Interaction Effect of Depth of Cut, Back Rake Angle and Rock Properties on Temperature of Single Polycrystalline Diamond Compact Cutter

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ABSTRACT

The single polycrystalline diamond compact (PDC) cutter’s performance is affected by temperature during rock cutting process. The study towards understanding the factors and its interaction affecting the cutter’s temperature is essential prior to cutting process optimization. Thus, this study aims to investigate the effect of various cutting parameters and its interaction on the temperature of a single PDC cutter. A series of test was conducted in a lathe machine which utilized facing operation to cut the rock samples at 0.5 to 1.5 mm depth of cut and back rake angle of 5° to 15°. Two types of rock being tested in this study were Indiana limestone and Carthage marble. The analysis of variance (ANOVA) output indicated that cutting parameters and rock properties and its interaction have a significant effect on cutter’s temperature except for interaction between back rake angle and rock properties. Increasing the depth of cut and decreasing back rake angle has resulted in increasing temperature. The temperature of the single PDC cutter is higher when cutting Carthage marble than Indiana limestone. Combination of low back rake angle and high depth of cut producing maximum temperature. It is also validated that the data developed from the mathematical model having a difference of 5% as compared to the experimental data obtained using similar parameters which indicates that the results are reliable and can be forwarded in the future study.

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NOMENCLATURE

| Symbol | Description |
|--------|-------------|
| mD     | Milidarcy   |
| MPa    | Megapascal  |
| mm     | Millimetre  |
| °C     | Degree Celcius |

1. INTRODUCTION

Polycrystalline diamond compact (PDC) cutter brazing onto the PDC’s bit and cut the rock formation during a drilling operation in the oil and gas industry. Rate of penetration, weight on bit and torque are the parameters that were controlled and affecting the bit’s performance [1]. On the other hand, the depth of cut, back rake angle, cutting speed and spindle rate are the parameters affecting the performance of single PDC cutter that directly correlates with PDC bit. It has been proven that the rock cutting theories produced in single PDC cutter study which was verified through analytical and numerical models applied in industry and improved the drilling operation [2]. The temperature which is one of the uncontrolled factors affecting the bit’s performance suggested to be considered when conducting a single PDC cutter study, respectively.

The generated temperature at the cutter-rock interface during rock cutting affecting the cutting performance of a single PDC cutter [3, 4]. Various studies have been conducted by researchers to investigate the relationship

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between rock cutting process with rock properties discussed in literature [5-9]; but, did not evaluate the temperature response. Meanwhile, studies to evaluate the effect of various cutting parameters on temperature have been conducted using experimental work and simulation analysis [2-4]. However, one can find that the data obtained from the experiment are more accurate as compared to the calculated temperature from the simulation [4]. The inaccuracy of the results happened due to simplification of calculation solution which is unacceptable in the complicated circumstance in the ‘real’ rock cutting. Thus, it is essential to employ the best temperature measuring technique in order to improve the accuracy and reliability of the temperature measurement in the experiment [2].

During rock cutting, the temperature of single PDC cutter was measured using thermocouple due to the principle of the Seebeck where dissimilar metals such as copper and iron are connected between one end to the other [10]. The wire is connected from thermocouple to the signal conditioning circuitry. The voltage is produced when the area between the measurement and reference junction is heated [11]. The magnitude of the produced voltage indicates the difference between the temperature at the junction with the thermocouple connectors and the data logged in the computer software [12].

Che et al. [3] used a thermocouple technique to measure the temperature of a single PDC cutter by placing the thermocouple at five locations on the PDC cutter surface to increase the accuracy of the measurement. The same technique is also used by Wilson and Vorono [13]. Both studies [3, 13] agreed that the temperature was the highest when the thermocouple is positioned at the edge of the PDC cutter (the interface area between cutter and rock). These findings proved that the heat was mainly generated at the cutter rock interface and suggested to be the area of measurement for this study. However, these studies did not include the effect of a parameter such as rock properties on the temperature response of a single PDC cutter.

