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HABANERO 4, DRILLING RESPONSE OF IMPREGNATED DIAMOND BIT, FIELD MONITORING VS. LABORATORY EXPERIMENTS

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Abstract. *This paper presents the results of an analysis of the drilling performance of impregnated diamond (ID) bits used to drill through deep sandstone and granite formations (3365 to 3760 m depth) while spudding Habanero 4, a geothermal well located in the Cooper Basin, Southern Australia. The analysis of drilling data, supported by the results of laboratory cutting tests carried out on a similar granite, indicate that diamond polishing dominates while drilling the granite section yielding low rate of penetration. Recommendations to improve drilling performance derived from experimental results are proposed in the conclusions.*

1 INTRODUCTION

This paper presents the results of an analysis of drilling data recorded while drilling the 12.25” section of Geodynamics geothermal well, Habanero 4, located in Southern Australia. This vertical section of the well was drilled through sandstones and granite intervals with two impregnated diamond (ID) bits mounted on a turbine. The data consists of standard drilling data such as rate of penetration, bit rotary speed, hook load and torque recorded on the rig floor. The first section of the paper focuses on the pre-processing of these data, and in particular, the methodology to estimate the drilling performance from parameters recorded on surface. The analysis relies on a phenomenological model of the bit-rock interface developed at CSIRO and supported by a wealth of cutting and drilling laboratory experiments with single ID segments and core bits, which is shortly introduced in the second section of the paper. Results of the analysis discussed in the second section indicate that the drilling response in the granite formation is governed by the bit state of wear, in particular, steady wear of the diamonds or diamond polishing (supported by visual inspection of the bit after the run) resulting in low rate of penetration. This is also confirmed by the results of laboratory scratching tests conducted on Riverina granite samples representative of the granite encountered on the field using various ID segments provided by the bit manufacturer. Relying on the model and laboratory observations, recommendations to improve drilling performance (bit design, selection of drilling parameters) are provided in the conclusion.

2 FIELD MONITORING WHILE DRILLING

This section summarises the results of the analysis carried on drilling data recorded while drilling the 12.25” section of Habanero 4, Geodynamics’ geothermal well located in cooper basin, Southern Australia. This vertical section, located between 3365 m and 3760 m deep, was drilled using two impregnated diamond bits mounted on a turbine.

The drilling data consists of standard mud-logging data recorded on surface such as torque, rate of penetration, hook load and rotary speed. A simple and convenient way of monitoring the drilling performance is by tracking the evolution of the specific energy (see Figure 1) that can be viewed as the energy spent to drill a unit volume of rock, defined as

$$E = \frac{2T}{a^2 d}, \tag{1}$$

where T is the torque-on-bit estimated from surface measurements, a is the bit radius and d is the depth of cut per revolution given by

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

where V is the rate of penetration and Ω is the angular velocity of the bit.

To first order, we observe a quite steady specific energy until the bit hits the weathered granite. The interval between 3460 m and 3550 m characterised by an increase of the specific energy is most probably associated to the presence of coal. It is suspected that some borehole instabilities lead breakouts to fall at the bottom of the hole and got wedged and re-grounded between the bit and the borehole wall.

The specific energy drops in the cleaner sandstones of Tirrawarra formation. There is no apparent change in overall performance that stems from the change of BHA and bit occurring at 3570 m. The performance is quite steady while drilling the Merrimelia formation. Overall,

