11th International Conference on Vibration Problems
Z. Dimitrovová *et.al.* (eds.)
Lisbon, Portugal, 9–12 September 2013

# EXPERIMENTAL INVESTIGATION OF THE DOMINANT MECHANISMS ACTING AT THE IMPREGNATED DIAMOND BIT / ROCK INTERFACE

**M. Mostofi*[1], L. Franca[2], T. Richard[3]**

[1]Curtin University, Deep Exploration Technology CRC
Masood.Mostofi@postgrad.curtin.edu.au
[2]CSIRO, Deep Exploration Technology CRC, Luiz.Franca@csiro.au
[3] CSIRO, Epslog, Deep Exploration Technology CRC, Trichard@epslog.com

**Keywords:** Impregnated Diamond Segment, Cutting Action, Dominant Processes, Experimental Study

**Abstract.** *The drilling action of Impregnated Diamond (ID) bits is accompanied by a continuous change of the contact surfaces due to diamonds and matrix body wear. To better understand the drilling action of ID bits, it is thus required to isolate the cutting action from the wear process. For this purpose, a rigorous experimental test protocol is established to identify the response of ID bits for a given status of wear. The study is conducted at the segment or crown scale, which corresponds to the smallest cutting element of ID bits. Experiments are performed with a state of the art drilling rig, dubbed "Thor", under kinematic control conditions, i.e. the rate of penetration ($V$) and the rotary speed ($\Omega$) are imposed. The results indicate that the cutting action of ID segments is governed by two dominant processes: pure cutting process, which is entirely devoted to rock destruction, and friction at diamond/rock and matrix/rock contacts. It was also observed that the cutting response can be described by three linear regimes.*

## 1 INTRODUCTION

The impregnated diamond (ID) bits, which are made of synthetic diamonds sintered in metal bonding powder, are specifically designed for drilling hard abrasive formations. The drilling performance of these bits is characterised by self-sharpening events, where the blunt diamonds are replaced by sharp ones embedded in the matrix bonding. By changing the segment properties (diamond size $\phi$, diamond concentration $c$, and matrix property), these bits can drill a wide range of formations from abrasive sedimentary to ultra hard competent igneous or metamorphic rocks. Despite frequent use, mechanisms mobilised at the bit/rock interface are not fully understood, resulting in inconsistent performance in the field.

This paper aims to gain insights about the drilling action of ID bits by conducting experimental investigation at the segment scale. A rigorous test procedure is applied to isolate dominant processes taking place at the bit/rock interface.

## 2 BASIC VARIABLES

The drilling action is often expressed by relationships between dynamic and kinematic variables acting at the bit/rock interface [1, 2, 3]. The dynamic variables are the weight-on-bit $W$ and the torque-on-bit $T$, whilst the kinematic variables are the rate of penetration $V$ and bit angular velocity $\Omega$. The kinematic variables can be summarised in a single variable, depth of cut $d$, which corresponds to the thickness of rock removed over one revolution of bit, see Eq.1. It is convenient to characterise the drilling response by relationships involving the dynamic variables and depth of cut, i.e. $W$, $T$ and $d$.

$$d = \frac{2\pi V}{\Omega} \tag{1}$$

At the segment scale, the dynamic variables are the normal $F_n$ and the tangential $F_s$ components of the force **F**, see Fig.1. As ID bits are composed of several segments, the depth of cut per segment $d_s$ can be defined from the contribution of each segment in the drilling process, which is function of the number of segments at the bit face. The segment/rock interaction is, therefore, expressed by relationships involving $F_n$, $F_s$, and $d_s$.

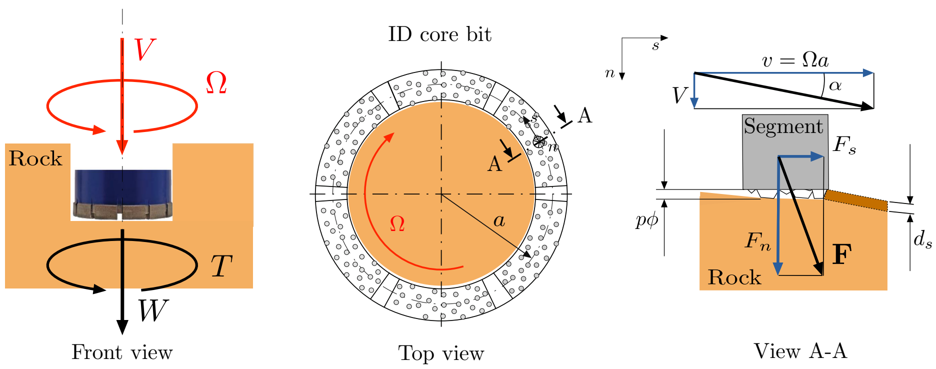


Figure 1: The schematic of bit and segment variables.

