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Performance evaluation of polycrystalline diamond compact percussion bits through laboratory drilling tests

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1. Introduction

Percussion drilling is frequently adopted in advancing boring performed for forward exploration and drainage in the construction of road and railway tunnels. It is also used to make blastholes for mine development and mountain tunnel construction, as well as in a variety of other civil engineering works. In percussion drilling, when the length of the drill string increases, the percussive energy transmitted to the bit decreases rapidly.[1] Therefore, the length of drilled sections (drilled length) is significantly limited (approximately 150 m at maximum).[2] However, the maximum rate of penetration (ROP) reaches 50–100 cm/min or higher in the percussion drilling of hard rock such as granite.[3] This ROP is one order of magnitude higher than that of rotary drilling, indicating that percussion drilling is an extremely efficient drilling technique.

Conventional percussion bits are equipped with cobalt (Co)-containing cemented tungsten carbide (WC-Co) tips. Recently, percussion bits with polycrystalline diamond compact (PDC) tips, as explained in the next section, have been put to practical use. These bits are respectively called WC-Co and PDC percussion bits in this study.

PDC is superior to WC-Co in terms of wear resistance. Therefore, PDC percussion bits are considered to exhibit better drilling performance than WC-Co percussion bits. However, to the best of our knowledge, there have been no reports on the quantitative comparison of the drilling performance between these percussion bits in a common environment with unified rock materials and drilling conditions.

In this study, percussion drilling tests on hard and highly abrasive granite were performed in a laboratory using PDC and WC-Co percussion bits to evaluate their drilling performance. The test result contains some published data.[4]

2. PDC

2.1. PDC cutters

PDC cutters,[5,6] developed by General Electric Company in 1973, are one of the advanced technologies used in the drilling industry. As shown in Fig. 1, a PDC cutter consists of polycrystalline diamond and WC-Co layers. The high-toughness WC-Co layer firmly supports the polycrystalline diamond layer and also serves as a brazing surface for attaching the PDC cutter to the bit body.

PDC cutters are fabricated by sintering a laminate consisting of Co-containing WC powder and artificial diamond particles of 1–10 μm diameter. The sintering conditions are a pressure of 5–6 GPa and a temperature in the range of 1500–1600 °C, which are similar to the synthesis conditions of artificial diamond. During sintering,

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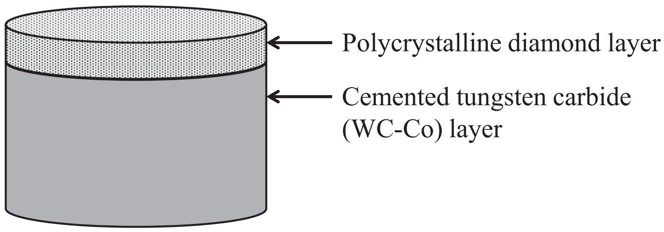

Fig. 1. Appearance of PDC cutter.

Co, which acts as a catalyst, is dispersed into the diamond layer, causing single-crystal diamond particles oriented in arbitrary directions to be bound to each other to form polycrystalline diamond structure. Polycrystalline diamond has improved impact resistance because of the lack of cleavability of single-crystal diamond. In addition, diamond has a Mohs hardness of 10, and is the world's most wear-resistant material.

Bits equipped with PDC cutters are called PDC bits and are currently commonly used in the drilling of petroleum and natural gas wells worldwide.[5] A report showed that PDC bits accounted for approximately 65% of the total length of drilled petroleum and gas wells in 2010.[7]

2.2. PDC tips

Fig. 2 shows the appearance and a cross-sectional schematic of a button-type PDC tip. The fabrication process for PDC tips is similar to that for PDC cutters.[8] Although it is unclear when PDC tips were first developed, they were already being used as gage inserts for cones constituting roller cone bits in 1988.[9] It is also reported that the use of PDC tips suppresses gage loss (a phenomenon in which the bit diameter decreases owing to the wear of the bit periphery) in the drilling of extremely abrasive hard rock abundant in geothermal regions, resulting in a reduction in the need for reaming and in the occurrence of problems in bores such as the twisting off of drill pipes.

In general, the end of PDC tips has a multilayer structure. The diamond content in each layer decreases from the polycrystalline diamond layer to the WC-Co substrate. Because the polycrystalline diamond layer and WC-Co substrate have extremely different thermal expansion coefficients, a residual stress is generated between them.[9] Laursen et al.[9] showed that the multilayer structure has the role of mitigating this residual stress to improve the load-bearing property of PDC tips.