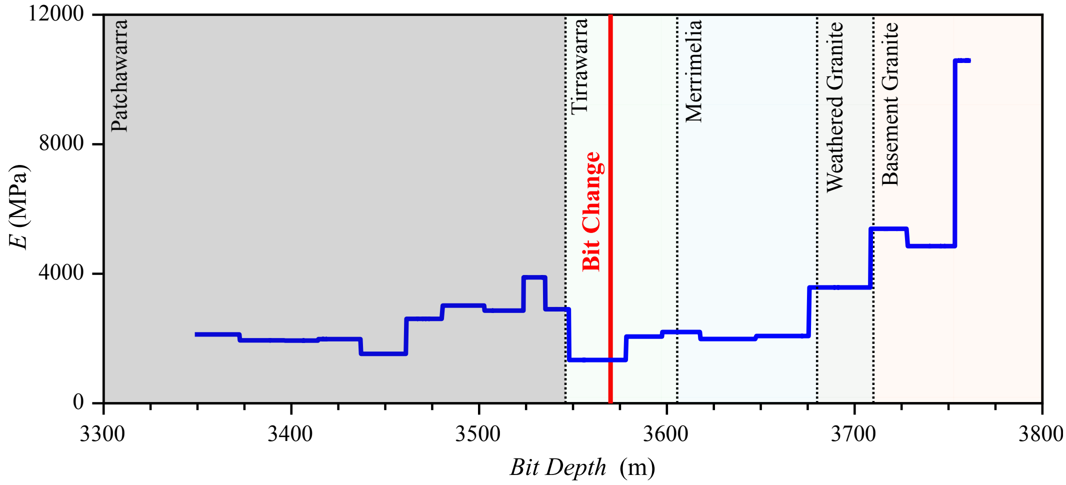

Figure 1: Log of the specific energy with depth for the two impregnated diamond bit runs.

the performance of the impregnated bits in the sedimentary formations is consistent and there is no evidence of bit polishing.

Once the bit enters the granite formation, we observe an abrupt drop in the performance (increase in the specific energy). A more detailed evolution of the specific energy in the granite section is shown in Figure 2. A steady increase of the specific energy is observed within the last 10 meters of drilling.

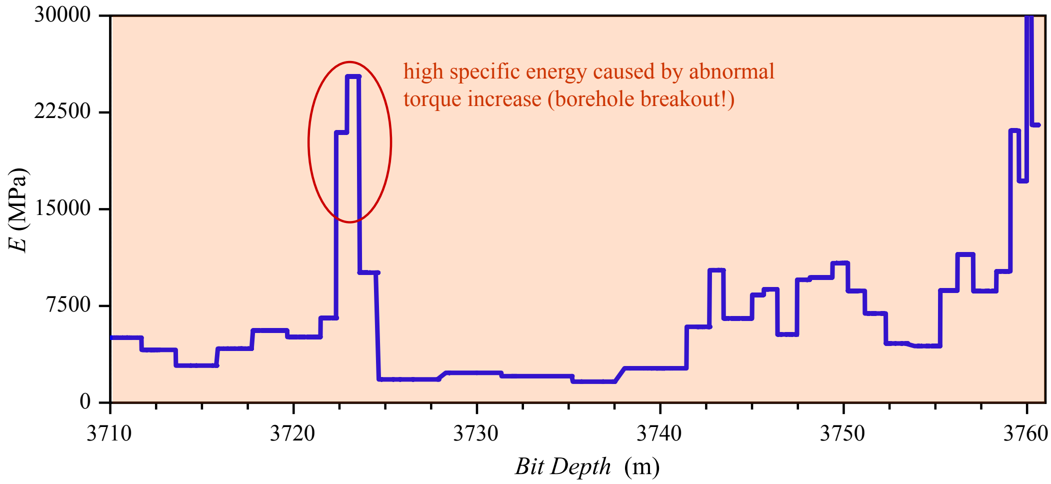

Figure 2: Evolution of specific energy over drilling the basement granite.

In the $E - S$ diagram [1] shown in Figure 3 (where the drilling strength S is defined as $S = \frac{WOB}{a\,d}$), the point representative of the bit response moves away from the origin toward the right up corner of the diagram along the so called friction line that is characterised by slope of about 0.1. Within the framework of the D&D model ([1]), this response is associated with an increase of the bit wear state and more precisely the polishing of the diamonds [3]. This explanation is supported by visual inspection of the bit after the run with clear evidence of diamond polishing, see Figure 3.

