of a model of the system which is essentially a check list of all significant components or elements, their significant properties, relationships and interactions with each other. The various forms and tools for systems analysis provide a structure for studying processes occurring within equipment, which may be mechanical, thermal, electrical, and chemical, or focused on the generation, storage, and transmission of "information", or any combination of these.

In systems analysis a methodical and open-minded construction of the model of the technical equipment of interest, the components and processes within it, and between it and what is outside the system, helps to ensure that we consider all that may be relevant to our purpose. We are likely to embark on a systems analysis because we are interested in the function of the system, its inputs and outputs, how they relate to each other, and how the system may change during its operation.

2.2.3.1. The drilling system, Differences between bearing and cutting tools as systems

Most tribo-systems, e.g. bearings, are auxiliary to the main function of the equipment of which they are a part, and wear is an undesirable but often inevitable phenomenon in them.

So unlike a bearing, where as little as possible wear is desirable, and the function of the bearing is to transmit torque and/or work, while the function of a drill bit, however, is to produce wear, of the material being drilled, i.e. to one or more materials in the system. The same is, of course, also true of any cutting tool. It is only the wear of the tool, also constituting one or more materials in the system that is undesirable.

In coring drill bits, which often consist of two components, the cutting elements, such as diamonds embedded in a matrix, the wear of the diamonds is undesirable, but inevitable. The wear of the matrix surrounding the diamonds is to some extent desirable. It is desirable that the wear of the matrix should proceed at a rate that ensures a continuing optimum function of the diamonds, as the latter wear down and eventually each diamond is destroyed or removed. When diamonds are removed the wear of the matrix allows diamonds previously covered by the matrix to emerge and take over the cutting process. (In the forgoing "cutting" is assumed to be the process by which the rock or other material being drilling is removed. Cutting is not necessarily the only process by which the drill functions, e.g. fracture may be also be important.)

In describing the tribo-system, consisting of a drill string and rock (or other material being drilled) we can, notwithstanding the differences outlined above between bearings and a cutting tool, examine the system and the processes in it in much the same way as for bearings.

2.2.3.2. The elements of the drilling tool system

A drilling tool system can be defined in various ways, depending on our purpose. The whole drill rig from the drill frame, motor drive, gearing, drilling fluid pump, drill string, down to the drill bit can be considered a system, of course. Indeed what happens at the drill bit depends on all the other components of this system, as well as on the rock being drilled.

We can also consider the portion of the total drill rig system that consists of the drill bit, the portion of the rock that is being drilled, along with the fluid and rock (and drill bit) debris in the interfaces between the rock and drill bit, as a system. So for the purpose of this wear study we can select a system which is a small portion of the total drill rig-rock system and distinguish between the *drill rig system*, and a *cutting and wear system* or, simply, the *tribo-system,* where the latter is selected to be as small as feasible for an analysis of the cutting and wear process (es).

The tribo system is by no means an isolated system, indeed it is an open system, connected to and exchanging inputs and outputs with its environment, with the environment defined as simply as possible, with components that have particular properties, and provide input to and accept output from the tribo-system.

The drill bit or at least the cutting head of the drill bit is clearly one key component of the tribo-system, and in embedded diamond bits this component actually consists of two elements: *diamonds* and *bit matrix.*

The size of diamonds is less than 1 mm and they are randomly placed in the whole of the matrix, then after some wearing of matrix, new diamonds will appear. Diamonds have different shape as observed in the laboratory, the predominant ones are octahedral, macle, and cubic. See figure 10 below for different kind of industrial diamonds:

Figure 10. Industrial diamonds (www.allaboutgemstones.com, 2011)

Rough industrial diamonds are quality-graded in five categories based on shape, surface quality and internal cracks, fissures or other flaws. The highest quality rating is "select" followed by AA, A, O, TA, B, and C. Diamond is the hardest known material not considering the artificially formed cubic modification of boron nitride (www.allaboutgemstones.com, 2011).

The drill bit is mounted on a drill string. In this experimental setup; the drill string and bit are in one body together and the material of the drill string part is steel. The drill string may have to be considered as a separate element in the tribo-system, or as one element in the environment of the tribo-system, connected to the tribo-system, which transmits force, torque, and work to the drill bit, and we may have to consider drill string properties that may influence the process. These properties would include mechanical inertia, stiffness, and impedance, and also thermal resistance or conductance. Mechanical stiffness is the ratio of force-to-displacement; mechanical impedances are the ratio of force over linear velocity and the ratio of torque over angular velocity. Thermal conductance is the ratio of heat flow rate over temperature difference and thermal resistance is the inverse. It is possible that transient thermal properties are relevant (which relate to thermal diffusivity, i.e. heat capacity plays a role along with heat conduction as is certainly important when considering transient temperatures at points of contact on the tool surface).

Another key component is the *Rock*. For the first phase of experiments, two types of concrete were used instead of regular rocks; one type of concrete is made with a long setting of concrete and another one was fast-setting cement.

Where would we draw the boundary between rock that is within and outside the tribo system? A final answer to this question need not be made at the outset, but it may well be convenient to include within the tribo-system that part of the rock that is subject to transient events related to the drilling process. That is all portions of the rock that experience significant (however, we define that) transient heat flow, and any significant transient forces, are within the system.

A third key component would be a *Fluid*, Which in the simplest case is water in our experiments, but may include other components, such as drilling mud. For the first phase of this work, there was no information about the input volume of water and speed of that as a flow rate, which may have an important effect on tribo-system. The fluid has at least two intended purposes: to carry away the *debris* and pieces of rock and also controlling the temperature of bit for preventing the dramatic bit wear due to increase of temperature in both matrix and diamonds.

To summarize, there are,

Within the tribo-system;

1) Two *solid stationary elements*: rock grains and rock matrix (which we are likely to consider separately)

2) Two *solid elements moving together*: diamonds and drill matrix

3) One *fluid moving element*: water or other drill fluid, and *many debris particles*

Outside the tribo-system, connected to it and interacting with it, and determining much, indeed all, that happens within the tribo-system;

1. *Solid rock*
2. *The drill string*
3. *The fluid supply column*
4. *The fluid return column*

The solid rock is stationary can be considered as uniform, in respect to properties, and supports the rock being cut, which is that portion of the rock at the cutting surface for which we probably should consider what happens to individual grains in the rock, and any matrix between grains.

The drill string which can be considered to include the steel portion of the drill bit on which the important properties of the fluid supply column are, of course, flow rate and pressure, and also temperature. The same is true of the fluid return column. However, For the fluid within the tribo-system, these properties may differ, and vary, according to location, and the debris particles within the fluid are separate elements.

Figure 11, below, shows the general figure of drill bit during work and also the macroscopic view with elements.

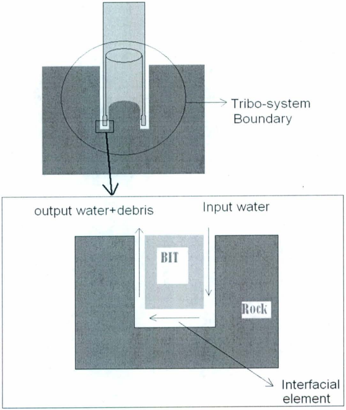

Figure 11. Tribo-system for coring bits

Our system boundary size depends on the conditions we need to consider, for example, if we need to check the effect of temperature in our system on thermal plane, we should use a larger boundary.

2.2.3.3. Relationships between elements

The main elements of the system are the teeth of the bit, the interfacial element, and rock. For solving this problem we have to define the relationship between these parameters. As mentioned above, the interfacial elements include water in this experiment which has a great effect on the wear processes.

In a great deal of tribological systems, the transactions of the relevant inputs and outputs occur at the contact interface between tribo-element 1 and 2. In these interfacial contact processes, the forces and displacements of the interacting bodies, the 'contact mechanics', as well as the materials interactions i.e., the contact 'physics and chemistry' should be taken into account.

For defining the relationship between the elements first we need to know about the contact mechanics in as much detail as possible as we can. For this, a great variety of situations must be considered depending on:

1. The number of bodies taking part in the contact process; 2 main bodies for our experiments,
2. The macro-geometry of the bodies; in this case we have 3-dimensional problem,
3. The surface topography; there are two rough surfaces,
4. The mechanical properties of the bodies; in our case one is concrete material and the other the tooth of the bit as a mixture of diamonds and matrix (cobalt alloy),
5. The deformation modes; concrete is almost quite brittle so it happens mostly by fracture deformation, concerning the matrix and diamonds in bit teeth, the former is quite hard metal and likely to have plastic deformation, and the latter one

should have more elastic than plastic deformation, but we can consider it as elasto-plastic material,

6. The contact forces (normal forces and tangential forces); we may consider the normal forces as WOB, but it should be solved for the exact value of that which is acting on the 2 surfaces, the tangential force can easily calculated from the torque,
7. The type of relative motion; which in our case is sliding,
8. The velocity of relative motion; in the general 2-body abrasion case it is the linear lateral velocity of the teeth, but in 3-body abrasion it also depends on the water flow rate and the linear velocity of teeth.

Each of the above should be considered individually for reaching optimum results, but in some cases we can omit some of these factors. Considering all of them is a very difficult analysis for the initial work on the system, and we can add the non-important factors later to the main model for modification.

The next step is to produce and consider the different planes in the two categories of *functional* and *structural* as we talked about it in the section 2.2.1. The emphasis on the functional plane must be on a representation of the proposed technical system and the evaluation and representation of the parameters which have most immediate relevance to this technical purpose.

Figure 12. Functional plane (Czichos, 1978)

In this plane the main parameters are:

(1) Bit teeth

(2) Rock

(3) Interface element, mostly water

The main function of the system is to cut the rock. The next question is about the arrows in the above figure, which is drawn below with explanation:

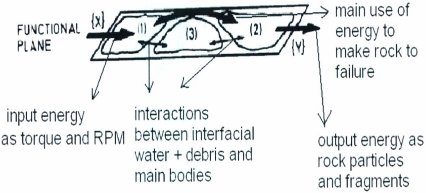

Figure 13. Functional plane with additional explanation (Czichos, 1978)

For the next step, we have to continue with structural planes and the first one is the work (energy) plane which is quoted here from the book by Czichos (1978).

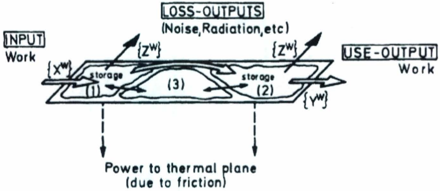

Figure 14. Functional plane with specified input/output arrows (Czichos, 1978)

$\{X^W\}$; input work as torque and RPM to storage (1) in the drill bit teeth,

$\{Y^W\}$; use-output work, which is here not directly relevant in drilling, however, energy is transformed to the rock (storage 2), where it contributes to fracture and produces fragment in the interface (3),

$\{Z^W\}$; loss-outputs as noise, vibration, and energy

- The dash arrows show us the power loss converted to heat due to friction converted on the thermal plane.

