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Drilling Performance of PDC bits for Geothermal Well Development in Field Experiments

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ABSTRACT

Large amount of cost and long duration required prior to commencement of geothermal power production extremely influence on promotion of the geothermal energy development in Japan. In order to reduce the cost and the duration, JOGMEC (Japan Oil, Gas and Metals National Corporation) has focused on drilling technique and has established a research and development project on the PDC bit with both of high drilling efficiency (speed) and long drilled length (durability) in 2015. In the project, we have studied manufacturing technique of PDC cutters, and have succeeded developing ones with high wear resistance and high impact toughness. In addition, we have carried out structural analyses to even the loads worked on the PDC cutters and fluid analyses to simulate the flow of drilling fluid on the bit face. These analyses have been done iteratively to determine the specifications of the bit, and then several kinds of the PDC bits of 8-1/2 inches in diameter equipped with manufactured PDC cutters with 13.44 mm in diameter on eight blades have been fabricated. The PDC bits have been applied to well drilling at active geothermal development sites, and the drilling behavior of the bits has been observed and evaluated.

1. INTRODUCTION

Geothermal energy is one of the principal renewable energies. Geothermal power generation emits less CO_2 than fossil power generation and can stably supply electricity as compared with other renewable energies. According to the report by METI, Japan (Ministry of Economy, Trade and Industry, 2017), total amount of geothermal resource in Japan is approximately estimated as 23,470 MW and is the third place of the world. However, the actual geothermal power generation in Japan is only 530 MW. It has been pointed out that less development (and then less utilization) of the geothermal energy is related to the construction cost and duration of geothermal power plant. Therefore, to activate the development and/or utilization of geothermal energy and to increase the electrical power plant capacity, reduction of drilling cost of geothermal wells is one of important factors. Specifically, it is an urgent issue to develop drilling bit with higher drilling efficiency and durability.

Recently, PDC (Polycrystalline Diamond Compact) bits have been rapidly spread in the drilling wells for oil and gas, replacing conventional roller-cone bits. This is probably because the strata to be drilled in oil and gas fields are mostly composed of soft to medium-hard rocks. However, the strata in geothermal developing sites is generally not only hard abrasive rocks such as granites but also heterogeneous with geological fractures. Consequently, a drilling bit degrades shortly due to large loads and impacts in such severe geological conditions. It can be summarized that research and development of the PDC bit as well as the PDC cutters for drilling geothermal wells is necessary to achieve the drilling with higher efficiency at lower cost as compared to the drilling using conventional roller-cone bits.

In the present study, we developed several kinds of PDC cutters and manufactured PDC bits with diameters of 8-1/2 inches, targeting application to the geothermal well drilling. We set following goals of the drilling performance in the concrete: Drilling speed (Efficiency): 120 m per a day, Drilled length (Durability): 750 m for a PDC bit in drilling strata (rocks) of uniaxial compressive strength (UCS) with about 100 MPa, and Gage loss of bit in drilling: less than 1/16 inches.

2. DEVELOPMENT OF PDC CUTTERS

The process of manufacturing PDC cutters has been accomplished by sintering diamond powder on a cemented carbide substrate with cobalt as a binder by applying high pressure and high temperature (HPHT) to the components (Field, 1992). The common actual region of the PDC sintering condition is shown in Fig. 1. A mass of a plurality of diamond particles are placed adjacent to a substrate, and the size of diamond grains used to form the polycrystalline diamond ranges on average from about 2 to 30 μm.

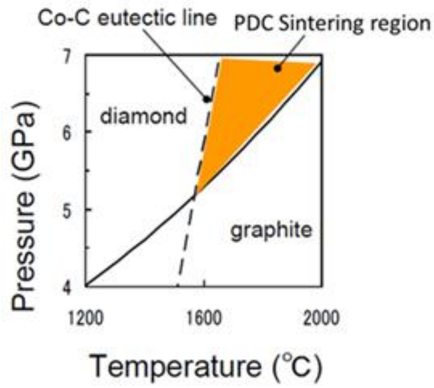


Figure 1: High pressure and high temperature sintering condition of polycrystalline diamond compact.