Overall, the drilling performance of the ID bit is characterised by very low depth of cut in granite section, with an average depth of cut of about 0.03 mm per revolution, which means

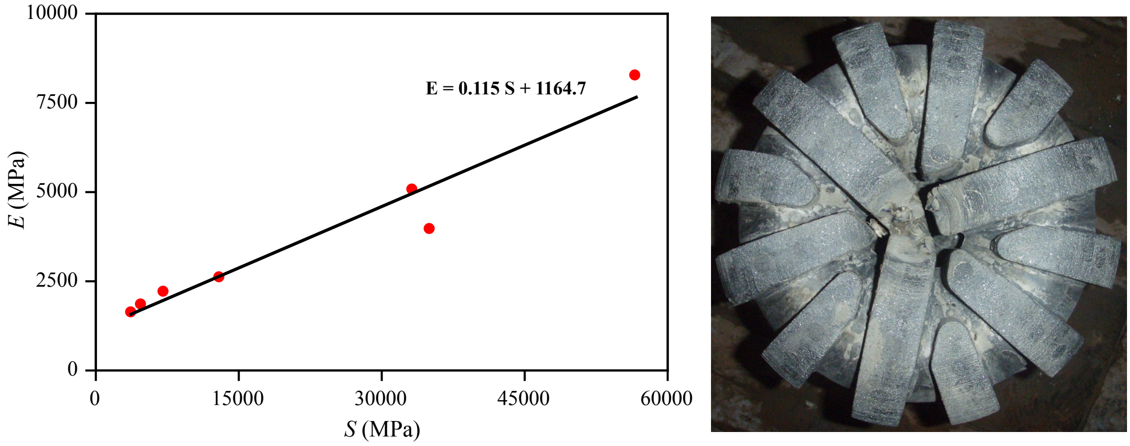

Figure 3: Evolution of the bit response in the $E - S$ diagram between 3750 and 3760 m depth (Left) and picture of the impregnated diamond bit after drilling the granite section (Right).

about 2.5 μm per blade (the bit consists of 12 blades). A wealth of experimental results with impregnated diamond segments and core bits have shown that the cutting/drilling response at such depth of cut is dominated by the diamonds state of wear (wear flats), and is thus very inefficient [3], meaning the incremental response in terms of rate of penetration to increment in weight-on-bit is very small. The shear number of diamonds (the bit consists of 12 thick blades with high diamond concentration) on the bit active surface yields a very large cumulative wear flat area.

3 LABORATORY EXPERIMENTS

This section presents the results of the laboratory experiments conducted on Riverina granite samples representative of the granite encountered on the field. The testing program aims to

- measure and compare the cutting efficiency of each segment or in other words, ability to drill or generate rate of penetration under given wear status, and
- confirm that polishing is the dominant wear process under operating conditions similar to the field, and
- compare the wear rate of each segment under similar operating conditions.

3.1 EXPERIMENTAL SETUP

A modified semi-CNC lathe labelled "Thor", is used to experimentally characterise the cutting response of ID segments, see Figure 4 (a). Cylindrical ID segments are fixed on a cutting assembly as shown in Figure 4 (b) and (c), attached on a load sensor mounted on the cross table of the lathe. The core rock sample is supported by a steel rod, which is fixed at one end in the spindle chuck and simply supported on the tail-stock centre on the other end. The cutting action takes place when the face of 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, see Figure 5.

All tests are conduced under kinematic control, i.e. the rate of penetration (or feed rate) V and angular velocity Ω are imposed, see Figure 5, meaning that the depth of cut per revolution is set constant. Figure 5 shows a schematic of a segment-rock interface, where V [mm/s] is the