The next step is considering the thermal plane, and it is drawn below with the definition of the parameters:

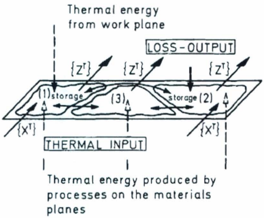

Figure 15. Thermal plane (Czichos, 1978)

- We have two types of dash lined arrows. The first one comes from the upper layer and it shows the thermal energy which is produced during the work, the second one is from the material plane, and it is produced from the internal friction of the material due to the shear of the rock,

$\{Z^T\}$; Loss-output, in our project, with two mechanisms for heat flow, the first one is using the circulated water via the convention method and the second one is conduction, in which the heat flows depending on the conductivity of rock,

$\{X^T\}$; input, that could be the heat transferred with the water, or mud,

similar as in previous layers, storage (1) in this case of thermal energy in the drill bit teeth, storage (3) is thermal energy in the drilling fluid or water, and storage (2) is thermal energy in the rock, generally in the thermal layer, they are thermal energy and not material. The next plane is the material plane as below:

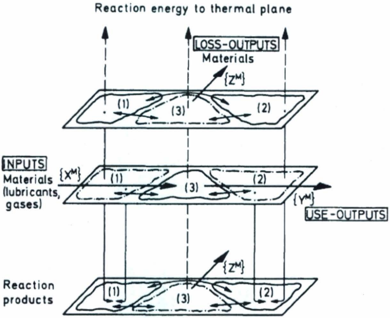

Figure 16. Material plane (Czichos, 1978)

- The dash lined arrows shows the thermal dissipation to the thermal layer from the materials,

- In this case our loss-output is the bit wear and the use-output is the rock fragments and particles from the rock,

- Input material is just the water which is circulated into the system and at last flushes the rock fragments as use-outputs,

- there are no significant reaction between materials to be considered.

2.3. Bit Wear

Bit wear is usually classified in different ways: by different bit type and different drilling conditions such as conventional rotary drilling or rotary percussion drilling. Three major industrial bit are PDC bits, Impregnated, and WC/Co (Tungsten carbide/Cobalt) bits, which have different wear behavior. In the following section, only impregnated diamond bit wear will be discussed because this type of bit was used in the experiments.

2.3.1. Impregnated Diamond Bits

Impregnated diamond tools are widely used for drilling, sawing, and grinding rocks and concretes in mining and civil engineering (Xuefeng and Shifeng, 1994; Madson, 1966). An impregnated diamond bit is usually made in two major shapes of full face bit and coring bit (Figures 17 & 18). The most common shape of this kind of bit is the coring bit.

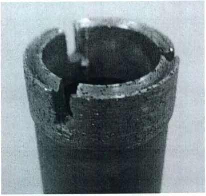

Figure 17. Impregnated diamond coring bit

Figure 18. Impregnated diamond full face bit

Impregnated diamond cutting tools are processed by powder metallurgy techniques (Przyklenk, 1993). They usually consist of a steel body mounted with impregnated diamonds as its cutting face. During cutting processes, matrix material is gradually worn away, and new unused sharp diamonds appear at surface. Matrix material should be designed especially to hold and support the diamonds up to time they are almost worn away. Thus, the performance of impregnated bit depends on the wear of both diamonds and matrix material during cutting processes (Xuefeng and Shifeng, 1994). In this case, the selection of matrix metal which is acting as bonding material is critical. The properties of this material depend on the abrasiveness and hardness of the rock to be cut. Normally tungsten (W) is used as a bonding matrix material for cutting concrete and some granite. W-cobalt (Co) and Co alloys are used mostly for granites and for cutting marbles Co, Co-bronze, iron (Fe)-Co, and Fe-bronze are bonding materials (De Oliveira et al., 2007).

Different composition of the alloy of the matrix can affect tool properties; for example, Co is efficient as a bonding metal in the diamond cutting tools. Silicon (Si), in small amounts (less than 2%) can increase adhesion of matrix to the diamonds and furthermore it avoids premature diamond pull-out. Tungsten carbide (WC) with mean particle size of 5μm and 0.5 to 2% in weight increases matrix wear resistance (Del Villar, 2001; Mészáros et al., 1996).

Majority of diamond cutting tools employ Co in matrix material. Because Co has different varations and is a strategic metal just some countries produce that, and it's not the best choice in some tool applications. Oliveira, L.J et al (De Oliveira et al., 2007) used Fe-Cu system as matrix material without any Co in it. The new matrix material (Fe-Cu) shows same wear as cobalt ones, but it cannot compete with high cobalt content based matrix yet.

Wear of impregnated diamond bit is a continuous process; the most exposed diamonds are pulled out from the matrix when these diamonds do not cut (flattened surface), and at this time new cutting diamonds raise up from matrix because of continuous wear of matrix during cutting action (Wright et al., 1986; Davis, 1996; Rosa, 2004).

For wear analysis of impregnated diamond bits, we should first look back to previous work. Miller and Ball (1991) categorized the wear of impregnated bits into five main sections: recently exposed – unworn diamond, grooved wear flat (flat wear), microfracture, macrofracture, and pull out (Figure 19).

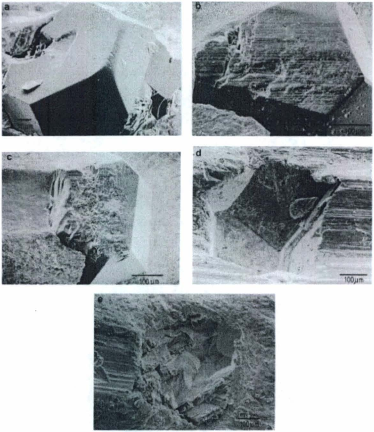

Figure 19. Different diamond wear, a: unworn, b: flat wear, c: microfracture, d: pull out, e: macrofracture (Miller and Ball, 1991)

Previous studies found that during rock machining with impregnated diamond tools both abrasive wear and microfracturing existed (Miller and Ball, 1991; Bullen, 1984; Ertingshauscn, 1985). With lower WOB, mostly wear flats were generated on exposed diamond particles; at higher WOB, microfracture was found to be predominant (Miller and Ball, 1991). Figure 20 shows type of wear and contact pressure on diamonds from Miller and Ball studies.

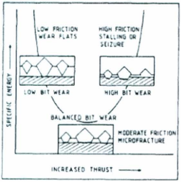

Figure 20. Specific energy vs. thrust (Xuefeng and Shifeng , 1994)

Studies by Miller and Ball mostly show concerns about diamond wear, but Xuefeng and Shifeng (1994) have worked more on both diamond and matrix wear. They found that the wear characteristic of diamond impregnated bit also depends on drilling parameters, and penetration per revolution was found to be most important factor affecting wear behavior of impregnated diamond bits. Xuefeng and Shifeng (1994) for their experiments used single-diamond cutter which is a kind of indenter, but it is incorrect to use static indentation process for the dynamic cutting processes (Abdel Moneim et al., 1997).

Miller and Ball (1991) did their experiments with different types of rocks and found that "for stable drilling in any given rock type a characteristic threshold pressure existed above which desirable microfracture of the exposed diamonds was promoted over undesirable wear flat generation. At lower load, flats are produced by sliding wear, with the silicate minerals ploughing plastic grooves in the heated surfaces of the diamonds". D.N. Wright et al (1990) reported some results for drilling on two different rock types. In drilling sandstone erosion of the matrix predominated, in particular around diamond particles. In both sandstone and granite were eventually pulled out of the diamond particles. In the case of granite, there were particles pulled out after they fractured; with sandstone pull out occurring before fracture. With both rocks breakdown occurred when the supporting matrix had been eroded. They also found that "the rate of diamond protrusion can be directly related to its position on the end face of bit and the rate of exposure of diamonds related to the abrasion of the matrix".

In conclusion, different drilling systems with and without vibration were explained. A review of wear as a process in a system and different classification of wear was presented. In drilling, the relevant system consists of the bit, the rock, and the fluid and rock debris between them was introduced. Previous work with impregnated diamond bits is reviewed. A common challenge is a useful way to measure and describe the wear of which there are several types.

Chapter 3

Wear Study and Measurement Techniques

3.1. Introduction to the study of wear and wear measurements

There are different ways to measure wear for any kind of bit. What will be discussed in this chapter is mostly organized and optimized ways for the study of diamond impregnated bits. Two different types of diamond impregnated bits were used. They are full face and coring bits. For each one, some combination of measurement techniques was used. This section explains all measuring ways in details. In this case, all of these measuring ways are categorized by bit type as: full face bit measurement ways and coring bit measurements ways. First, we look at the ways; second, in more details for each bits.

3.2. Measurement methods

Different tools were used for measurement. Some for marking to have a reference point for comparing before and after each experiment, and the others for measurements. In the case of marking, center punch and electro discharge machining (EDM) were used for making indentations on bit teeth faces. In the case of measuring, optical microscopy, micrometer, precise analogue weight balance were used. Each one will be explained separately.

3.2.1. Length measurements

This method is used mostly for full face bit because of restriction on measuring the weight. Simply using micrometer in a proper range could give the length of bit, but there are some difficulties with that. For example, protruded diamonds on top of bit teeth can easily damage the micrometer. The best way found is to use a glass plate on top of the bit (Figure 21) to avoid any direct contact between micrometer and diamonds on bit matrix.

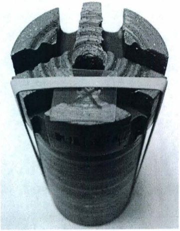

Figure 21. Glass plate on top of full face bit

Another problem for this measurement is how we could get the minimum value. Just a little deviation can affect the length (increase it). For this, the easiest possible way is to rotate the slipping clutch and jerk the micrometer very little to reach the minimum value possible (Figure 22). This method was checked and the results were reproducible. The micrometer resolution is 0.001mm.

Figure 22. Full face bit - length measurement

Another way for finding changes in length – L - is using indentations as references and measuring the length before and after experiment on bit teeth using optical microscope (Figure 23).

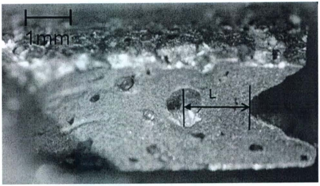

Figure 23. Using indentation for length change measurement

3.2.2. Weight measurement

An analogue GRAM-ATIC balance was used for the experiments. This weight balance resolution is 0.0001 g, and it is accurate enough for mass measurements. Before and after each experiment the cleaned bit was measured in order to record the weight loss (change) after each experiment.

3.2.3. Optical microscopy

Optical microscopes were used for several measurements. One of the most important uses was to study and compare wear of diamonds individually and in a group. It can be used for both real bit and on replicas (replication will be described in 3.3.1). It is possible to use a camera and take photographs from the microscope to record the data permanently.