In the previous literature [13-16] depth of cut, back rake angle and rock properties are reported to have a significant effect on single PDC cutter performance such as cutting force and mechanical specific energy. However, the effect of these parameters on temperature is not much explored. Thus, it is the objective of this study to evaluate the effect of various cutting parameters on the temperature of single PDC cutter during rock cutting process.

This article is organized as follows: Section 2 described the materials; rock sample and cutter, experimental setup and design of experiment used in this study. Section 3 portrayed the obtained result and analysis of temperature mechanism in single PDC cutter test, analysis of variance, the effect of various cutting parameters on temperature and validation of the mathematical model, followed by brief conclusion drawn in section 4.

2. MATERIALS AND METHODS

2.1. Research Methodology Figure 1 shows the flowchart of this study which is divided into three sections. The first section involves the development of experimental setup and the selection of the materials consist of PDC cutters and rock samples; Carthage marble and Indiana limestone, and cutting parameters consist of depth of cut, back rake angle and rock properties based on comprehensive literature review.

The second section includes the application of design of experiment in lathe rock cutting to obtain the temperature responses. The final section involves the analysis of the interaction effect between cutting parameters on temperature. Finally, the mathematical models obtained from an ANOVA output were validated. The experimental result was compared to the predicted result from the obtained mathematical model.

Figure 1. Research flowchart
2. 2. Materials
In this experiment, Indiana limestone and Carthage marble of cylindrical shape with 101.6 mm diameter and height are used as rock samples as shown in Figure 2. The samples provided by Kocurek Industries Inc. with physical properties given in Table 1. The selection of these rocks based on distinguished strength and hardness and expected to be one of the factors affecting the temperature of single PDC cutter. The hardness of these rocks is classified by Wang et al. [17] where Indiana limestone and Carthage marble are fairly hard and hard rock, respectively.

PDC cutters used in this study were manufactured by Glynn Technical Diamonds had a dimension of 13.4 mm diameter and 8.0 mm height as shown in Figure 3. The single PDC cutter built by 6 mm thick carbide substrate and 2 mm thick diamond (chamfered at 45° chamfered with 0.6 mm length).

2. 3. Experimental Setup
Figure 4 shows the single PDC cutter test conducted using electronic centre lathe 2-axis by Harrison A400 Alpha having 7.5 kW spindle and a maximum spindle speed of 2500 rpm.

In this study, the temperature of the PDC cutter is measured using K-type thermocouple which connected to DAQ system instruments consist of DEWESoft®

![Figure 2](image2.png)

**Figure 2.** One of the rock samples for Indiana limestone (left) and Carthage marble (right) used in rock cutting experiment

![Figure 3](image3.png)

**Figure 3.** Single polycrystalline diamond compact (PDC) cutter

![Figure 4](image4.png)

**Figure 4.** Schematic diagram of temperature measurement

KRYPTONi-8xTH multichannel charge amplifier and DEWESoft® X2 software. This thermocouple can measure a range of temperature between -200°C to 1372°C. The measurement of PDC cutter temperature started when the thermocouple heated during the cutting process. Then, the thermocouple sends the signal to the amplifier to be processed by setting the maximum sampling rate, 100 Hz, to produce more temperature data points. Thus, the higher accuracy of temperature measurement can be obtained. The software is used to visualize the temperature reading in time (s) vs temperature (°C) graph.

2. 4. Design of Experiment
Design of experiment has been numerously utilized by researchers to study the significant effect of parameters on interest response output as discussed in literature [18-21]. Analysis tool such as ANOVA is beneficial to validate the adequacy of the mathematical model and the corresponding significance of each tested parameters under the assumption of 95% confidence [22]. In this study, the two-level factorial design was employed to study the significant effect of depth of cut, back rake angle and rock properties while setting the temperature of PDC cutter as a response. The parameters design and range of depth of cut, back rake angle and rock properties are summarized in Table 2.