The combination of the high pressure and the heat allows the catalytic material (usually cobalt) to flow from the substrate to the diamond enabling the diamond-to-diamond sintering process and the substrate to diamond bonding (Bertagnolli and Vale, 2000). An HPHT apparatus is utilized to exert the pressure and conduct an electric current to a cell assembly. The cell assembly is the combination of many components responsible for transferring the pressure, heating, and containing the samples to be sintered. Following formation of the integral PDC compact, the sintered PDC compact was processed through a variety of finishing operations for the final product. Such finishing operations include grinding and polishing the outside diameter of the compact, cutting, grinding, lapping, and polishing the faces of the PDC.

As a final product, the PDC cutter as shown in Fig. 2 with a dimension of 13.44 mm in diameter and 8 mm in total thickness having a thick diamond layer of about 1.7 mm was made. The SEM observations confirmed that the microstructure of the PDCs showed uniform diamond grain distribution and sintered well. Fig. 3 (a) and (b) show the microscopy photographs of PDCs with relatively fine and coarse grain sizes, respectively. The dark parts are diamond grains and the white areas are cobalt binders. It is clear that diamond grains are bonded to each other with some cobalt residual existing at the grain boundaries.

Figure 2: PDC cutter with 13.44 mm in diameter and 8 mm in thickness.

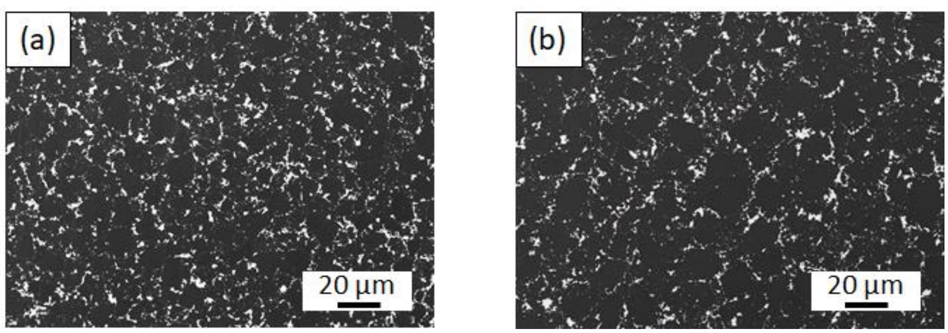


Figure 3: Microstructure of the PDC cutters. (a) high wear resistance type, (b) high toughness type.

The aim in using the fine and coarse diamond grains as a starting material was an attempt to make the high wear resistance PDC and high toughness PDC, respectively. In general, a negative correlation is observed between the abrasion resistance of PDCs and the grain size of the diamond grits (Deng, Nilen and Ozbayraktar, 1997). PDC cutters with high impact toughness were successfully manufactured by using coarse diamond grains for tough and uneven drilling conditions. PDC cutters with high abrasion resistance were also successfully manufactured by using fine diamond grains, which was thought to be suitable for drilling highly abrasive formations.

The wear resistance and the impact toughness of the above mentioned PDC cutters were evaluated in laboratory using turning lathe on granite log for the wear test and the industry de facto standard of drop-tower impact testing for the toughness evaluation before actual use in geothermal drilling field. The results of the wear and impact tests are summarized in Fig. 4. Open circle indicates the test result of general PDC made from standard size of the diamond grains. From the graph, it is confirmed that the PDC (a) with fine diamond grains is high wear resistance type and the PDC (b) with coarse diamond grains is high impact toughness type.