Two different types of optical microscope were used: high power (Reichert) and low magnification (Wild – M420) (Figure 24). Mostly, the Wild microscope was used for taking photographs because of the ability to use the real bit directly instead of replica. The problem with higher magnification microscope is for very much closer gap between the bit surface and the microscope lens that could damage the lens by accident contact between optic lens and the diamonds on the bit surface.

One issue with Wild microscope is illumination. The direction and intensity of the lighting has a big effect on the appearance of surface. With the low power microscope low intensity blue light from the one side was used to fill the shadows produced by higher intensity white/yellowish lighting from the other side.

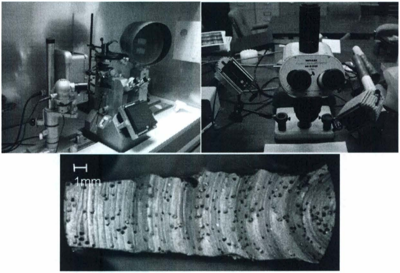

Figure 24. Top left: High power optical microscope; Top right: Low magnification microscope; Bottom: Illumination

3.3. Measurement techniques

Some techniques could easily improve the measurements and record the data well. These techniques were developed through lots of experience and optimized to be best for each type of bit. In the following sections, both techniques (replication and indentation) will be discussed and explained in detail.

3.3.1. Replication

Replication was used to exactly reproduce the bit teeth with resins. The main goal of any replication is to make a permanent record of the physical shape of the subject. For making another copy of any body, two replicas should be produced; negative and positive replica. The negative replica is made from the real bit teeth (bit head), and the positive replica is made from the negative replica. The positive replica would be exactly same shape as real bit.

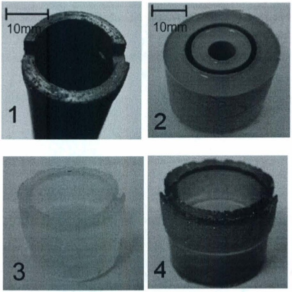

Figure 25. Picture 1: Real bit, Picture 2: Negative replica, Picture 3: Positive replica, Picture 4: Gold coated positive replica

For the final step the positive replica should be gold coated to be visible under microscope, as the material used is transparent. The gold coating procedure involves physical vapor deposition from a tungsten basket in a Varian VE10 belljar operating at below atmospheric pressure (i.e. typically $10^{-2}10^{-5}\ torr$).

Purposes of making replica:

- Permanent record of bit condition after each test,
- No concern of missing of data during tests,

- It makes easier to compare the bit profiles at the same time beside each other (for different experiments),
- It is easier to place it under microscope due to size restriction,
- No problem with high power microscope touching the lens and damage it (plastics or resins are less likely than diamond and metal to scratch optic glasses),
- However, replicas do not reproduce color, such as the different colors of diamond and matrix,
- Also, some defects, in particular due to small air bubbles, do appear on some replicas, which must be ignored. In most cases enough useful information is gained from the rest of the replica.

3.3.2. Indentation

Another beneficial technique is indentation on the teeth of the bit to have a reference mark for future study and measurements. It depends on which side of bit face it is located: side, end, or water way. Next few images show the place of indentations on different sides:

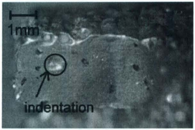

Figure 26. Indentation on water ways of coring bit

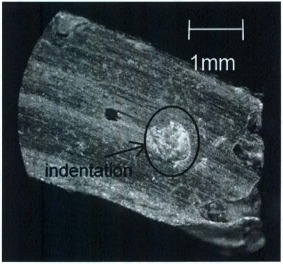

Figure 27. Indentation placed on End face

In the above pictures, some of the different places for indentation are shown, the most important one is water ways which can help in finding profile change and also length change.

There are two possible ways to make an indentation on bit: using center punch and hammer or using electro discharge machining (EDM). Above pictures all the indentations were produced by center punch easily. In the case of narrow and very precise indentations, EDM is better and more accurate.

3.4. Full face bit measurement types

Two possible ways for measuring wear of full face bit are length measurement which is described in section 3.2.1 and optical microscopy for study on diamonds shape and length measurements.

It was not possible to use lab's weight balance because the weight of the bit exceeded the range and continued study on individual and groups of diamond.

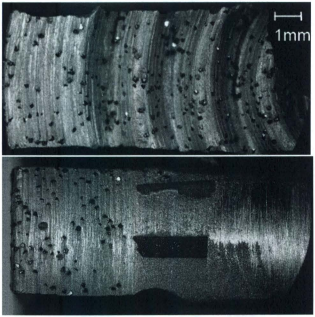

Figure 28. Pictures from full face bit; top: end face, bottom: side view

Figure 28 shows pictures were taken from different views of the full face bit. Protruded diamonds cut the rock and produce cuttings. Cuttings wear away the matrix. Ridges behind the diamonds on the bit surface are often referred to as "comet tails" caused by flowing media which contains cuttings.

3.5. Coring bit measurement types

The weight of the coring bit was low enough for it to be weighed on our most sensitive balance. For coring bit, two methods of pictures using optical microscope and weight measurement were used. Before and after each experiment the weight of cleaned bits was measured (Figure 29) and some pictures from real bit face (Figure 30) were taken. Experience showed that pictures from real bit show better image of diamond than pictures from replicas.

Figure 29. Bit weight measuring

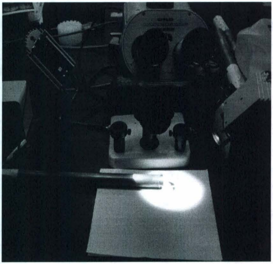

Figure 30. Surface analysis, taking pictures using microscope

Chapter 4

Experimental Investigation

4.1. Experimental setup (Drilling Machine)

For an accurate wear study, all the drilling conditions and materials (samples) used should be recorded completely. The experimental drilling system (rig) was used for the experiments (Figure 31).

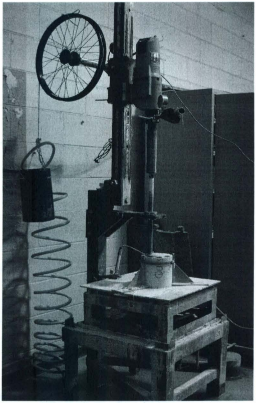

Figure 31. Experimental drilling system (Heng et al. 2010)

Experimental drilling facility of the VARD project is built up from a Milwaukee 4079 electrical powered coring drill rig. The rig has two rotary speeds: 300 and 600 RPM. The drill and motor assembly travels along a guide rail. A weight is suspended on a wheel at the side instead of the original handle bar, as the source of constant weight on bit (WOB).

Different sensors and transducers were attached to drill rig to measure all drilling parameters. Digital flow meter is attached to record flow rate during experiment. Both a digital and an analogue pressure gauge are attached on drilling device to measure the pressure on top of bit. Other devices were available to measure the vibration amplitude, ROP, and WOB.

The impregnated diamond bits are driven by the motor. An electromechanical axial shaker (magnetic) is mounted at the bottom of the drill stand as the vibration source. The test specimen was placed and held on a steel plate fixed on the shaker. The shaker is operated under different values of frequency and amplitudes. For all of the experiments the frequency of 60 Hz was used. The shaker controller has power levels marked from 0 to 60 by increments of 10 (arbitrary units). Levels from 10 to 30 were used. Due to limitations of the drill rig frame, the maximum possible hung weight is around 10 kg for non-vibration drilling, but for vibration drilling it is around 5 kg.

Two different types of diamond impregnated bit were used: full face bit and coring bit (Figure 17 and 18). Full face bit has 116 mm length and 48mm diameter at head with 1078 g weight. The coring bit has the length of 410mm with 25mm diameter (1 inch) and 540 g weight.

Equations convert hung weight to WOB. Different hung weights were used and WOB was measured by load-cell with the following equation obtained from that data (Heng et al. 2010):

WOB(kg) = 27.26 + 16.82*Hung weight(kg) (Equation 1. WOB-Hung weight conversion for coring bit)

WOB(kg) = 28.83 + 16.82*Hung weight(kg) (Equation 2. WOB-Hung weight conversion for full face bit (Heng et al. 2010))

4.2. Sample preparation

Three different types of concrete samples were used, as analog for rock, in all of the experiments. One was made with quick setting concrete and the other two are made from aggregate and type 10 Portland cement. The aggregate was sieved to include only sizes less than 2mm.

Type 0 of samples were made for full face bit experiments. The drill specimens were made from mixture of following combination of cement, aggregate, and water: the ratio was 36.5%, 38.7% and 24.8% respectively. The sample has reached to 50.7 MPa at the day 28^{th} after curing. The samples were prepared 2 months before the drilling experiments. At the day of the full face bit drilling test, the samples reached 57 MPa UCS value on average (Heng et al. 2010).

Other samples were made from Quikrete Portland cement type 10. The samples were cured in 100% relative humidity for a month to achieve the highest possible strength value. To ensure 100% relative humidity, all of the samples were submerged in water, after initially setting for 20 hours, according to the ASTM standard ASTM C873. Table 1 shows the ingredients and UCS (unconfined compressive strength) values at the standard time test of 7 and 28 days. Two more tests after two months for type A concrete were done. The results are 46 and 48 MPa.

	Type 0	type A	Type B
Aggregate Mass	-	95 kg	77kg
Cement Mass	-	33kg	43kg
Water mass	-	17 kg	21 kg
C/Agg	36.5	0.33	1/1.78
W/C	38.7	0.5	0.5
UCS 7 days	24.8	37.12	45.75
UCS 28 days	50.7	37.5	48.2

Table 1. Concrete sample specification

4.3. Full face bit experiments

4.3.1. Introduction

Some preliminary tests were done on full face diamond impregnated bit (Figure 32) with and without vibration to get some guidance for designing more efficient main experiment runs. Five experiments were done with concrete samples with total drilling length of 1.5 meter, some with and some without vibration. The results just show only a little wear on matrix at some edges and some wear on diamonds.

This is the first time we used a bit for a laboratory drilling range depth as large as 25 cm. Full description of the experiments is in the next section (4.3.2).

Figure 32. Full face bit (www.boartlongyear.com, 2011)

For this study, we chose different places of bit to be photographed and examined during experiments. Figure 33 shows the location and names given to these areas.

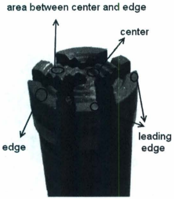

Figure 33. Bit areas (locations and names)

4.3.2. Experiment runs

Five experiments were done. Full experiments conditions are in the table below:

Table 2. Full face bit runs

Exp. #	WOB (kg)	RPM	Vibration Level	Length of run(cm)	Flow rate(gal/min)	ROP(mm/min)
1	197	600	0	25	3	5.3
2	113	600	20	25	1	7.12
3	113	600	20	25	3	---
4	113	600	20	25	3	7.13
5	113	600	0	25	3	1.91

In the next section, pictures from different selected places will be compared to show the change in matrix and diamonds after each experiment.