3. Procedure of percussion drilling test

3.1. Apparatus

Fig. 3 shows a schematic of the apparatus used in the test. The shaded regions in Fig. 3 indicate the system for transferring an impact blow given by the percussion drill and a rotation driven by the direct-current motor (the transfer system). A magnified view of the system is shown in Fig. 4. An impact blow given by the hammer to the hammer sub is transferred to the spindle, rod, and then the percussion bit. The rotation driven by the direct-current motor is transferred to the gear reducer, bevel gear, and then the spindle to rotate the rod and bit.

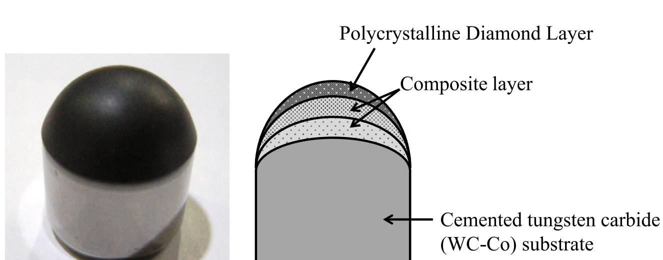

Fig. 2. Photograph and cross section of a PDC tip.

In the test, as shown in Fig. 3, the torque T was measured using a torque transducer, the drilling depth (the displacement of thrust yoke) was measured using a displacement transducer, the oil pressures at the inlet and outlet of the percussion drill, p_{in} and p_{out}, respectively, were measured using pressure gauges, and the oil flow rate in the percussion drill Q was measured using a flowmeter.

3.2. Bit and rock

Two types of bit, i. e., PDC and WC-Co percussion bits, were used in the tests. Fig. 5 shows overall and top-view photographs of the PDC percussion bit. For both bits, a total of eight tips (three on the face, five on the gage) are mounted in the same arrangement. The initial bit diameter is 65 mm and the initial bit body diameter is 63 mm at the thickest part. Fig. 6(a) shows the dimensions of the profile of a tip mounted on the two types of bit. The diameter of the tip bottom is 11.0 mm and the radius of the arc of the tip r is approximately 6 mm.

As rock samples, $50 \times 50 \times 80$ cm granite was used in the tests. Each rock sample was subjected to nine drilling trials. The drilling depth was 65 cm in each trial. Sori granite (Sori Gt.) was used up to a drilled length of 47 m. For larger drilled lengths, Takine granite (Takine Gt.) was used. A core with a diameter of 25–30 mm was obtained from each drilled rock sample and subjected to an unconfined compression test and a diametral tensile strength test. Table 1 shows a summary of the mechanical properties of the drilled Sori Gt. and Takine Gt.

3.3. Conditions

The weight on the bit F_s, rotary speed N and percussion frequency f were set at 6.5 kN, 75 rpm and 17 Hz, respectively. F_s is equivalent to the sum of the thrust force produced by the hydraulic rams and the total weight of the transfer system. A drilling fluid (water) was circulated at a flow rate of 60 L/min to remove cuttings out of a bore. The inlet pressure, p_{in}, which is set by a throttle valve, controls the percussive energy transferred to the bit and was maintained at approx. 15.3 MPa during the tests. Fig. 7 shows the relationship between the percussive energy per unit time P_p and the power of the percussion drill per unit time P_d. The percussive power P_p was determined in a preliminary test, as described in the next section. The approximate line in Fig. 7 is expressed by

$$P_p = 0.18 \times P_d + 0.0263 \ \text{kW}. \tag{1}$$

where P_d is expressed in terms of p_{in}, p_{out}, and Q, which are measured in the test, as

$$P_d = (p_{in} - p_{out}) \times Q. \tag{2}$$

Therefore, P_p was calculated using Eqs. (1) and (2). The rotary energy per unit time P_r was calculated as follows using T and the rotary speed N, which are measured in the test:

$$P_r = 2\pi \ N \ T. \tag{3}$$

It has been observed in percussion drilling that the tips at the end of a bit penetrate the rock and immediately separate from the bottom of the resulting bore after each blow owing to a reactive force.[10] In this case, negligible torque acts on the rock. Therefore,