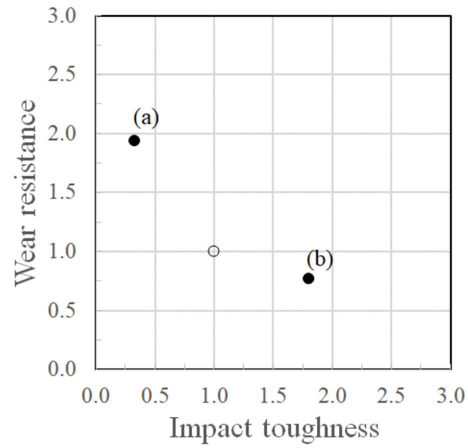


Figure 4: Characteristics of two types of PDC cutters: (a) high wear resistance type and (b) high impact toughness type.

3. MANUFACTURING TECHNIQUES OF PDC BIT

3.1 Design evaluation methods of 8-1/2" PDC bit

To develop PDC bits applicable to the drilling of geothermal wells in Japan, firstly two 8-1/2" PDC bits were designed targeting higher penetration rate and durability compared with those of conventional roller-cone bits. We have adopted PDC bits with eight blades so as to place as many PDC cutters as possible on the bit for facing hard abrasive rocks with inhomogeneous geological fractures and to reduce the load (reaction force) worked on an individual PDC cutter.

Structure analysis was carried out in designing stage of the 8-1/2" PDC bit. Fig. 5 shows 3D CAD model of Bit-A designed using 3D CAD software (Autodesk Inventor Simulation 2016). Bit-A has 50 PDC cutters with 13.44 mm in diameter arranged on its bit face. To equalize the reaction forces worked on the PDC cutters that are involved mainly in rock drilling, the structure analysis has been repeated iteratively to find better arrangement with less force of each PDC cutter under the general drilling conditions for the relevant bit size: the weight on bit (WOB) is 70 kN and the torque on bit (TOB) is 5 kN·m. As shown in the left of Fig. 6, it was confirmed that the reaction forces were ever-increasing outward from the bit center, but those on the adjacent cutters were almost equal. The right figure of Fig. 6 also shows the result of the structure analysis performed under the same conditions of WOB and TOB on Bit-B, which had additional 25 PDC cutters (backup cutters) arranged behind the 25 primary cutters in nose and shoulder portions of Bit-A. The reaction forces worked on the primary cutters of Bit-B are obviously smaller than those of the cutters of Bit A, as compared with the cutters at the same distance from the bit center. The forces of secondary cutters are less than those of primary cutters.

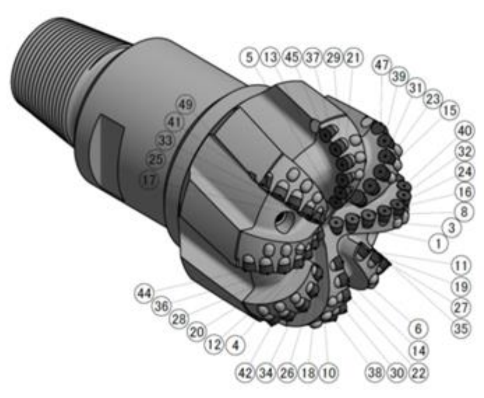


Figure 5: 3D CAD modeling for 8-1/2" PDC bit.