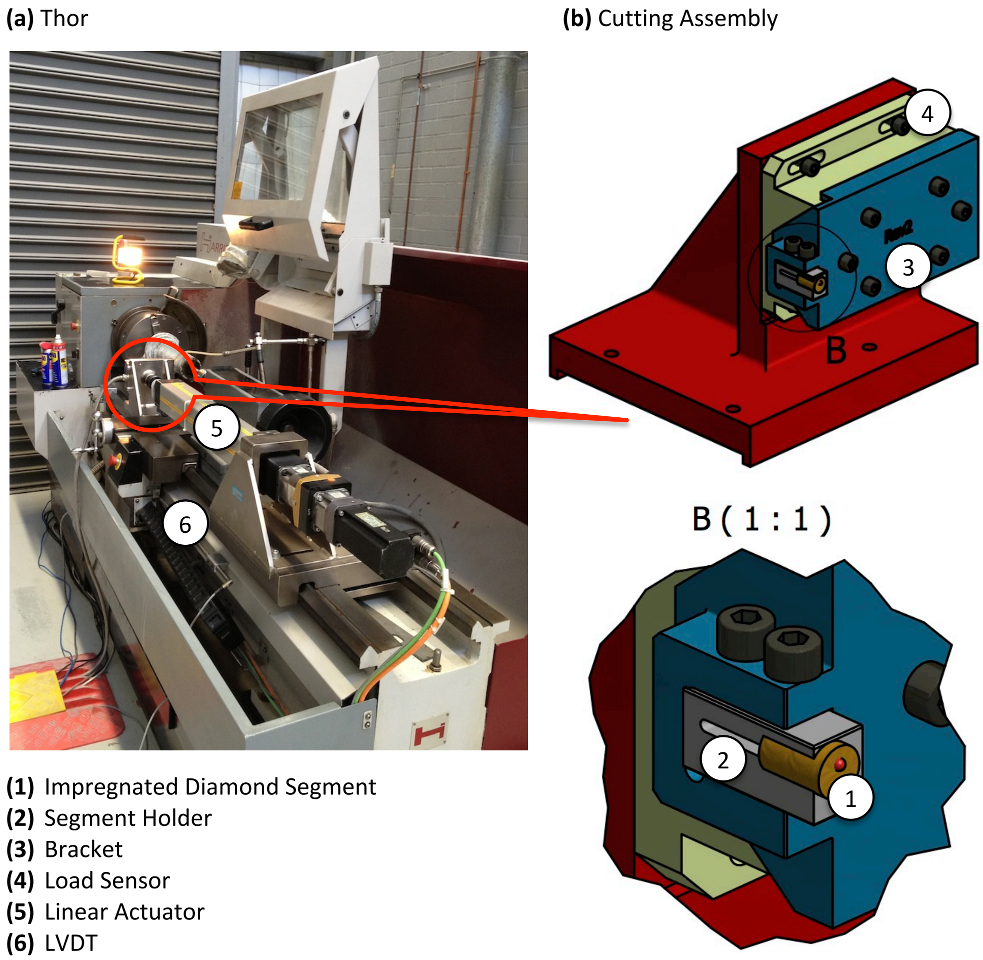

Figure 4: Laboratory cutting rig - *Thor*.

feed velocity imposed on the segment, Ω [rad/s] the sample angular velocity, a radial distance between the rock sample centre line and the tool centre line (or centre point of the contact surface) and F is the force acting on the cutting tool. The force F can be decomposed in two components: normal (F_n) and parallel (F_s) to the rock surface. The relative linear velocity v between the tool and the rock is thus equal to Ωa [m/s]. Note that the interface between the segments and the rock is flushed continuously with water.

The monitoring consists of force and displacement measurements. The three components (F_n, F_s and F_t) of the force F acting on the segment while cutting are measured via a piezo-electric load sensor which is characterised by a very high stiffness. The linear displacement U ($V = \frac{dU}{dt}$) of the segment is measured using an inductive displacement transducer.

3.2 ROCK SAMPLE AND SEGMENTS

One essential constraint for the experimental campaign is to conduct the tests on a rock material that is representative of the granite drilled in the field, for which a detailed mineralogical report on the cutting (from previous geothermal wells drilled nearby) is available. A quarry granite, Riverina, was found to display very similar mineralogy to the granite encountered in the field. As indicated by a simple visual inspection of the rock samples (see Figure 6) and confirmed by the results of a mineralogical analysis, the rock is actually characterised by a very large quartz content known to be a very abrasive material susceptible to cause bit polishing.