Other parameters such as spindle speed and feed rate were kept constant at 750 rpm and 0.15 mm/rev, respectively. It should be notable that the constant
surfaces speed mode is not applied in this facing operation due to the limitation of the lathe machine. The constant surface speed mode is used to ensure constant cutting speed throughout the cutting process. When it is not applied, the cutting speed is changing during the rock cutting process as the diameter of the rock sample being cut is reduced, which can be proved by using cutting speed formula as shown in Equation (1). This is in agreement with a similar finding reported by Che et al. [3].

\[
V_c = \frac{\pi D n}{1000}
\]  

(1)

Where \( V_c \) represents the cutting speed (m/min), \( D \) represents the diameter of the rock sample (mm) and \( n \) represent spindle speed (rev/min).

These selected ranges of parameters are made by considering of comprehensive literature of previous study [13-16]. Thus, the lower range depth of cut and back rake angle is selected. Design expert software is used to develop the design of the experiment of this study.

### 3. RESULTS AND DISCUSSION

A set of single PDC cutter test was performed at low depth of cut and back rake angle by cutting different rock properties consist of Indiana limestone and Carthage marble rock samples. The set of tests were randomized and repeated thrice in order to perform a significance test, increase the sensitivity of the statistical test, and ensure the independence of experimental errors [23]. Overall, there were 24 sets of runs to complete the matrix and the suggested combinations of the run, as well as the temperature result, is portrayed in Table 3.

This section starts with the discussion on mechanism of temperature during this rock cutting experiment. After all the results are obtained, ANOVA approach is used to evaluate the relation effects between factors on temperature [14]. It is also used to obtain mathematical models in predicting the response [24]. Then, the interaction effect between depth of cut, back rake angle and rock properties on temperature are analyzed. Supplementary rock cutting experiment was performed to validate predicted models and discussed in section 3.4.

![Figure 5. Temperature (°C) vs Time (s) graph captured from DEWESoft® X2 software](image_url)
TABLE 3. Temperature result of design parameters applied in single PDC cutter test

| Run | Depth of Cut (mm), A | Back Rake Angle (°), B | Rock Properties, C | Temperature (°C) |
|-----|---------------------|------------------------|-------------------|------------------|
| 1   | 1.5                 | 5                      | Carthage marble   | 214.68           |
| 2   | 1.5                 | 5                      | Carthage marble   | 209.91           |
| 3   | 0.5                 | 15                     | Carthage marble   | 121.02           |
| 4   | 0.5                 | 15                     | Indiana limestone | 66.96            |
| 5   | 0.5                 | 5                      | Carthage marble   | 130.21           |
| 6   | 1.5                 | 15                     | Indiana limestone | 100.86           |
| 7   | 0.5                 | 5                      | Indiana limestone | 94.19            |
| 8   | 0.5                 | 15                     | Indiana limestone | 69.58            |
| 9   | 1.5                 | 15                     | Carthage marble   | 179.38           |
| 10  | 1.5                 | 5                      | Indiana limestone | 120.75           |
| 11  | 1.5                 | 5                      | Carthage marble   | 205.66           |
| 12  | 0.5                 | 5                      | Carthage marble   | 131.52           |
| 13  | 0.5                 | 5                      | Indiana limestone | 92.04            |
| 14  | 1.5                 | 5                      | Indiana limestone | 118.98           |
| 15  | 0.5                 | 5                      | Carthage marble   | 135.91           |
| 16  | 0.5                 | 15                     | Carthage marble   | 124.63           |
| 17  | 1.5                 | 15                     | Indiana limestone | 105.88           |
| 18  | 1.5                 | 15                     | Carthage marble   | 180.29           |
| 19  | 1.5                 | 15                     | Indiana limestone | 100.13           |
| 20  | 0.5                 | 15                     | Carthage marble   | 125.38           |
| 21  | 0.5                 | 15                     | Indiana limestone | 62.83            |
| 22  | 1.5                 | 5                      | Indiana limestone | 119.52           |
| 23  | 0.5                 | 5                      | Indiana limestone | 80.53            |
| 24  | 1.5                 | 15                     | Carthage marble   | 178.28           |

cool down until it returns to the ambient temperature. The result obtained agreed with previous work carried out by [3] where the temperature tends to decrease at the end of the cutting process as the interaction between cutter and rock decrease.