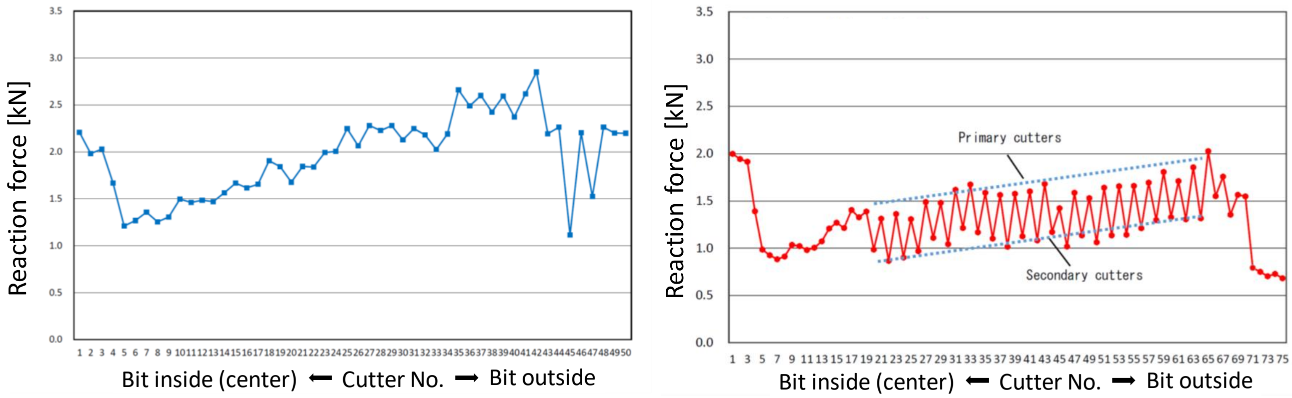


Figure 6: Distribution of reaction forces of PDC cutters on Bit-A (left) and Bit-B (right).

In addition to the arrangement of PDC cutters, the efficiency of the removal of cuttings is one of the important factors influencing the drilling performance of the bit. The visualization of drilling fluid flows was carried out by using a fluid analysis software, SCRYU / Tetra V12, to verify the drilling fluid flow discharged from nozzles and holes of the PDC bit. Autodesk Inventor Simulation 2016 was used for the 3D modeling of the fluid analyses. The particle tracking method was applied to visualize trajectory of virtual particles in the flow. Since the trajectory of particles (drilling fluid flow) significantly depends on the clearance between the surfaces of bit blade and the hole bottom, the clearance was set in the fluid analysis to "in-between space," which is intermediate between the "maximum space" and "minimum space." The former is the case that the edges of cutters are just in contact with the surface of the hole bottom, and the latter is that the surfaces of the bit blade, where the cutters are worn out, are in close contact to the hole bottom.

Path lines of the particles arbitrarily selected are shown in Fig. 7 (a). The flow passages around the faces of PDC cutters on each blade appear to be still sufficient even though the clearance was restricted. Therefore, both the removal of cuttings and cooling of the PDC cutters are thought to be well performed. Fig. 7 (b) shows the flow velocity distribution, and it became clear that the flow velocity in the vicinity of two water holes around the bit center was large and that four nozzle holes placed outside the bit cone area contributed to increase of the flow rate around the secondary blades.

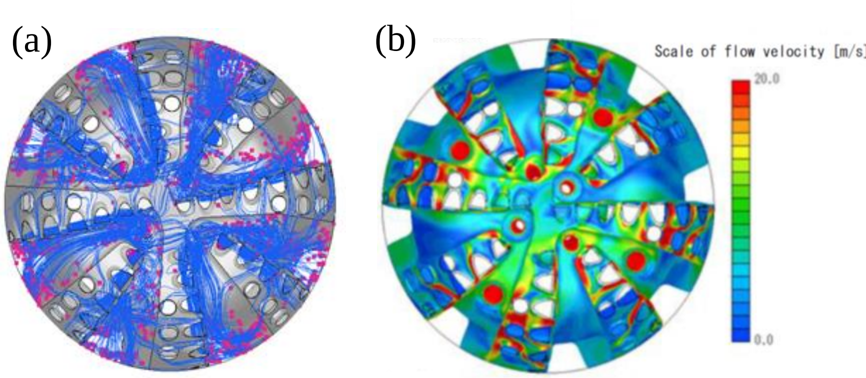
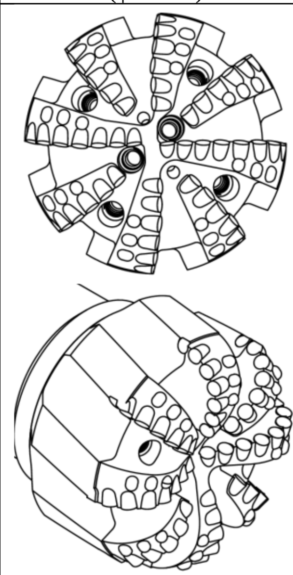
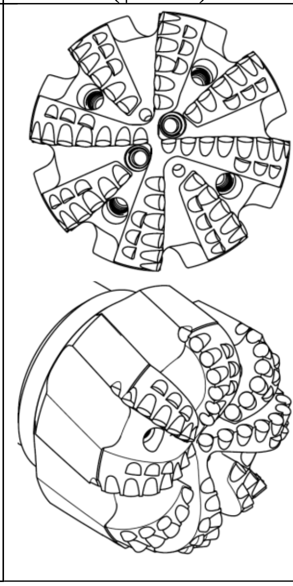