4.3.3. Results and Discussion

For the wear study, some different parts of the bit face are analyzed in this section. Six photos were taken from different parts of bit for comparison. Figure 34 is a surface before experiment 1. All the subsequent pictures are after the experiment mentioned. All the pictures show no significant change after several experiments. In all of these pictures, the surface as matrix and diamonds on it didn't change. No more diamonds appeared due to matrix wear, and also not much in the way of significant comet tails appeared.

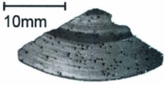

Figure 34. Before Exp. 1 Full face bit

Figure 35. Exp. 1 Full face bit

Figure 36. Exp.2 Full face bit

Figure 37. Exp. 3 Full face bit

Figure 38. Exp. 4 Full face bit

Figure 39. Exp. 5 Full face bit

Pictures from leading edge are attached below with 50 times magnification for comparison in this area of the end face of the bit. In these pictures, it is possible to look at diamonds in more detail because of higher magnification. No significant wear was from experiment 1 to the last experiment 5.

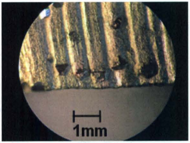

Figure 40. Before Exp.1

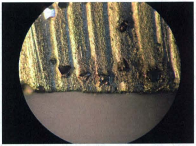

Figure 41. Exp. 1

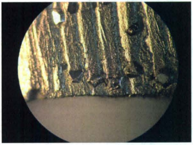

Figure 42. Exp. 3

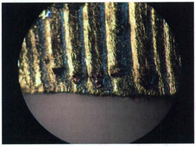

Figure 43. Exp. 3

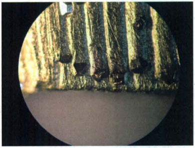

Figure 44. Exp. 4

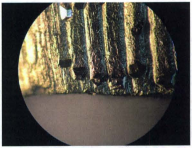

Figure 45. Exp. 5

Pictures were taken from edge of the bit (with 50 times magnification):

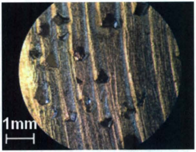

Figure 46. Before Exp. 1

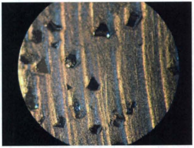

Figure 47. Exp. 1

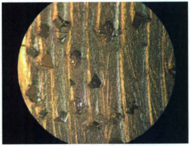

Figure 48. Exp. 2

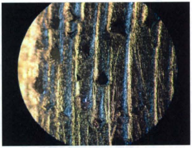

Figure 49. Exp. 3

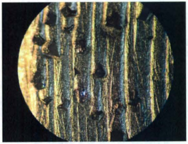

Figure 50. Exp. 4

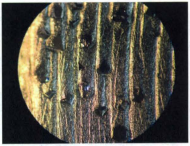

Figure 51. Exp. 5

Pictures were taken from the area between edge and center of bit (36 times magnification):

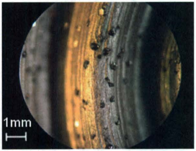

Figure 52. Before Exp.1

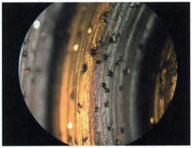

Figure 53. Exp. 1

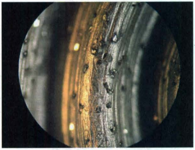

Figure 54. Exp.2

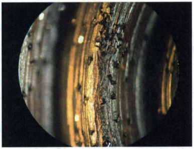

Figure 55. Exp.4

Figure 56. Exp. 4

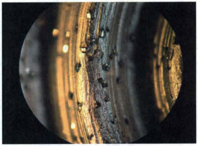

Figure 57. Exp. 5

Pictures from the center of bit (36 times magnification):

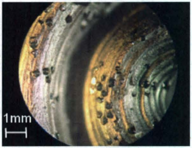

Figure 58. Before Exp. 1

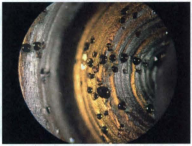

Figure 59. Exp. 1

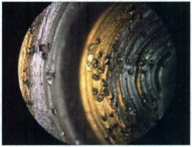

Figure 60. Exp. 2

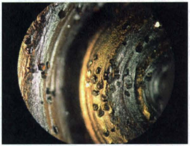

Figure 61. Exp.3

Figure 62. Exp.4

Figure 63. Exp. 5

Over most of the matrix surfaces and for most of the diamonds in pictures 34 to 64 it is difficult to see any wear. The main reason is low WOB because of drill rig load restrictions. Looking in more detail a little wear on diamonds individually can be seen somewhere in the center of the bit (Figure 64). The type of wear is mostly pull out. Main reason for this wear is higher work for individual diamonds than the ones at more distance from center.

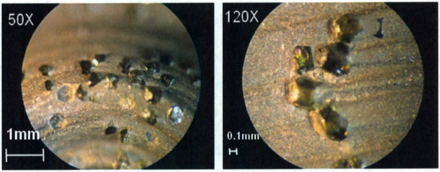

Figure 64. Center of full face bit, diamond pull out

Replication was tested in this study; the result is acceptable. Figure 65 and 66 compare the images which were taken from real bit at left and replica at right for the same portion.

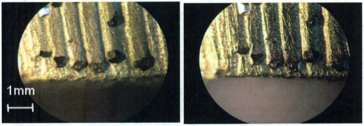

Figure 65. Leading edge, left: real bit; right: replica (50X magnification)

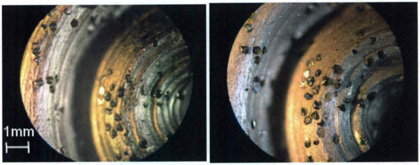

Figure 66. Center of bit, left: replica; right: real bit (36X magnification)

In both of the pictures, the replica shows an accurate copy of real bit. However, it's better to use the pictures from real bit, if we want to study individual diamonds because of better light reflection from the real bit than replica made material.

The experiments described with the full-faced bit resulted in very little wear and change in the surface structure. Limitations in time and available samples prevented the use of longer runs. The accuracy and value of taking replicas of the bit surface was, however, confirmed. The low wear rates are due to the low bit pressures possible; higher bit pressures were possible with coring bits.

4.4. Coring bit experiments

4.4.1. Introduction

Different kinds of experiments were done on coring bits. The reason we moved from full face bit to coring bits was the lower contact area of one inch coring bit in comparison to full face bit. Apparent contact area of coring bit is around 170 mm^2 in comparison to 850 mm^2 for full face bit. Moving from full face bit to coring bit could increase significantly the bit pressure up to 5 times. This should make it possible to reach the founder point on WOB/ROP diagram. The founder point is simply defined as the highest ROP which after that point increasing WOB could results in declining of ROP. This phenomenon happens due to insufficient flushing processes.

Li Heng's experiment showed for the full face bit, that we couldn't reach maximum ROP using this drill rig (Figure 67).

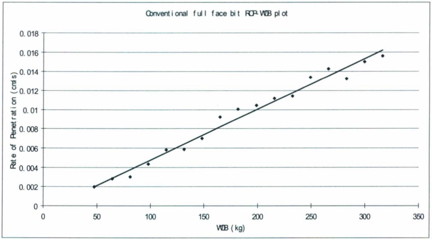

Figure 67. Plot of ROP vs. WOB (Heng et al. 2010)

Experiments with 1 inch coring bits were divided into 3 main sections: vibration/non vibration drilling, RPM tests, and pressure and flow rate tests. For all of these categories, each time 104 pictures from different places of bits were taken; more than 1700 pictures were taken with the optical microscope for wear study. Replication method was also used to ensure recording all information after each drilling run.

4.4.2. Vibration and non-vibration experiments

Three main sequences of experiments were done: Series 1(initial tests), Series 2, Series 3 (main experiments). Series 1 consists of some initial experiments on two new bits to find out the effect of vibration on new unused bits. In Series 2, some similar experiments as first run were done to confirm the results; the third Series was done with guidance from results from Series 1 and 2 with modified set of experiments on four bits instead of 2 as Series 1 and 2.

4.4.2.1. Series 1 (Initial Tests)

4.4.2.1.1. Series 1. Tests without vibration

This set of experiments was done with a new bit. The goal of this set of experiments was to find the founder point and the effect of drilling depth on ROP. The UCS of concrete samples used for these experiments was 46 MPa. All the tests were done with the flow rate of 11 litre/min. The following tables (3-5) show all the experiment details. Three sets of experiments were done. First set of experiments (Test 1) were done to find the founder point, second set of experiments (Test 2) to find the effect of depth on ROP, and third or last set (test 3) to confirm the results of Test 1. Test 1 and 3 were plotted together for better comparison.

Table 3, Test 1 shows tests involved in an increasing WOB over each 40 mm of run to find the founder point.

Table 3. Series 1 Test 1 (without vibration)

Length of run(mm)	Depth(mm)	RPM	WOB(kg)	ROP(mm/sec)
40	-40	600	60.9	1.08
40	-80	600	77.72	1.67
40	-120	600	94.54	2.00
40	-160	600	111.36	1.79
40	-200	600	102.95	1.54
40	-240	600	102.95	1.95

Table 4, Test 2 shows the experiments with constant WOB to find the effect of depth (possibly due to fluid pressure change at bottom) on ROP. Table 5 shows repeats of experiments of Table 3 of Series1 to see the effect of profile change after some drilling.

Table 4. Series 1 Test 2, Constant WOB (without vibration)

Length of run(mm)	WOB (kg)	RPM	WOB(kg)	ROP(mm/sec)	Depth(mm)
40	102.95	600	102.95	2.22	-40
40	102.95	600	102.95	2.27	-80
40	102.95	600	102.95	2.63	-120
40	102.95	600	102.95	2.33	-160
40	102.95	600	102.95	2.33	-200
40	102.95	600	102.95	2.29	-240

The results of Test 1 and 3 are plotted in Figure 68. This plot shows the effect of profile change through experiments under same conditions other than different profiles. Set1 was with an unused bit, but Test 3 was performed with V-grooved profile shape. Higher ROP was obtained from V-Grooved shape of profile rather than an unused bit of Test 1.

Table 5. Series 1 Test 3 (without vibration)

Length of run(mm)	Depth(mm)	RPM	WOB(kg)	ROP(mm/sec)
40	-40	600	60.9	2.48
40	-80	600	77.72	2.53
40	-120	600	94.54	2.61
40	-160	600	111.36	2.33
40	-200	600	98.745	2.56
40	-240	600	102.95	2.56

Table 5 and Figure 69 show the experiments of Test 2 done to find the effect of depth on ROP. Except the third measured data for the depth of 120mm, which seems to be odd, the rest of points show an optimum point of drilling at the depth between 160 to 200 mm.