3.2. Statistical Analysis

ANOVA is used to analyze the interaction and significant effect between depth of cut, back rake angle and rock properties on temperature. Table 4 shows the ANOVA for temperature response. In ANOVA, factors with Prob > F less than 0.05 and large F-value are considered significant [25, 26].

Based on Table 4, Factors A, B, C, AB, AC and ABC are significant as Prob > F is 0.0001 while factors BC is insignificant because Prob > F is 0.9845. This means that only the interaction between back rake angle and rock properties did not have a significant effect on temperature.

Based on F value, the significance of the sequence of parameters and their interaction effects on the temperature response can be conveyed as: C > A > B > AC > AB > ABC > BC. Combining the interaction between factors and evaluating the effect of the interaction on temperature is considered more reliable as compared to the previous experiment [3, 13] that conducted using one factor at a time.

The model highly fitted the data and validated as the adjusted R-squared is 0.9931. The model of this study is considered acceptable when the adjusted R-squared value is approaching 1 [27]. The mathematical models for temperature response also have been obtained with a 95% confidence level. The linear regression expressions are the output of ANOVA and presented in Equations (2) and (3). This equation illustrates that the interaction between cutting parameters has a critical impact on the determination of temperature in a single PDC cutter experiment [28].
TABLE 4. ANOVA for temperature response of single PDC cutter test

| Source | Sum of Squares | DF | Mean Square | F Value | Prob > F |
|--------|----------------|----|-------------|---------|----------|
| Model  | 46370.9        | 7  | 6624.41     | 475.47  | < 0.0001 |
| A      | 14951          | 1  | 14951       | 1073.12 | < 0.0001 |
| B      | 2363.74        | 1  | 2363.74     | 169.659 | < 0.0001 |
| C      | 27009.1        | 1  | 27009.1     | 1938.59 | < 0.0001 |
| AB     | 104.918        | 1  | 104.918     | 7.53055 | 0.0144   |
| AC     | 1667.33        | 1  | 1667.33     | 119.674 | < 0.0001 |
| BC     | 0.0054         | 1  | 0.0054      | 0.00039 | 0.9845   |
| ABC    | 274.727        | 1  | 274.727     | 19.7187 | 0.0004   |
| Pure Error | 222.917 | 16 | 13.9323 |
| Cor Total | 46593.8 | 23 |       |

\[ T_{cm} = 92.7392 + 88.4850A + 0.2078B - 2.1897AB \quad (2) \]

\[ T_{il} = 86.1125 + 28.0783A - 2.5048B + 0.5170AB \quad (3) \]

Where \( T_{cm} \) and \( T_{il} \) represent the temperature (°C) for Carthage marble and Indiana limestone, respectively while A is depth of cut (mm) and B is back rake angle (°).

3.3 Effect of Cutting Parameters and Rock Properties on Temperature

Figures 6 and 7 shows the interaction effect between the back rake angle and depth of cut on temperature. Interaction effect of depth of cut on temperature is not included in other single PDC cutter studies as they used a constant depth of cut [3, 13]. It can be observed that temperature increased when the depth of cut increase from 0.5 to 1.5 mm. Based on Figure 6, a steep increase in temperature is observed using 5° and 15° back rake angle with increasing depth of cut. A similar trend was found in Figure 7.