Figure 7: Flow simulation of drilling fluid (water) on the bit face of Bit-A. Figures (a) and (b) show path lines of particles and flow velocity distribution, respectively. Bit rotation and flow rate are 200 rpm and 1,800 L/min, respectively.

3.2 Fabrication of 8-1/2" PDC bits

Considering that there are frequently hard formations with high abrasivity and heterogeneous strata in most cases in Japanese geothermal development, the two 8-1/2" PDC bits corresponding to IADC classification code M433 were fabricated. For Bit-A, the PDC cutters with high impact toughness (PDC cutter (b) in Fig. 4) were used, and those with high wear resistance (PDC cutter (a) in Fig. 4) were used for Bit-B. While the PDC cutters on both bits were in a dimension of 13.44 mm in diameter, the chamfers for Bit-A and Bit-B were in width of 0.3 and 0.45 mm, respectively. Specifications of both bits are summarized in Table 1. Bit-A and Bit-B have eight blades each other and their bit face designs are basically common. For Bit-A, back rake angle of -15° was adopted and aims at larger rate of penetration (ROP). 24 arrestors (impact suppression chips) were attached behind the PDC cutters in nose to shoulder portion, aiming at protecting the primary PDC cutters from excess vibrations, impacts and depth of cut during drilling. For Bit-B, relatively gentler back rake angle (-20°) was adopted with the aim of making the bit life (durability) longer. Moreover, the 25 backup cutters were placed just behind the primary cutters in nose to shoulder portion, where the loads worked on these cutters became larger during drilling and thus the PDC cutters were arranged in two rows on each bit blade.

Table 1: Specifications of 8-1/2” PDC bits; Bit-A and Bit-B.

Developed 8-1/2” PDC bit		Bit-A	Bit-B
Number of blades		8	8
IADC classification code		M433	M433
PDC cutter	Size	ϕ13.44 mm	ϕ13.44 mm
	Number of Primary cutters	50	50
	Number of Backup cutters	-	25
	Number of Gage cutters	8	8
	Total	58	83
	Chamfer	exist	exist
Arrestor		exist	none
Nozzle	Number of nozzle holes (Nozzle OD)	6 (ϕ20.4 mm)	6 (ϕ20.4 mm)
	Number of water holes (Hole ID)	2 (ϕ10 mm)	2 (ϕ10 mm)
Bit face			

4. FIELD EXPERIMENTS-1

4.1 Drilling performances of Bit-A and Bit-B before field experiments

Prior to the field experiments, drilling test using Bit-A and Bit-B was conducted in a laboratory to obtain their initial drilling performances, which is hereafter referred to as “pretest.” Drilling apparatus used in the pretest is shown in Fig. 8. Drilling depth, WOB, TOB and rotary speed were measured using a displacement transducer, two load cells, a torque transducer and an electromagnetic tachometer, respectively. ROP was calculated by time derivative of the drilling depth. In the pretest, Emochi andesite (UCS = 80-100 MPa, average: 86 MPa) was used as drilled rock samples. During drilling, rotary speed was kept constant at 100 rpm and a drilling fluid (water) was circulated to remove cuttings out of a bore.