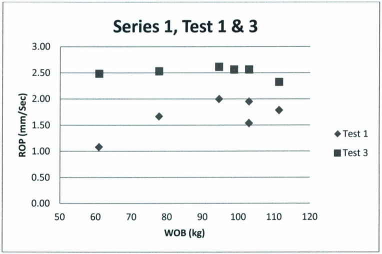

Figure 68. Run 1, Tests 1&3 (without vibration)

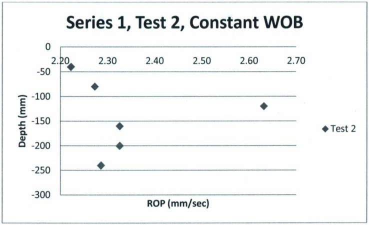

Figure 69. Series1, Test 2, Constant WOB – (without vibration)

4.4.2.1.2. Series 1. Tests with vibration

Experiments were repeated as previous ones in Series 1, Tests 1 and 3, which were without vibration, but this time with a vibration to consider the effect of vibration on ROP. The following tables (6-8) show the details of the experiment for vibration drilling:

Table 6. Series 1, Test 1 (with vibration)

Length of run(mm)	RPM	WOB(kg)	ROP(mm/sec)	Depth(mm)	Vibration level
40	600	60.9	1.80	-40	20
40	600	77.72	2.30	-80	20
40	600	94.54	2.50	-120	20
40	600	111.36	2.86	-160	20
40	600	102.95	2.86	-200	20
40	600	98.745	2.76	-240	20

Table 7. Series 1, test 3 (with vibration)

Length of run(mm)	RPM	WOB(kg)	ROP(mm/sec)	Vibration level	Depth(mm)
40	600	60.9	2.63	20	-40
40	600	77.72	3.28	20	-80
40	600	94.54	2.82	20	-120
40	600	111.36	1.94	20	-160
40	600	98.745	2.09	20	-200
40	600	102.95	2.02	20	-240

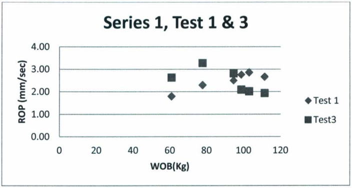

Figure 70. Series 1, Test 1 &3 (with vibration)

The difference here for vibration drilling is faster speed of change in profile shape of teeth of the bit. This causes change in ROP during test 3, the third run of experiment (Figure70). Test 3 shows a higher ROP in initial runs, up to 100 kg, but in the following experiments the ROP decreased significantly because of profile change to flat end. A general tentative conclusion from these experiments shows more wear on the bit with vibration. Other experiments with vibration, conducted in the same way as previous ones without vibration shows more scattered data in comparison with non-vibration drilling, but except for one odd data point at 150 mm depth the trend is almost the same and the maximum ROP occurs at the depth between 150 to 200 mm (Figure 71).

Table 8. Series1, Test 2 (with vibration)

Length of run(mm)	RPM	WOB(kg)	ROP(mm/sec)	Vibration level	Depth (mm)
40	600	102.95	2.76	20	-40
40	600	102.95	2.92	20	-80
40	600	102.95	3.08	20	-120
40	600	102.95	2.61	20	-160
40	600	102.95	2.82	20	-200
40	600	102.95	2.76	20	-240

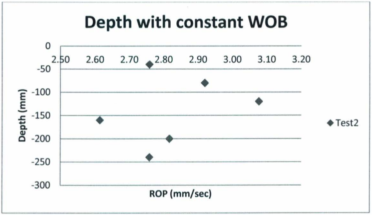

Figure 71. Series 1, Test 2, Constant WOB (with vibration)

4.4.2.1.3. Comparison of vibration and non-vibration drilling

For better comparison, pictures were taken during each set of experiments (test 1, 2, and 3). In left hand side, pictures from non-vibration drilling are collected and on the right side, vibration drilling pictures were collected. Pictures below show end face view of the bit.

Non-vibration drilling Vibration drilling

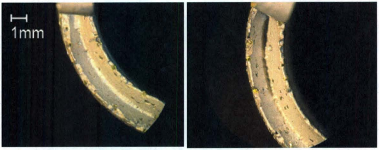

Figure 72. New bit

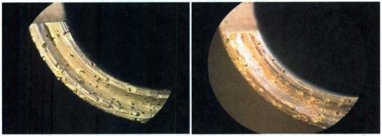

Figure 73. After Test 1 and 2

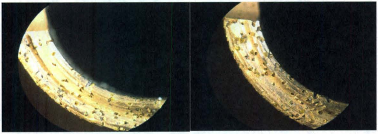

Figure 74. After Test 3

Comparison of wear in the side face of the bits between two modes of drilling:

Non-vibration drilling | Vibration drilling

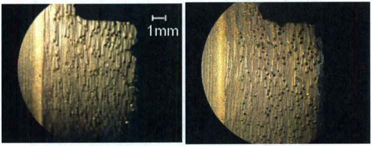

Figure 75. New bit

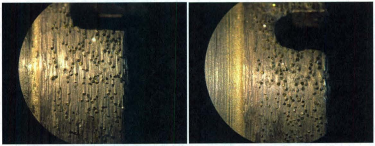

Figure 76. After Test 1 & 2

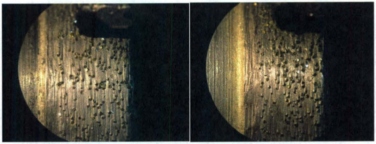

Figure 77. After Test 3

End face pictures show more wear in vibration drilling, but side face pictures show no significant wear on bit teeth.

4.4.2.1.4. Discussion-of Series 1 experiments

The profile of the coring bits changed quite quickly as a bit wears, particularly initially, and the experiments showed that profile shape affects ROP. This means that as drilling proceeds there is no steady state, i.e. a constant profile. There is no unique value of ROP at a given WOB or a constant relationship between ROP and WOB, at a given RPM and hole depth. This is true for drilling without vibration as well as drilling with vibration (Figures 68 and 70). This was true even for the short drill runs conducted in this study, particularly with vibration, as profiles changed rapidly when drilling was done with vibration. Figures 72 to 77 show this profile shape change due to considerable matrix wear.

Figure 72 shows the V-grooved shape of the surface of the unused bits; diamonds are only evident and in focus along the sharp inner and outer edges. As the edges wore, more of each surface is in focus; most of all in Figure 74 for the bit used in with vibration. Little change, i.e. little wear, was observed on the side faces, Figures 75 – 77. Note the clear comet tails in all the photographs, these resulted evidently from a polishing process at the manufacturer.

4.4.2.2. Series 2 (Repeating Experiments)

The second series of experiments were done to confirm the results of first series (Series 1). In order to achieve this, the experiments started with minimum WOB and finished at maximum WOB in test 4 and vice versa for test 5. One bit was just used for non-vibration and another one for vibration drilling. All experiments were done with 600 RPM and 40mm length of drilling with initial water pressure at the entry to the drill rig of 5 psi. In test 4, at every 40 mm intervals, the WOB increased to the one after founder point which was found in previous experiments. Test 5 started from surface of same concrete sample, but in reverse order of WOB (from high to low). The results show overall lower ROP in test 5 compared to test 4 which could be due to bit wear and the effect of profile change (Figure 78).

Table 7. Series 2, Test 4, without vibration

Test 4,	Without	Vibration
ROP(mm/sec)	Depth(mm)	WOB (kg)
2.48	-40	60.9
2.88	-80	77.72
2.76	-120	94.54
0.00	-160	98.745
2.88	-200	102.95
3.05	-240	111.36

Table 8. Series 2, Test 4, vibration drilling

Test 4	Vibration	Drilling	
ROP(mm/sec)	Vibration level	WOB(kg)	Depth (mm)
0.00	20	60.9	-40
2.67	20	77.72	-80
2.52	20	94.54	-120
0.00	20	98.745	-160
2.29	20	102.95	-200
1.77	20	111.36	-240

Table 9. Series 2, Test 5, without Vibration Table 10. Series 2, Test 5, Vibration drilling

Test 5	Without	Vibration	Test 5	Vibration	Drilling	
ROP(mm/sec)	Depth(mm)	WOB (kg)	**ROP(mm/sec)**	Vibration level	WOB(kg)	Depth (mm)
2.42	-40	111.36	**2.67**	20	111.36	-40
2.67	-80	102.95	**2.48**	20	102.95	-80
2.68	-120	98.745	**2.25**	20	98.745	-120
2.47	-160	94.54	**2.35**	20	94.54	-160
2.12	-200	77.72	**2.86**	20	77.72	-200
2.20	-240	60.9	**2.47**	20	60.9	-240

Plots (Figures 78 and 79) show previous information better for the experiments.

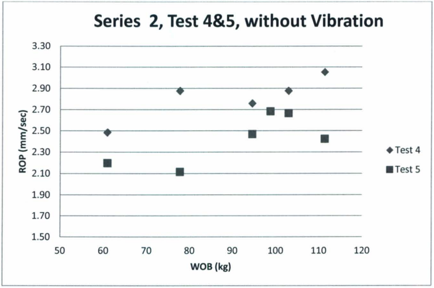

Figure 78. Series 2, Test 4&5, without vibration

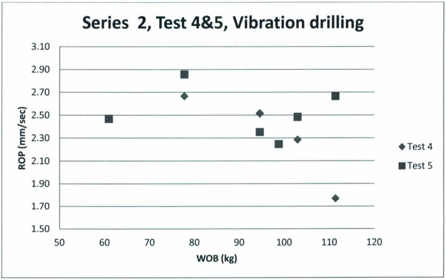

Figure 79. Series 2, Test 4&5, vibration drilling

The plots above (Figure 79) show scattered data and not very well organized; the possible reason for that could be change in profile shape and it follows change in ROP values significantly.

Clearly, in each case: the two sets of runs with no vibration, Figure 80 to 83, and the two sets with vibration, Figure 82 to 83, the data do not match well. It would appear that the best conclusion in the case of no vibration is a trend towards higher ROP with increasing WOB and a founder point had not be reached, while with vibration a founder point was reached above which there is a trend towards lower ROP with increasing WOB, with much scatter in the data. However, an alternative explanation is that change in profile or other effect of wear does affect the dependence of ROP on WOB, and possibly that effect differs when there is vibration compared with no vibration.

Photos before and after these experiments of bit profile and end face could easily show this wear. Photos for Tests 4 and 5 for non-vibration drilling, for different segments on the bits follow:

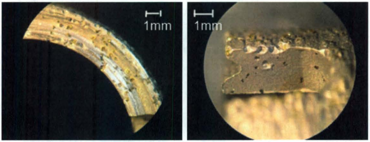

Figure 80. Series 2, Test 4&5, before experiments, Non-vibration

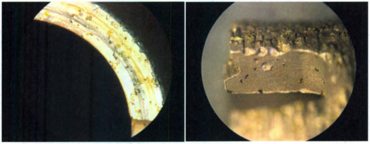

Figure 81. Series 2, Tests 4&5, after experiments, Non-vibration

Figures 80 to 81 for non-vibration drilling show not very much wear on bit. The bit after test 4 was going to flat end situation from V-grooved shape. The results show better ROP for the V-grooved than an unused bit with very sharp edges. In the Test 5, bit again starts transition from V-grooved to flat end; this changes the ROP for test 5 for the final experiments (Figure 78). Note that the inner edge (towards the bottom of the picture) is higher than the outer edge.