The higher the depth of cut, the larger the contact length between the PDC cutter and the rock sample as illustrated in Figure 8. Larger contact length leads to a larger contact area between cutter-rock resulted in higher friction and increasing temperature. Energy consumption to break a fragile material is commensurate with the amount of new surface created [11]. Thus, at 1.5 mm depth of cut, more volume of rock is needed to be cut as compared to 0.5 mm depth of cut. The temperature increase as the depth of cut increase due to the increasing cross-sectional area of cut and generate more frictional heat [11]. Similar finding can be found in a study conducted by Rajabov et al. [15] where mechanical specific energy is analysed. As the depth of cut increase, the area of cut increased and put higher stresses on a PDC cutter. This significantly affects the temperature response by generating more heat at a cutter-rock interaction area of a single PDC cutter. It should be mentioned that high correlation of force to the temperature was observed in a study conducted by Wilson and Vorono [13]. Thus, the changes in magnitude of cutting force is directly proportional to the temperature changes.
The cutting condition of 0.5 mm and 1.5 mm depth of cut are presented in Figure 8. The interaction effect between the depth of cut and rock properties are presented in Figures 9 and 10. The temperature increases sharply when cutting Carthage marble and Indiana limestone with increasing depth of cut. It is also observed that temperature is higher when cutting Carthage marble as compared to Indiana limestone. Classified as very hard rock based on unconfined compressive strength (Table 1), the higher cutting force required to cut Carthage marble and possibly generate more heat which resulted in higher temperature as compared to cutting Indiana limestone, respectively.

On the other hand, Rajabov et al. [15] and Cheng et al. [29] suggested that the analysis of rock cutting cannot depend solely on the UCS of the rock and must also support with the analysis on the sedimentology of rock including rock type and its formation characteristic. Hence, the formation characteristic of Carthage marble and Indiana limestone were identified.

Carthage marble originated from a metamorphic type of rock which is formed through the alteration of existing rocks at the same environment of high pressure and temperature [15, 29]. This condition produced homogeneous behaviour where grains are well cemented and interaction forces between these grains are very high. Hence, the rock becomes harder and required a larger force and induce more heat to cut through this rock.

Meanwhile, Indiana limestone created from a sedimentary type of rock formed by deposition of materials in different environments over hundreds of years [30]. This condition leads to heterogeneous behaviour of this rock where it had poor cementation between grains. Therefore, the temperature generated in cutting this rock is much lower than Carthage marble.

The interaction effect between the back rake angle and rock properties are portrayed in Figures 11 and 12. The temperature trend in these figures indicates an inverse relationship between temperature and back rake angle. But hardly any changes of temperature are observed when cutting Carthage marble and Indiana limestone with increasing back rake angle. This is possibly due to the use of a low range of back rake angle. The results show in agreement with ANOVA output of Prob>F is higher than 0.05 where interaction between rock properties and back rake angle has no significant effect on temperature.

This is possibly due to the action of frictional impact between the rock and the cutter’s rake face. Increment of back rake angle leads to the decrease of force component tangent to the rake face [31]. In addition, a study conducted by Akbari et al. [32] also indicates that at...
low back rake angle, the friction between cutter and rock is higher than cutting at high back rake angle. These findings explain the higher cutting force at lower back rake angle.

In general, Figures 6-12 show that the result is more reliable when the interaction between factors are included in the study. For example, increasing depth of cut is obvious on temperature changes when using 5° back rake angle as compared to 15° back rake angle. This result is in agreement with Akbari et al. [32] where at low back rake angle, the friction between cutter and rock is higher than cutting at high back rake angle. Meanwhile, larger depth of cut causes the cutter to cut more cutting surface area as compared to the low depth of cut [15, 33]. Combination of the high depth of cut and low back rake angle causes the cutter’s edge to cut the rock in the larger cutting area and higher friction.

3.4. Validation of Predicted Temperature Model
The predicted values for temperature using 1.0 mm depth of cut and 10° back rake angle for Carthage marble and Indiana limestone was calculated using the linear model through Equations (2) and (3). Experimental results for Carthage marble and Indiana limestone cutting are compared with the predicted results and shown in Figures 13 to Figure 16.