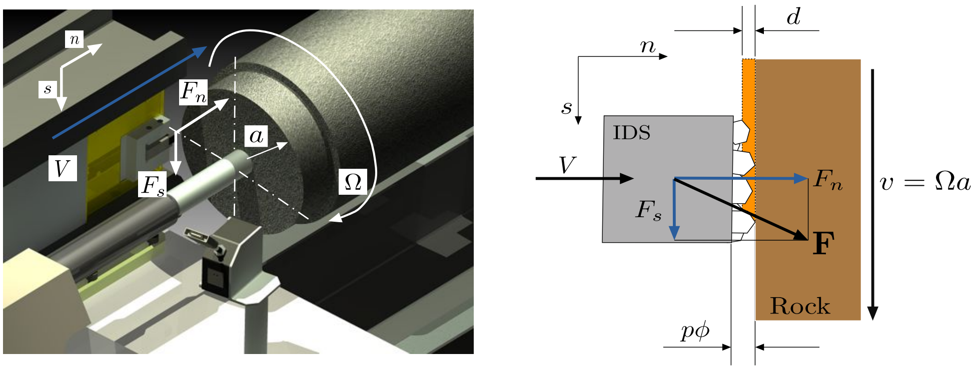

Figure 5: Input parameters (V,Ω) and output parameters (F_n,F_s) (left) and rock cutting process with ID segment (right).

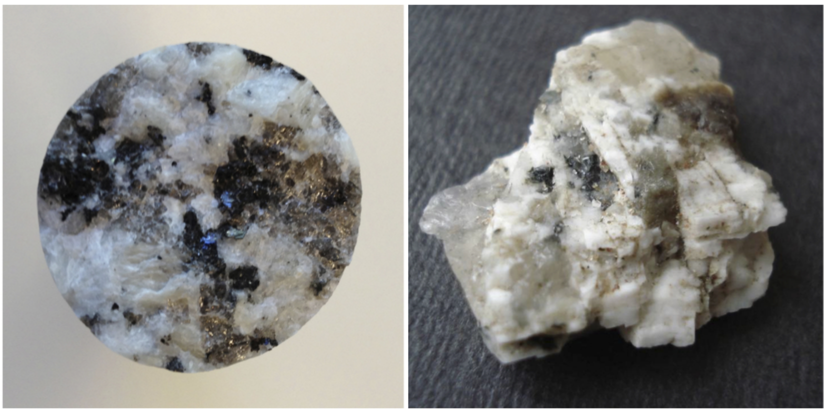

Figure 6: Riverina granite (left) vs. Habanero granite sample (right). High percent of quartz content is observed in both samples.

Four classes of ID segments characterised by hard, medium and soft bonding matrix and different diamond size and concentration were provided by the bit manufacturer for performing laboratory tests. The properties of all the ID segments are summarised in Table 1. Two classes of segments share the same matrix hardness (Segment classes 1 and 2) and were used as studs on the bit used to drill Habanero 4. Segment 3 shares the same recipe with the blade materials while the last class has a soft bonding matrix and is provided for comparison purposes.

Segment Name	**Diamond Size**	**Diamond Concentration**	**Bonding Matrix Hardness**
Segment 1	35/40	100C	Hard
Segment 2	25/35	110C	Hard
Segment 3	35/40	100C	Medium
Segment 4	20/25	85C	Very Soft

Table 1: Specification of different ID segments used for laboratory experiments on Riverina granite.

3.3 EXPERIMENTAL PROCEDURE

Two type of tests have been conducted: (i) tests referred as stationary test to estimate the cutting efficiency of each segment under conditions of constant state of wear and (ii) wear test to estimate the wear rate (polishing regime) of each segment and how it is affected by control parameters.

3.3.1 STATIONARY RESPONSE

Stationary response refers to the cutting response obtained under conditions of negligible wear, negligible in the sense that the effect of the wear rate on the recorded force is negligible when compared to the other effects. In order to capture the cutting response, the depth of cut, d, is varied by steps, and more precisely decreased by stages. Results are considered as representative of a stationary response when the depth of cut, cutting velocity, but also the averaged force components are constant over many revolutions. We commonly rely on 10-20 revolutions to set a representative window, however, when the material is very abrasive (as in the case of the Riverina), it might be necessary to shorten the duration of the test to limit the development of polishing. Each time the depth of cut is increased incrementally, the recorded force rises sharply and stabilises around a plateau (under the condition of very severe polishing, the force does not stabilise and continuously increases). The data processing consists of averaging the force components over a representative section (considered as stationary), the average values (one for each force components) is then plotted against the corresponding depth of cut in a force-depth of cut diagram.