Photos for vibration drilling for the tests 4 and 5:

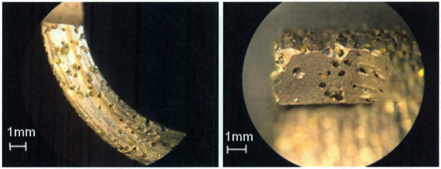

Figure 82. Series 2, Tests 4&5, vibration drilling

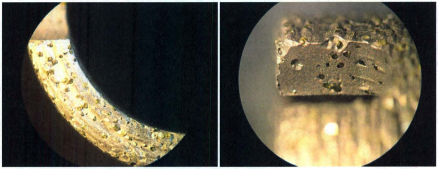

Figure 83. Series 2, Tests 4&5, vibration drilling

The above pictures (Figures 82 to 83) show the latest step in transition from V grooved to flat end face. It is interesting that the latest step is wear on inside edge to reach a complete flat end face. This changes the plot of ROP vs. WOB significantly. Note that it takes more drilling length to reach a flat end shape in non-vibration drilling than in vibration drilling.

4.4.2.3. Series 3 (Main Experiments)

4.4.2.3.1. Introduction

The possibly significant effect of bit profile and profile change was realized after the experiments of Series 1 and 2. Series 3, the main experiment, was designed using the experience of the previous series. Four bits were used to perform all of the experiments. Main goal of this series of experiments is to find accurately the effect of profile change and vibration both on ROP and wear rate. At this point it was realized that the profile shape of the impregnated diamond coring bit can be categorized in four major shapes of: Unused (new), V-grooved, flat end, and rounded edge illustrated in Figures 84 to 87.

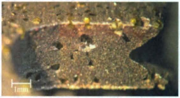

Figure 84. Unused bit

Figure 85. Flat end

Figure 86. Rounded edge

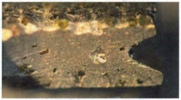

Figure 87. V- Grooved

Experiments were designed to show the effect of these profiles shapes completely. Three sets of test in this run were performed. Next sections show the tables and results of all of the experiments and the last section is a discussion of the results.

4.4.2.3.2. Series 3, Test 1

In this test the focus is mainly on ROP for different bit profile and vibration/non-vibration drilling. The four bits were used in different conditions as below:

Bit 1 and 2: Flat end profile

Bit 3 and 4: V-grooved profile

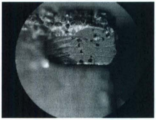

Figure 88. Bit 1 - Flat end

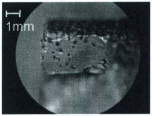

Figure 89. Bit 2 - Flat end

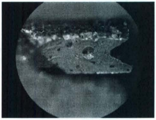

Figure 90. Bit 3 - V-grooved

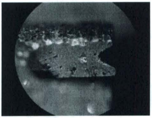

Figure 91. Bit 4 - V-grooved

Tables 11 - 14 show the the Test 1 conditions on all four bits separately. Figure 92 shows the results in plot of ROP versus WOB. Bit 1 and 2 are in same initial condition of flat end profile. One of them (Bit 1) was used for non vibration drilling and the other one (bit2) was used for vibration drilling to check the effect of vibration on same profile. Bit 3 and 4 had similar profile conditions of V-grooved. Bit 3 was used for non-vibration drilling and bit 4 was used for vibration drilling. A new (shallow) hole was drilled in each run.

Table 11. Series 3, Test 1- Bit 1

Length of run(mm)	RPM	Vibration level	ROP(mm/sec)	Depth	WOB(kg)	Seq.
100	600	0	2.25	0-10	60.9	1
100	600	0	2.33	0-10	111.36	2
100	600	0	2.70	0-10	77.72	3
100	600	0	2.33	0-10	102.95	4
100	600	0	2.63	0-10	94.54	5

Table 12. Series 3, Test 1 - Bit 2

Length of run(mm)	RPM	Vibration level	ROP(mm/sec)	Depth	WOB(kg)	Seq.
100	600	20	2.16	0-10	60.9	1
100	600	20	2.00	0-10	111.36	2
100	600	20	2.63	0-10	77.72	3
100	600	20	2.44	0-10	102.95	4
100	600	20	2.02	0-10	94.54	5

Table 13. Series 3, Test 1 - Bit 3

Length of run(mm)	RPM	Vibration level	ROP(mm/sec)	Depth	WOB(kg)	Seq.
100	600	0	1.30	0-10	60.9	1
100	600	0	2.13	0-10	111.36	2
100	600	0	2.13	0-10	77.72	3
100	600	0	2.38	0-10	102.95	4
100	600	0	2.62	0-10	94.54	5

Table 14. Series 3, Test 1 - Bit 4

Length of run(mm)	RPM	Vibration level	ROP(mm/sec)	Depth	WOB(kg)	Seq.
100	600	20	1.61	0-10	60.9	1
100	600	20	2.44	0-10	111.36	2
100	600	20	2.45	0-10	77.72	3
100	600	20	2.55	0-10	102.95	4
100	600	20	2.76	0-10	94.54	5

For the test 1, the water inside the coring bit caused incorrect reading of weight of the bit. This was a good experience to dry out completely the bits after experiments to have accurate weight measurements.

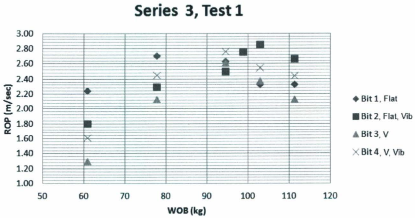

Figure 92. Plot ROP vs. WOB, Series 3 - Test 1

Above plot shows the results of ROP for all the bits. If we just want to consider the effect of vibration, we should compare bits 1 and 2 (Flat end), to 3 and 4 (V-grooved) together. Bits 1 and 2 show almost same ROP; it means that for flat end profile, vibration and non-vibration drilling give almost same ROP results. Considering bits 3 and 4 for V-grooved profile shows a higher ROP for bit 4; it means that for this profile vibration drilling is faster than non-vibration drilling. Bits 3 and 4 (V-grooved profile) had better ROP at higher WOB than flat end (bits 1 and 2).

At low WOB the flat profile produced the higher ROP, The maximum ROP was about the same for all four bits, but the WOB for the maximum ROP was higher for the V profile than for the flat profile. At high WOB, above the maximum, the ROP was about the same for both profiles. Taking the foregoing into account there was little consistent difference between ROP with and without vibration for bits with the same profile.

It should be noted that all these runs were done at very little hole depth. These conclusions may not hold for drilling at some depth. In normal practice any drill bit will be worn once some depth is reached, and the type of coring drill used for this work would in any event not have a V profile, but either a flat or round profile.

4.4.2.3.3. Series 3, Test 2

Test 2 was designed to see the effect of another profile shape, the rounded edge. In this study, the weight loss of the bit was also considered to also compare different drilling and bit conditions for wear rate. Pictures in Figures 98-101 show bit profiles.

Bit 1: Rounded edge profile

Bit 2: Flat end profile

Bit 3 and 4: V-grooved shape

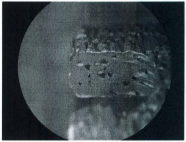

Figure 93. Series 3, Test 2 - Bit 1

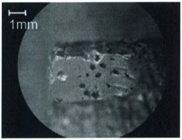

Figure 94. Series 3, Test 2 - Bit 2

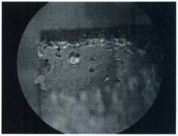

Figure 95. Series 3, Test 2 - Bit 3

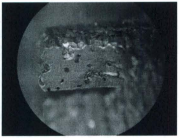

Figure 96. Series 3, Test 2 - Bit 4

Tables 16-19 show the full details and results of each drilling experiments for all the four bits separately. Bits 2 and 3 were used with vibration, bits 1 and 4 with no vibration. Note the sequence of the hung weights/WOB values used.

Table 15. Series 3, Test 2 - Bit 1

Length of run(mm)	RPM	ROP(mm/sec)	Depth	Vibration Level	weight change	Seq.	WOB(kg)
100	600	2.23	0-10	0	0.059	1	69.31
100	600	1.92	0-10	0	0.058	2	102.95
100	600	2.12	0-10	0	0.064	3	77.72
100	600	1.85	0-10	0	0.029	4	94.54
100	600	2.17	0-10	0	0.022	5	86.13

Table 16. Series 3, Test 2 - Bit 2

Length of run(mm)	RPM	ROP(mm/sec)	Depth	Vibration Level	weight change	Seq.	WOB(kg)
100	600	2.23	0-10	20	0.105	1	69.31
100	600	2.40	0-10	20	0.076	2	102.95
100	600	2.48	0-10	20	0.071	3	77.72
100	600	2.38	0-10	20	0.053	4	94.54
100	600	2.44	0-10	20	0.088	5	86.13

Table 17. Series 3, Test 2 - Bit 3

Length of run(mm)	RPM	ROP(mm/sec)	Depth	Vibration Level	Weight change	Seq.	WOB(kg)
100	600	2.50	0-10	20	0.257	1	60.9
100	600	3.12	0-10	20	0.138	2	102.95
100	600	2.90	0-10	20	0.15	3	77.72
100	600	2.08	0-10	20	0.078	4	111.36
100	600	3.28	0-10	20	0.09	5	94.54

Table 18. Series 3, Test 2 - Bit 4

Length of run(mm)	RPM	ROP(mm/sec)	Depth	Vibration Level	weight change	Seq.	WOB(kg)
100	600	2.35	0-10	0	0.093	1	60.9
100	600	2.36	0-10	0	0.071	2	102.95
100	600	2.63	0-10	0	0.05	3	77.72
100	600	2.04	0-10	0	0.039	4	111.36
100	600	2.62	0-10	0	0.038	5	94.54

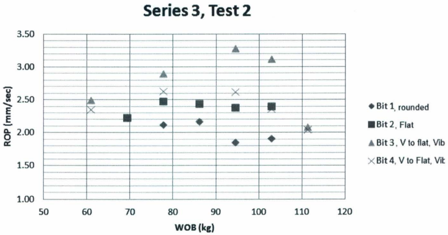

Figure 97. ROP vs. WOB, Series 3 - Test 2

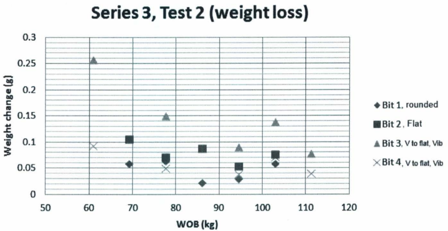

Figure 98. Weight loss vs. WOB, Series 3 - Test 2

The upper plots of results, Figure 97, show the: effect of different conditions on ROP and the lower plots, Figure 98, the effect of different conditions on weight loss. From Figure 97, it is easy to see the effect of profile on ROP. The highest ROP was with the bit with

V- grooved shape, in the middle is flat end, and the lowest ROP was with a rounded edge. Of course, the vibration should be considered, but the V- grooved shape for non-vibration drilling shows better ROP than the flat end bit at some WOBs. The difference between the V-grooved bit in these experiments and that in Test 1 is more contact area at the two flat surfaces around the V area (Figures 99 and 100). This difference could be a possible reason for more ROP in Test 2 than in Test 1.