## 3 EXPERIMENTAL PROGRAM

The laboratory drilling rig used in this study is shown in Fig.2. This setup is dubbed ”Thor”, which is a modified semi-CNC lathe specifically designed to study the cutting action of single

ID segments. In this setup, the cutting action occurs when the segment, facing the chuck, is completely in contact with the cross sectional surface of the spinning rock sample and moving into a longitudinal direction towards the spindle chuck. The feed rate $V$ is imposed by a precise electric linear actuator, whilst a piezo-electric dynamometer sensor is located between the segment holder and carriage to measure the reactive force in terms of $F_n$ and $F_s$.

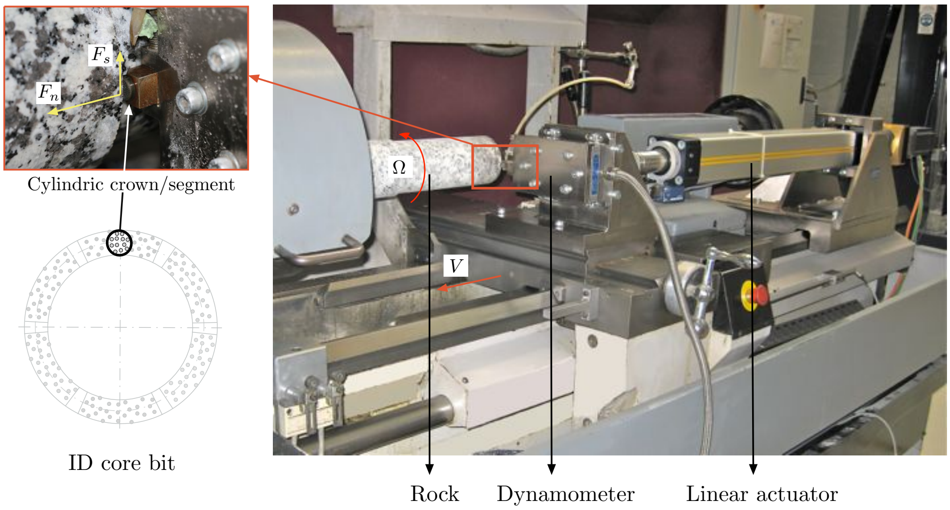


Figure 2: Thor drilling rig.

The cutting response is obtained by imposing a set of depths of cut at constant angular velocity, where the cutting in each step proceeds for 20-30 revolutions. The responses of different segment classes, characterised by different bonding matrix properties, diamond sizes and concentrations are obtained through cutting tests performed on three granites.

## 4 EXPERIMENTAL RESULTS

### 4.1 Typical wear-invariant response

The average of the reactive force in each increment of depth of cut is calculated and the response is represented in $d - F_s$ and $d - F_n$ spaces, see Fig.3. Notice that the response is characterised by three linear regimes.

### 4.2 Dominant processes

Following an approach proposed for the drilling action of PDC [2, 3], roller-cone [4], percussive [5] bits, and grinding wheels [6], the drilling/cutting action can be assumed as a combination of two independent processes, pure cutting and friction. In the former, the energy is totally consumed in rock fragmentation, whilst the energy is dissipated across the bearing surfaces in the latter. Referring to the image of the diamond/matrix element at the segment cutting face, it is alleged that two friction contacts take place at the diamond/rock and matrix/rock bearing surfaces, see Fig.4.

To isolate each process, a series of cutting tests are performed with matrix-removed segments, in which the matrix around the diamonds is removed through sand blasting or acid leaching treatments, see Fig.4. The purpose of this procedure is to remove/minimise the effect of friction contact mobilised on the matrix bearing surface by increasing the diamond protrusion and removing the matrix surface behind the diamonds.