In order to validate the results of a test classified as stationary, the segment is tested twice and only if the response is invariant, are the results labelled representative of a stationary regime.

Results of stationary tests yield a snapshot of the cutting response of a segment, or in other words, the relation between the force and the depth of cut (or equivalently weight-on-bit to rate of penetration) for a given state of wear. Comparing the cutting response of different segments provides a relative measure of their cutting efficiencies or in another word the ability of a segment to generate depth of cut or rate of penetration.

When comparing the stationary response of different segments, the essential parameter is the slope in regime II that controls the incremental response of the segment, meaning the increment in depth of cut associated to a given increment in normal force [2, 3]. Therefore, in the sequel, the stationary responses are plotted in terms of the incremental response in regime II.

3.3.2 NON-STATIONARY RESPONSE OR WEAR TEST

The second series of tests consist in cutting under fixed depth of cut and linear velocity and allowing the tool to wear over time. The test is stopped once a given volume of rock has been removed. In this study, we are in particular, interested in the wear occurring at very shallow depth of cut (representative of the field conditions) but also would like to explore the wear process at higher depth of cut. It is commonly accepted that diamonds polish at shallow depth of cut with the amplitude of the force acting on the tool increasing, while they tend to fragment at larger depth of cut.

With the test being conducted under constant depth of cut, variations in the recording of the force components are analysed in order to identify the wear mode and its severity (related to the rate of growth of the recorded force). As the coefficients of friction associated to diamond wear flat-rock interface and the matrix-rock interface are quite different, relative variation between the normal and tangential components of the cutting force as the segment wears out indicates if the wear is governed by an increase of diamond-rock contact or matrix-rock contact.

3.4 RATIONALE FOR THE SELECTION OF OPERATING PARAMETERS

The two operating parameters are the depth of cut per revolution d and the cutting linear velocity v. The objective is to cover a range of parameters representative of the parameters encountered on the field.

While drilling the granite section on the field, the depth of cut (for the entire bit) varies between 20 and 80 microns (0.35 m/hr and 2.5 m/hr at 600 RPM). On a new bit, cutting is performed by the studs which are located on the bit face such that between 5 to 12 segments are located at the same distance from the bit centre (and thus have overlapping trajectory). This means that the depth of cut per segment varies between about 1.5 microns and 13.5 microns.

In order to build a more complete snapshot of the cutting response, stationary tests were actually carried out over a wider range of depth of cut from 2 to 50 microns. In particular, it is of interest to run tests at larger depth of cut as one of the practical objective is to reach larger depth of cut and thus rate of penetration on the field. The wear tests were run at three different depth of cuts; 2.5 and 10 microns (representative of field conditions) at which diamond polishing is dominated. We therefore also explore higher depth of cut of 20 microns with the hope of triggering self-sharpening.

The tests have been conducted at a linear velocity of 3 m/s (representative of the linear velocity of a segment located at about 50 mm from the bit centre on a bit rotating at 600 RPM).

3.5 SUMMARY OF RESULTS

The results of stationary tests carried out with all segment types (except Segment 3) on Riverina granite along with the slope associated to each response (drilling strength, s) are shown in Figure 7. The results for each segment correspond to the average of all the results obtained under the same depth of cut and linear velocity (3 m/s). The results confirm that the matrix hardness affects the intrinsic cutting response with softer matrix yielding higher cutting efficiency (aggressiveness). The results also show that larger diamond exhibits higher efficiency as the slope is smaller. Pictures of the segments after the cutting tests have been performed are shown in Figure 8.