Figure 8: Drilling apparatus for laboratory test.

Fig. 9 shows ROP-WOB relationship measured in the pretest. ROP increased linearly with WOB for both bits. ROP of Bit-A reached as high as 30 m/hr when WOB was 25 kN. At equal WOB, ROP of Bit-B was approximately 18 m/hr. The main factor for the lower ROP of Bit-B compared with that of Bit-A is considered to be the difference in the back rake angle of PDC cutters.

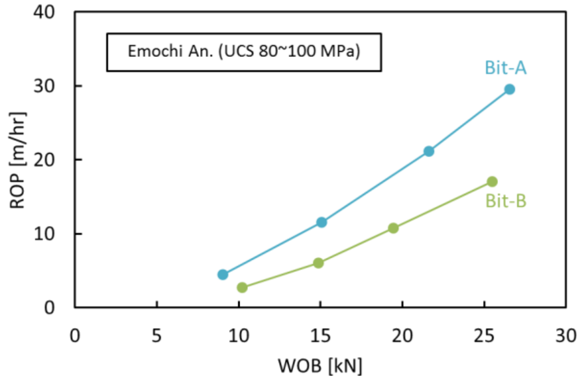


Figure 9: ROP-WOB relationships measured in the pretest using Bit-A and Bit-B.

4.2 Site specifications

Bit-A and Bit-B were installed in two different sites of geothermal development, site-B and site-K1, respectively. Specifications of the sites are summarized in Table 2. In each site, the drilling performance test was made as a part of drilling the structural boring well. The bits were used in the hold section (tangent section) of directional wells. The geological formation of the target well section in site-B consists of dacite tuff breccia and lapilli tuff with breccia. In the site-B, some rock cores were sampled from the well section just above the well section where Bit-A was used. Its uniaxial compressive strength (UCS) obtained from the laboratory strength test was 122 MPa on average. Andesite lava and hornblende dacite pyroclastic rock were mainly drilled by Bit-B in site-K1. The UCS of the formation was estimated to be 150-200 MPa from the laboratory strength test conducted on the rock samples acquired from a different well in neighborhood of the site-K1. Adjustable bent housing (ABH) system was employed in the drilling performance test and the bent angle was set to 0.93°.

Table 2: Summary of site specifications, test conditions and results at site-B and site-K1.

Site specifications		
Site	B	K1
Well	Structural boring well (directional well)	Structural boring well (directional well)
Depth of target section (8-1/2” hole diameter)	1,600-2,000 m (hold section)	1,200-1,800 m (hold section)
Geological formation	Late Miocene dacite tuff breccia and lapilli tuff (mostly welded) with breccia	Neogene andesite lava and hornblende dacite pyroclastic rock (with basalt intrusive rock)
Uniaxial compressive strength (UCS)	122 MPa	150-200 MPa (estimated)
Test conditions		
Bit	Bit-A	Bit-B
Rotary speed	206 rpm (combination of downhole motor and top drive)	100-150 rpm (combination of downhole motor and kelly drive)
ABH angle	–	0.93°
Test results		
Drilled length (Measured depth)	161.0 m (1,756-1,917 m)	109.0 m (1st use: 1,210-1,249 m and 2nd use: 1,414-1,484 m)
Drilling time (bit-run time)	31.0 hrs	56.0 hrs
Average drilling speed (1 day = 24 hrs)	125.0 m/day	48.0 m/day
IADC dull grade (in/out)	3/3	1/3
Gage loss	< 1/32 in.	< 1/32 in.