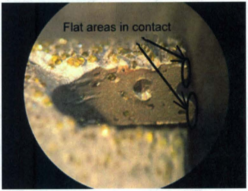

Figure 99. V-grooved at Test 2

Figure 100. V-grooved at Test 1

The WOB for the optimum (highest) ROP was higher for the V profiles than for the rounded ones with Bit 3 producing, with vibration, the highest ROP of all the bits at the optimum. That was also the last run in the set for that bit. This bit also showed the steepest rise in ROP with increasing WOB up to the maximum and then the steepest drop in ROP above that. Bit 1, with a round profile and no vibration had the lowest ROP values, with a trend towards lower ROP, by a small amount, with increasing WOB.

Figure 98 shows data from the same experiment as figure 97 but for weight loss instead of ROP. In this plot, bit 3, the one with highest ROP, has the most weight loss; after that come from bits 2, 4 and 1 in order of decreasing weight loss. The bit with lowest ROP makes lowest wear or weight loss. In general, vibration made around 2 times more wear rate than non-vibration drilling for V-grooved profile. An interesting point is the trend of the data of this plot, which is for all of them declining at higher WOB values.

4.4.2.3.4. Series 3, Test 3

The main goal of Test 3 is to check the effect of different vibration amplitudes on ROP and weight loss. In the previous experiments vibration level 20 were used. In this set of experiments vibration levels of 10 and 30 were performed. The amplitude of vibration is also by WOB. In this study, the average value of that is considered for each vibration level. Vibration level at level 10 power produced a 0.38mm average amplitude, and vibration power level 20 and 30, respectively, produced average amplitudes of 0.48 and 0.58 mm.

Pictures in Figures 101 to 104 show the initial bit profile condition:

Bit 1 and 2: rounded edge

Bit 3 and 4: transition from V-grooved to flat end

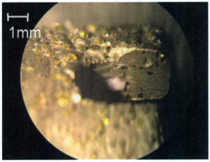

Figure 101. Series 3, Test 3 - Bit 1

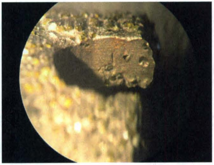

Figure 102. Series 3, Test 3 - Bit 2

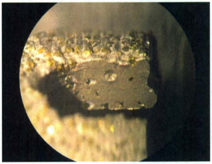

Figure 103. Series 3, Test 3 - Bit 3

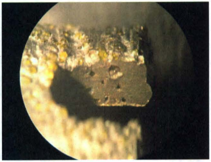

Figure 104. Series 3, Test 3 - Bit 4

Bit 1 and 2 started with the same profile, rounded edge. In order to achieve the best results, bits 1 and 2 were used with same drilling conditions with just a difference in vibration level (10 and 30). The same was true for bits 3 and 4 because they had the same profile, in this case transition from V-grooved to flat end.

Following tables (19-22) show the detail and results of experiments.

Table 19. Series 3, Test 3 – Bit 1

Length of run(mm)	RPM	ROP(mm/sec)	Depth(mm)	Vibration level	Weight change(g)	Seq.	WOB(kg)
100	600	2.78	0-10	10	0.068	1	60.9
100	600	2.92	0-10	10	0.05	2	111.36
100	600	2.63	0-10	10	0.062	3	77.72
100	600	2.38	0-10	10	0.071	4	102.95
100	600	2.50	0-10	10	0.081	5	94.54

Table 20. Series 3, Test 3 - Bit 2

Length of run(mm)	RPM	ROP(mm/sec)	Depth(mm)	Vibration level	Weight change(g)	Seq.	WOB(kg)
100	600	3.13	0-10	30	0.096	1	60.9
100	600	2.58	0-10	30	0.061	2	111.36
100	600	2.90	0-10	30	0.151	3	77.72
100	600	2.66	0-10	30	0.143	4	102.95
100	600	2.86	0-10	30	0.127	5	94.54

Table 21. Series 3, Test 3 - Bit 3

Length of run(mm)	RPM	ROP(mm/sec)	Depth(mm)	Vibration level	Weight change(g)	Seq.	WOB(kg)
100	600	2.92	0-10	10	0.086	1	60.9
100	600	2.82	0-10	10	0.051	2	111.36
100	600	2.74	0-10	10	0.136	3	77.72
100	600	2.50	0-10	10	0.11	4	102.95
100	600	2.70	0-10	10	0.102	5	94.54

Table 22. Series 3, Test 3 - Bit 4

Length of run(mm)	RPM	ROP(mm/sec)	Depth(mm)	Vibration level	Weight change(g)	Seq.	WOB(kg)
100	600	2.47	0-10	30	0.149	1	60.9
100	600	2.65	0-10	30	0.122	2	111.36
100	600	3.25	0-10	30	0.196	3	77.72
100	600	2.86	0-10	30	0.082	4	102.95
100	600	3.45	0-10	30	0.113	5	94.54

Figures 105 and 106 show plots of ROP and weight loss versus WOB for above experiments. The highest ROP was from bit 4; the reason is simple: higher vibration amplitude and better profile shape (transition from V-grooved to flat). The next highest ROP is for bit 2 with the same vibration amplitude but not very good profile shape (rounded edge). In general, higher vibration amplitude show better ROP result and profiles with shape closer to V-grooved show better ROP result (Figure 105).

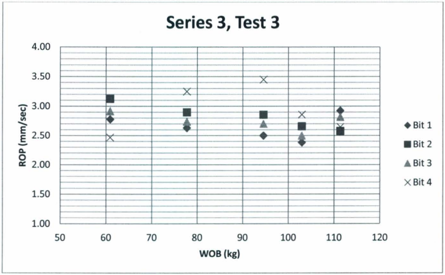

Figure 105. Series 3, Test 3 - ROP vs. WOB

Figure 106 shows weight loss for the test 3. Bit 4 the highest weight loss and bit 2, the second highest. Bit 1 and bit 3 shows lower weight loss; of course, the reason is lower vibration power. At higher WOB the data were scattered more; the reason could be higher load on shaker table and ensuing lower vibration amplitudes.

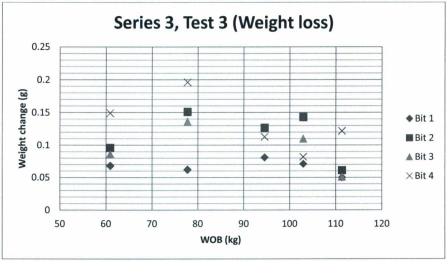

Figure 106. Series 3, Test 3 - Weight loss vs. WOB

All the bits except bit 4 show almost same ROP vs. WOB, and ROP reducing with increasing WOB. Bit 4, with vibration level 30, showed a peak ROP at about 90 -95 kg of WOB. The higher vibration level (level 30) results in the higher weight loss. Figure 106 shows above 77 kg of WOB, increasing of WOB results a trend in of declining weight loss.

4.4.3. Experiments on the role of RPM

4.4.3.1. Introduction

Some experiments were done to analyze the effect of different RPM as well as vibration on the wear rate of impregnated diamond coring bits. Previous tests were done at 600 RPM, but in this set of experiments two rotary speed of 300 and 600 were used. The other conditions such as hung weight and water flow rate were same as previous runs. For better understanding of wear rate on the bit with and without vibration drilling, designed tables of experiments were used to also consider the effect of profile change. Experiments were designed to have minimum profile change effect to avoid any further problems. Length of run was changed from 100 mm to 70 mm to reduce the effect of profile change on RPM and also wear rate. Two new bits were used, and both were first run-in to a depth of 70 mm, to achieve a stable profile. Runs were also shortened from 100 mm to 70 mm to reduce the profile change during runs. A WOB of 1205 kg was used in all the runs. With each bit the rpm alternated in the sequence of runs, the first run at 300 rpm with bit A, and starting with 600 RPM with bit B. With both bits all the runs were without vibration, except runs 3 and 4 which were at vibration level 20.

4.4.3.2. Table of Experiments

For these runs, two new unused bits (bits A and B) were used. They were conditioned first by drilling to a depth of 70mm without vibration with 4.5kg hung weight (103 kg WOB) and 10 psi water pressure at the inlet to the bit before start of experiment (pressures changed during drilling in relation to different depths).

Table 23 and 24 shows detail and results of the RPM experiments.

Table 23. RPM tests - Bit A

Run sequence	Length of run(mm)	RPM	ROP(mm/sec)	Depth(g)	Vibration level	Weight change(g)	WOB (kg)
1	70	300	1.08	0-70	0	0.095	102.95
2	70	600	2.80	0-70	0	0.074	102.95
3	70	300	1.73	0-70	20	0.25	102.95
4	70	600	3.14	0-70	20	0.188	102.95
5	70	300	1.44	0-70	0	0.061	102.95
6	70	600	2.78	0-70	0	0.065	102.95

Table 24. RPM tests - Bit B

Run sequence	Length of run(mm)	RPM	ROP(mm/sec)	Depth(g)	Vibration level	Weight change(g)	WOB(kg)
1	70	600	2.59	0-70	0	0.146	102.95
2	70	300	1.46	0-70	0	0.128	102.95
3	70	600	3.15	0-70	20	0.225	102.95
4	70	300	1.94	0-70	20	0.12	102.95
5	70	600	3.03	0-70	0	0.05	102.95
6	70	300	1.65	0-70	0	0.07	102.95

The experiments were designed in the way to understand the effect of both vibration and RPM on bit wear, as well as on ROP, with runs at 300 RPM and 600 RPM, as well as with and without vibration with the least possible effect of profile differences and change. The RPM alternated in the sequence of tests. The order for bit B was the reverse of the order for bit A. It is possible that RPM affects the profile change. For each bit the first two runs without vibration should achieve the same profile change. There runs for each bit was followed by two runs with vibration (run 3 and 4), and then by two more runs without vibration (run 5 and 6). This makes it possible to compare the results for runs 1 and 2. After vibration runs (3, 4), we again switched to non-vibration drilling. To compare the effect of vibration the averages was taken of ROP and weight changes in run

1 with bit A and run 2 with bit B and similarly for run 2 with bit A, run 1 with bit B. The same procedure was followed for run 3 and 4 with vibration with the two bits.