However, tests performed with Segments 3 were considered not conclusive as sharpening tests yield very shallow diamond exposure (see Figure 8), very high force and numerous sparks, although the matrix hardness is referred as medium. These results stress that considering only matrix hardness is probably not sufficient to predict the erosion-abrasion of the matrix. Finally, it is important to stress that this type of segment was the based material for the blade of the bit used on the field, which could partly explained the results obtained on the field.

Wear tests were conducted under constant depth of cut and linear velocity until a given volume rock has been cut away. Four tests were carried out successively with the same segment for depth of cut of 20, 10, 2.5, and 20 microns. The results displayed in Figure 9 show the incremental variation of the normal force F_n (scaled by the effective width of cutting) as a function of the volume of rock removed. Visual observation of the segment before and after the test indicates that overall wear is limited to diamond wear (polishing and fracturing) and no self-sharpening taking place during these tests.

Overall and regardless of the segment type, the results show that diamond polishing is dominant at shallow depth of cut (2.5 and 10 microns depth of cut) which is confirmed by visual observations of the segments after the test. Steady polishing results in a steady increase of the overall diamond wear flat area which in turn results in a steady increase of the cutting force (under conditions of imposed depth of cut). We also observe that the rate of growth of the force

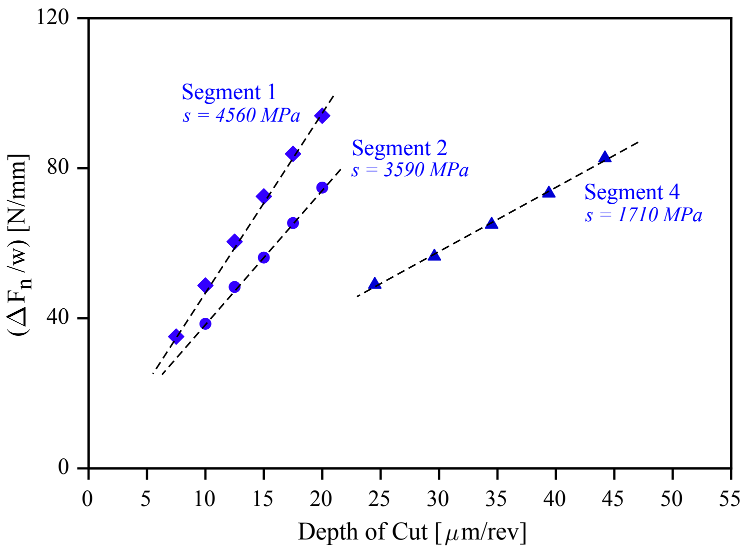

Figure 7: Stationary response of ID segments (incremental response in regime II) for tests carried out on Riverina granite with linear velocity of 3 m/s. The measured normal force is scaled by the effective cutting width for comparison purposes. Detail specification of each segment is provided in Table. 1.

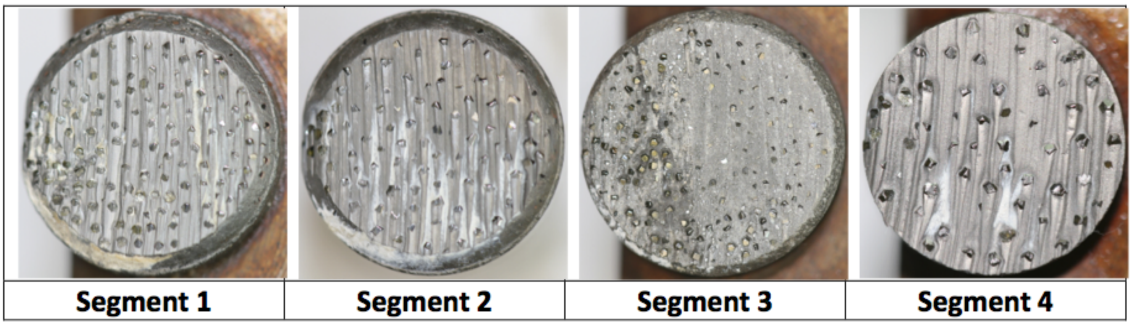

Figure 8: ID segments after the tests.