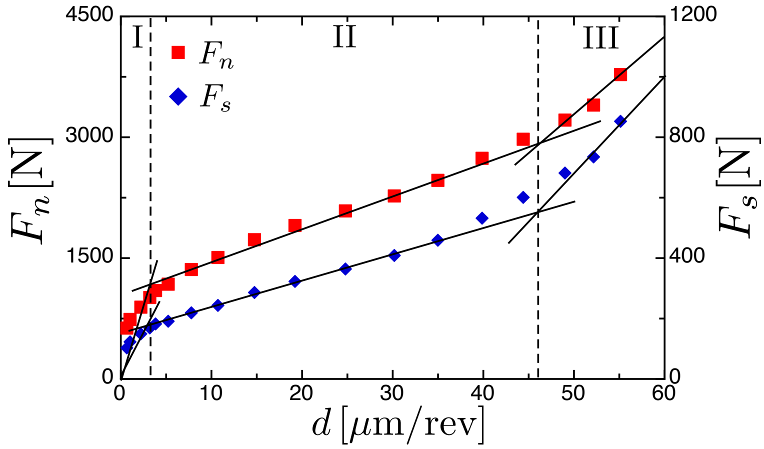


Figure 3: The stationary cutting response at $d - F_n$ and $d - F_s$ spaces carried in Riverina granite.

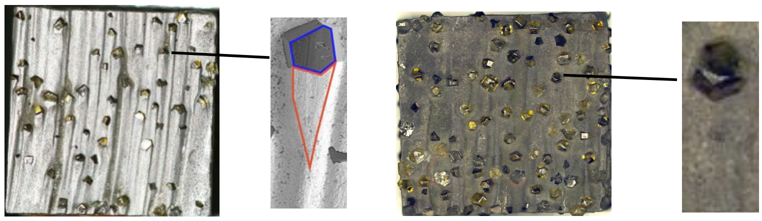

Figure 4: The normal (left) and matrix-removed (right) segments.

The pure cutting process and diamond/rock friction contact are studied by tests conducted in American Black granite with a matrix-removed segment at two diamond wear states, see Fig.5. The results show that the slope and extent of regime I change with the diamond bluntness level, whilst the responses in regime II have identical slopes. It suggests that the friction mobilised across the diamond/rock interface grows with depth of cut in regime I until it reaches a plateau at the onset of regime II. As both responses have identical slopes in regime II, it is argued that regime II is not affected by the diamond/rock friction contact.

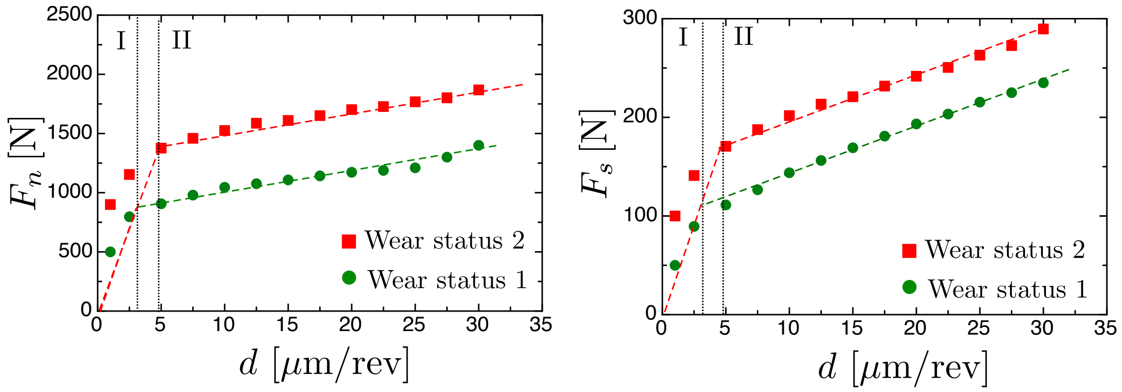


Figure 5: The stationary responses of a matrix-removed segment (35/45 mesh, soft matrix and 20% concentration) at two wear statuses conducted in Harcourt Granite.

The matrix/rock friction contact is isolated by comparing instantaneous responses performed with normal and matrix-removed segments, considering identical diamond size and concentration, see Fig.6. The responses have different slopes in regime II, suggesting that the matrix/rock friction contact progressively increases with depth of cut. As the slope in regime II for normal segment is almost twice the slope for matrix-removed segment, it suggests that the contribution of friction force mobilised at the matrix bearing surface is in the same order of pure cutting force.