Assuming that there is continuous change in profile on drilling progress, the profile change should be same after runs 1 and 2; likewise, after runs 3 and 4, and runs 5 and 6. Furthermore, it appears appropriate to compare the average of runs 1, 2, 5, and 6 with the average of runs 3 and 4 to establish the effect of vibration compared to non-vibration. Each run was to have the same depth on the same sample. The duration of each run depends on the ROP.

Table 25 shows the different values of drilling time for each drilling conditions. The numbers show the time elapsed for same drilling depth of 70mm for each run. The values are close to each other for different bit and sequences and it shows not very much profile effect. In most of the set of data, e.g. with vibration at 600 rpm, the values are similar.

4.4.3.3. Results and Discussion

Table 25 lists the duration at each RPM and for both with and without vibration. The values are close in each group. Table 26 lists the average values of ROP with each condition.

Table 25. RPM data

	300(RPM)	600(RPM)
Vibration drilling time (sec)	40.5, 36 (sec)	22.29, 22.25
Non-vibration drilling time (sec)	42.53, 55, 48.65, 48	25, 25.2, 27, 23.1

Table 26. Average value of ROP for RPM tests

	300(RPM)	600(RPM)
Vibration drilling – ROP (mm/sec)	1.83 (mm/sec)	3.14
Non-vibration drilling – ROP (mm/sec)	1.44	2.79

Table 27 shows the values for wear in average weight loss for each drilling condition.

Table 27. Weight loss vs. RPM

	300(RPM)	600(RPM)
Vibration drilling - weight loss (g)	0.185(g)	0.2065
Non-vibration - weight loss (g)	0.0885	0.0838

Figure 112 shows that ROP increases with increasing RPM, and it is almost the same increase for both with and without vibration. Another plot (Figure 113) shows the weight loss for both with and without vibration; more wear for higher RPM achieved in comparison to 300 RPM. For non-vibration drilling, the trend is reverse; just a little lower wear at 600 RPM than at 300 rpm.

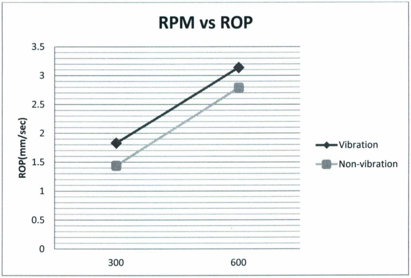

Figure 107. ROP vs. ROP

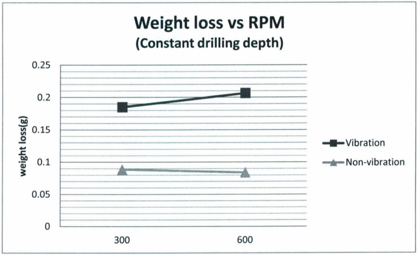

Figure 108. Weight loss vs. RPM

4.4.3.4. RPM tests image analysis

Pictures from water ways show clearly the change in profile shape. For comparing different RPMs and with/without vibration, pictures were placed beside each other. For this, experiment one and three show good relative images of profile change for non-vibration and vibration drilling with different RPM.

4.4.3.4.1. Non-vibration drilling photos

The result in the below picture is interesting, because it shows more wear on the outer edge of the bit for 300 RPM. It proves the low flushing speed of water, which causes debris to remain more in the contact area there and consequently more matrix wear.

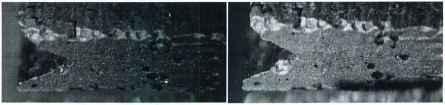

Figure 109. Non-vibration drilling, 300 RPM, Left: before exp., Right: after exp.

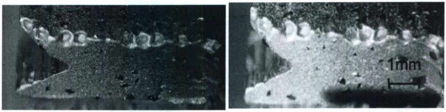

Figure 110. Non-vibration drilling, 600RPM, Left: before exp., Right: after exp.

4.4.3.4.2. Vibration drilling photos

The same thing happened with vibration drilling; more wear on the outer edge of bit in comparison to inner edge because of less flushing in 300 RPM than 600RPM.

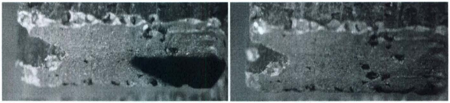

Figure 111.Vibration drilling, 300RPM, Left: before exp., Right: after exp.

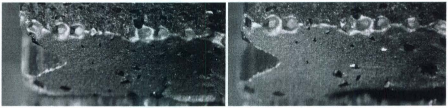

Figure 112. Vibration drilling, 600RPM, Left: before exp., Right: after exp.

4.4.4. Pressure and Flow experiments

4.4.4.1. Introduction

It was decided to do some experiments with coring bits to find the effect of different flow rate and bottom hole pressure on bit wear. For this a cylindrical concrete sample was specially designed to achieve the best possible measurements (Figure 113). Every time, the pressure on top of the bit was measured via pressure transducers, but this design could help to find the pressure at the bottom hole (pressure in contact area of bit end face and rock). For this matter, another pressure transducer was attached to a plastic tube, and when the bit drills through the plastic, the filled tube with water could transfer the pressure to the pressure transducer.

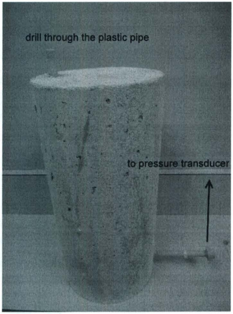

Figure 113. Concrete Sample with special design

Figure 114 shows this design more clearly. A pressure transducer was attached to the plastic tube which was placed inside the concrete sample. Before the start of experiments, this tube was filled with water completely to prevent any possible mistake in reading pressure data. This setup could show pressure at bottom hole during drilling.

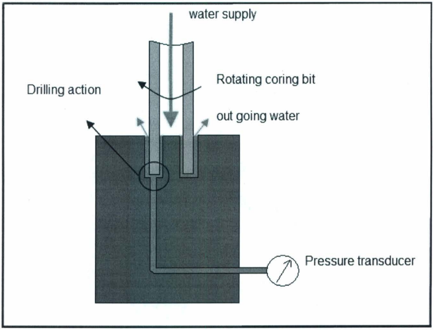

Figure 114. Bottom hole Pressure measurement

4.4.4.2. Experiments and results

Experiments were done to find the relationship between top, bottom pressure, and the relationship to water flow rate. Water was the flushing media for all of drilling tests. The flow rate and initial pressure on top of the bit was set by regulating the laboratory tap water flow rate of laboratory.

In total, 5 flow experiments were done. All of these experiments were done without vibration and the same initial flow and pressure conditions. The initial flow rate was set at 15 liter/min. When the experiment was started, the flow rate decreased and pressure on top of bit increased. The key point is the pressure after a couple of centimeters reached the maximum available tap water pressure (50-60 psi) and the flow rate decreased to around 3.8 liter/min. This shows the pressure drop is very high, and this causes insufficient water supply power to maintain constant water flow rate to perform the experiment.

Another set of experiments were done by using special concrete samples to compare vibration and non-vibration drilling for bottom-hole pressure. The experiments were done with initial flow rate of 11 liter/min, with 120 kg of weight on bit and 600 RPM. The first 2.5 s was performed without vibration, and the last seconds with vibration (Figure 114). The pressure fluctuated but the average supply pressure did not change when vibration was used.

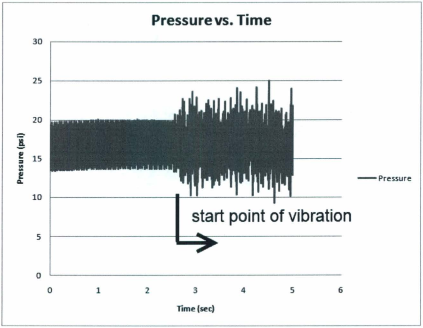

Figure 115. Bottom pressure vs. time (left side: non-vibration, right side: vibration)

Chapter 5

Conclusions and Recommendations

5.1. Conclusions

It is well known that rate of penetration is a function of WOB and ROP. The work reported here with embedded diamond coring bits focused also on vibration and included a study of wear using both weighing and microscopy of the bit surfaces. Microscopy was used on both replicas and directly on the bit surfaces. Replicas were found to be very useful; providing the opportunity to show the bit surface at various stages of time.

For the vibration level used, vibration had a significant effect on bit wear, and wear changed the bit profile. There was no steady- state profile shape in all experiments. Profile change affects ROP and wear, and it must be taken into account in this kind of study.

In all experiments, three main profile shapes appeared after some drilling in the sequence of: V-grooved, flat end, and rounded edge. The highest ROP results were obtained with V-grooved, decreasing in the order: unused, flat end, and rounded edge. Profile shapes with sharper edges wore away more rapidly than flat or rounded profiles.

For choosing the best drilling condition, generally the V-grooved with non-vibration drilling had a good drilling result; otherwise, in the case of drilling productivity optimization for vibration drilling, it is best to look at both plots of ROP vs. WOB and

Wear vs. WOB to find optimum WOB, considering both factors, and this depends on vibration level.

Increasing RPM showed the same effect on the rate of penetration, but it caused higher wear rate in vibration drilling and lower bit wear in non-vibration drilling. Weight loss per drilling depth is less affected by RPM and not at all for non vibration.

As the vibration power is used, the factor by which vibration increases ROP is much less than the factor by which the vibration increases weight loss per unit drilling depth.

In the limited range of depth and drilling times, the following observation were made that drilling depth affects ROP.

There can be different WOB values for the optimum ROP depending on vibration. It is possible to observe a decreasing ROP with increasing WOB, a situation which to be due to a change of profile.

This work was also a test of techniques for studying wear, in particular in short drilling runs usual in our laboratory studies of ROP and WOB relationships. A limited number of runs were performed at each set of variables, and resulting in some scatter in the data.

5.2. Future Recommendations

Some tests were performed to find the effect of drilling flow rate and pressure. These tests were incomplete because of restrictions with this drilling rig setup. The water supply power was not enough to run the tests with sufficient flow rate to flush the cuttings very well. Fluctuations on tap water supply also could play an important role on drilling conditions; for example, changing the flow rate changes the pressure drops in the system, including the bottom hole pressure which can affect the actual WOB. In this case, the recommendation is to use a separate water supply to have constant flow or pressure.

Profile shape can change ROP drastically. It is recommended for future studies to use a bit with less effect of profile change in it. This might help to investigate in more detail important factors like vibration.

For wear measurements, mostly weight loss and matrix shape were considered. Diamonds play an important role in matrix wear and generally in total bit wear. Looking more closely at diamonds individually could help to find the reason behind excessive matrix wear in vibration. There was more pull out of diamonds in vibration drilling than in conventional drilling. More consideration should be given to force per diamond or average force on each diamond that could be useful in future investigation.

Future work should be designed with longer runs, more WOB, higher flow rates with better control, and a wider range of RPM.

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