It was observed that the experimental and predicted results are overlapping each other with 5% error bars and indicate the accuracy of the linear models [34]. The linear models predict the temperature of single PDC cutter with a high degree of accuracy. From these results, it can be deemed that the proposed linear model can be applied to predict the temperature of a single PDC cutter in cutting Carthage marble and Indiana limestone at low depth of cut between 0.5 to 1.5 mm and low back rake angle between 5 to 15°.

Figure 17 has portrayed the experimental data obtained in this study to show the interaction effects between depth of cut, back rake angle and rock properties on temperature. The graphs show that the temperature increased linearly with increasing depth of cut which was in agreement with Shao et al. [11]. It was also concluded...
Figure 16. The experimental and predicted temperature values at constant 10° back rake angle in Indiana limestone cutting

Figure 17. The comparison of all experimental interaction effects between depth of cut, back rake angle and rock properties on temperature

that the temperature exhibit by Carthage marble cutting is much higher than Indiana limestone due to different properties of Carthage marble and Indiana limestone [11, 15].

4. CONCLUSION

The rock cutting experiment was successfully conducted to evaluate the effect of back rake angle, depth of cut and rock properties and its interaction on temperature. This study contributed to the literature where the effect of low back rake angle (0.5-1.5 mm) and depth of cut (5-15°) did not evaluate in previous single PDC cutter study. It can be concluded that the depth of cut, back rake angle and rock properties have a significant effect on the temperature where Prob> F is lower than 0.05. The interaction between depth of cut and back rake angle also shows a significant effect on temperature. Another interaction between factors (depth of cut and rock properties) also indicate significant effect towards temperature. However, the interaction between back rake angle and rock properties imply insignificant changes on temperature. Nonetheless, the interaction between all factors provides a significant effect on temperature. A validation study has also been performed where a small difference (5%) between experimental and predicted data were observed. This study was limited to different formation type of rock samples; Carthage marble from metamorphic rock while Indiana limestone from sedimentary rock. The effect of different rock properties between similar formation type on temperature response is yet to be explored. Thus, it is suggested to conduct a single PDC cutter study of various rock samples from the same formation type such as sedimentary rocks.

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چکیده
عملکرد برش یکپارچه الماس چند بلور (PDC) تحت تأثیر دما در طی فرآیند برش سنگ است بالا از بهینه سازی فراورده برش، مطالعه در مورد درک عوامل و تأثیر متقابل آن بر دمای برش ضروری است. بنابراین، این مطالعه با هدف بررسی تأثیر پارامترهای مختلف برش و اثر متقابل آن بر دمای برش PDC منفرد انجام می‌شود. یک سری آزمایش در دستگاه تراشکاری انجام شد که با استفاده از عمل روبرو، نمونه‌های سک ساخته شد که درجه حرارت زیر 5 درجه تا 15 درجه حرارت یکپارچه الماس چند بلور برخوردار بودند. درجه برش داده در نوع سنگ مورد آزمایش در این مطالعه سنگ هندی و سنگ مرمر کارتاژ است. اجرای و تحلیل واریانس (ANOVA) خروجی نشان داد که پارامترهای برش و خصوصیات سنگ و اثر متقابل آن تأثیر قابل توجهی بر روی دما و تغییر می‌کند. درجه حرارت برش گزارش داد که برهم کنش بین دمای برش و زاویه شیب عمکرکه برخوردار از افزایش برش و کاهش زاویه شیب عمکرکه برخوردار از افزایش دما و تغییر در زاویه شیب از پارامترهای در دیواره است. افزایش دما در زاویه شیب کم پشت و عمل زیاد برش که حداکثر دما را تولید می‌کند. نتایج نشان داد که دما و زاویه شیب در تغییر حالت از دما و زاویه شیب با اختلاف 5 درصد در مقایسه با داده‌های آزمایشی به دست آمده با استفاده از پارامترهای مشابه نشان می‌دهد که نتایج قابل اعتماد هستند و می‌توانند در مطالعات آینده استفاده شوند.