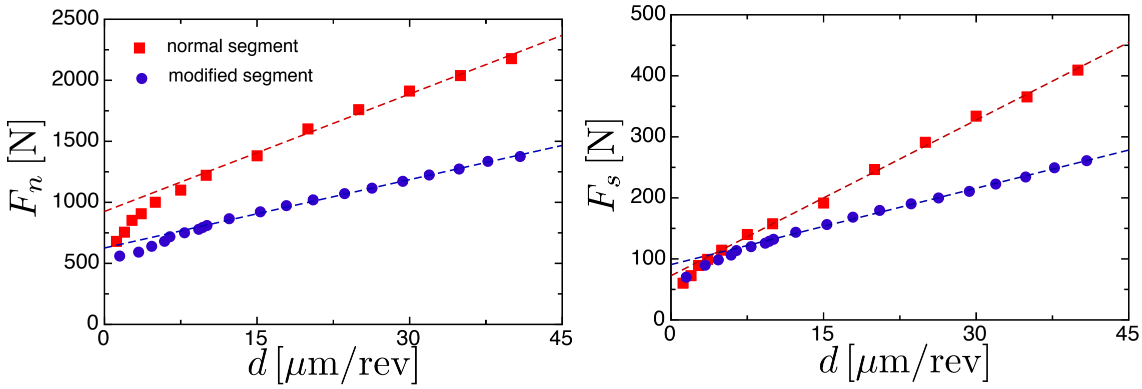


Figure 6: The stationary responses of a matrix-removed segment (35/45 mesh, soft matrix and 20% concentration) at two wear statuses conducted in American Black Granite.

Based on previous experimental results, the characteristics of each cutting regime can be determined. In the first regime, the reactive forces of all processes increase with depth of cut, however, the response is governed by the diamond/rock friction contact. After a critical depth of cut, the diamond/rock friction contact is fully mobilised, which corresponds to the beginning of regime II. The response within this regime is invariant to the diamond wear status and controlled by rock fragmentation and matrix/rock contact. It can be speculated that the intercept of the linear fit of regime II with the force axis (where $d \to 0$) corresponds to the fully mobilised friction force at the diamond/rock interface, i.e. represents the bluntness level of the segment. At higher depths of cut corresponding to regime III, additional friction occurs at the matrix/rock contact due to the decrease of clearance between the matrix and rock surface. Thus, this critical depth of cut varies with the diamond size and protrusion. In regime III, the segment is subjected to frequent change in the cutting face and high wear rates.

## 5 CONCLUSION

In this paper, a rigorous experimental investigation is conducted to measure the instantaneous or wear invariant response of impregnated diamond segments. A state of the art drilling rig is used to precisely measure the cutting responses under various operating conditions. The instantaneous response is presented in depth of cut-force space and characterised by three linear cutting regimes. Particular experiments are then conducted to determine the dominant processes taking place at the segment/rock interface. It is stated that regime I is predominantly governed by the frictional contact occurring at the diamond wear flat/rock contact, whilst regime II is dominated by the pure cutting and matrix/rock friction. After a threshold of depth of cut, the clearance at the matrix/rock body contact decreases to such a level that an additional friction occurs, corresponding to regime III.

## 6 ACKNOWLEDGEMENT

The work has been supported by the Deep Exploration Technologies Cooperative Research Centre. Authors wish to thank Luis Mariano, Amirali Soroush, Stephen Banks, and Gregory

Lupton for their assistance in the equipment design and collection of data.

**REFERENCES**

[1] L. F. P. Franca and E. Lamine, Cutting action of impregnated diamond segments: Modelling and experimental validation. *44th US Rock Mechanics Symposium and 5th U.S.-Canada Rock Mechanics Symposium*, **ARMA 10-439**, 2010.

[2] E. Detournay and P. Defourny, A phenomenological model for the drilling action of drag bits. *International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts*, **29(1)**, 13–23, 1992.

[3] E. Detournay, T. Richard and M. Shepherd, Drilling response of drag bits: Theory and experiment. *International Journal of Rock Mechanics and Mining Sciences*, **45(8)**, 1347–1360, 2008.

[4] L. F. P. Franca, Drilling action of roller-cone bits: Modelling and experimental validation. *ASME Journal of Energy Resources Technology*, **132(4)**, 2010.

[5] C. Fairhurst, W. D. Lacabanne, Hard rock drilling techniques. *Mine and Quarry Engineering*, **23**, 157–161, 1957.

[6] S. Malkin and N. H. Cook, The wear of grinding wheels Part2 - Fracture wear. *ASME Journal of Engineering for Industry*, **93(4)**, 1129–1133, 1971.