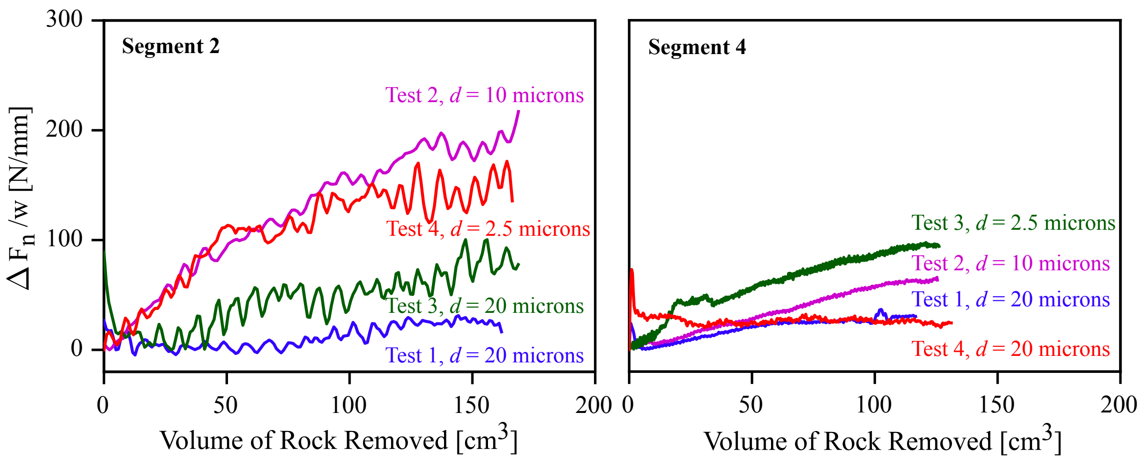

Figure 9: Variation of the normal force increment, ΔF_n, with the volume of the rock removed during wear test conducted with Segments 2 and 4 at $v = 3$ m/s and different depth of cuts. The measured normal force is scaled by the effective cutting width for comparison purposes.

with time decreases (the force signal tends to flatten), one could argue that the force reaches eventually a plateau corresponding to the maximum total wear flat area that can be achieved with the exposed diamonds. Bit polishing corresponds to a state of maximum wear flat area (with diamonds flushed with the matrix), in that instance, the evolution of the segment topology and thus cutting response will be governed by the ability to erode or abrade the matrix away to sharpen the bit.

Tests carried out at larger depth of cut (20 microns) produce a force signal that can be regarded as stationary (or at least characterised by a much slower polishing rate) suggesting the occurrence of diamond fracturing. As a diamond fractures, its wear flat area reduces which in turn reduces the force acting on the diamond. At larger depth of cuts, the occurrence of diamond fracturing (probably promoted by the larger cutting force) compensates the effect of diamond polishing on the cutting response.

Although the wear response is quite similar between the tested segments, we observe some differences in the wear rate, with some evidence that segment with softer matrix yield smaller polishing rate. However, these results must be taken with caution as there is also evidence that the initial state of wear, diamond exposure and diamond size do affect the polishing rate.

4 CONCLUSIONS

Cutting experiments were carried out with different segments provided by the bit manufacturer on core samples of Riverina granite similar to the granite encountered on the field and characterised by very high quartz content. The main conclusions of the analysis of the experimental results are summarised below:

- The matrix properties have a non-negligible effect on the cutting efficiency or "aggressiveness", meaning the ability to generate depth of cut or rate of penetration under a given weight-on-bit.
- The very high quartz content of the Riverina granite combined with very shallow depth of cut (below 5 microns per segment) strongly promotes the occurrence of diamond polishing which in turn affects the cutting efficiency (aggressiveness) of the segments.
- Sharpening of diamond (via fracturing) requires much larger depth of cut, of the order of 20 microns per segment (equivalent to a rate of penetration of about 6 m/hr considering the current bit design).
- Although labelled as segment with a medium hardness matrix, segment used in the manufacturing of the bit blade has proven very difficult to sharpen, such that both stationary and wear test could not be carried out within the mechanical constraint of the testing equipment.

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