4.3 Results

Fig. 10 shows the changes in ROP and WOB with the drilled length in the field experiment for Bit-A in site-B. When the WOB was raised to 70 kN during the first 5 hrs of the test, the ROP reached about 16 m/hr with increase of WOB and was kept until the drilled length of about 40 m. After that, the ROP slightly dropped to 11 m/hr and continued decreasing step-by-step to 1.5 m/hr, while the WOB was almost constant at 70 kN. Then, the bit reached its life at the drilling time of 31 hrs. The drilled length was 161 m, and the average drilling speed of Bit-A was 125 m/day. The drilling speed (efficiency) is larger than that targeted as the goal.

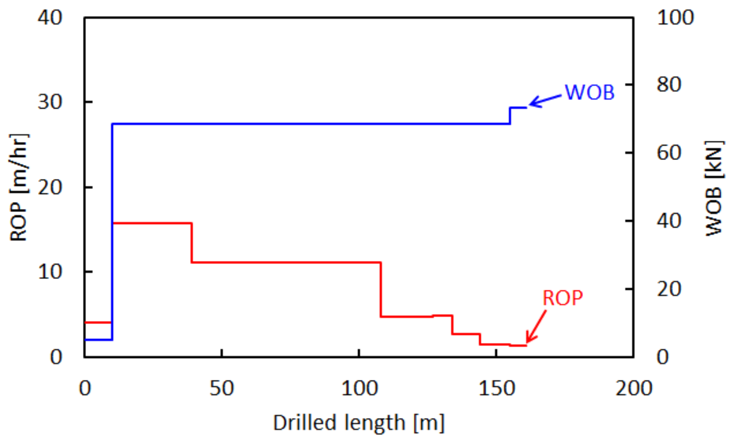


Figure 10: Changes in ROP and WOB in the field experiment for Bit-A in site-B.

Fig. 11 shows the changes in ROP and WOB with the drilled length for Bit-B in site-K1. The WOB was gradually raised up to 30 kN. The ROP reached 8 m/hr in maximum at the drilled length of 18 m, before the test was halted due to the unexplained decline of ROP at the drilled length of 39 m. Since the wears of the PDC cutters equipped with Bit-B was very little, we decided to reuse Bit-B in the same well after drilling subsequent formation with another bit. In the 2nd use of Bit-B, the ROP ranged from 2 m/hr to 5 m/hr while the WOB was maintained under 50 kN before the ROP decreased rapidly at the total drilled length of 82 m. At the drilled length, Bit-B was considered to encounter with hard intrusive basalt from observation of the cuttings. Bit-B was continuously used with the WOB over 50 kN until the ROP decreased to 1 m/hr or lower. From the total drilled length (109 m) and the drilling time (56 hrs), the average drilling speed of Bit-B was calculated to be 48 m/day.

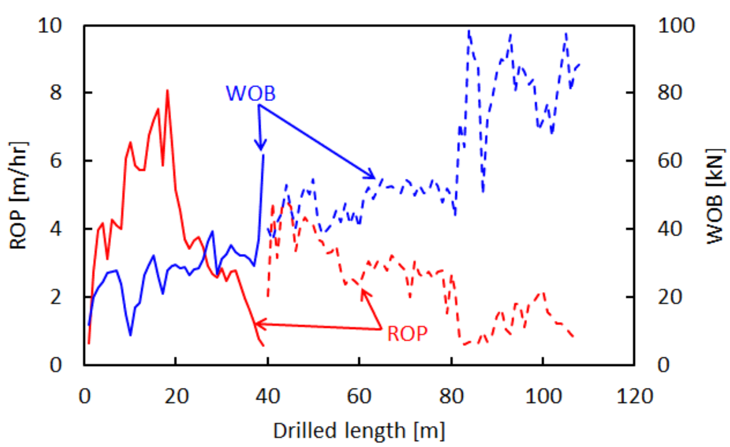


Figure 11: Changes in ROP and WOB in the field experiment for Bit-B in site-K1. Solid/Broken line indicates the result obtained in the 1st/2nd use of Bit-B.

4.4 Wear observation

Fig. 12 shows top-view images generated by 3D scanning of Bit-A and Bit-B after the field experiments. Yellow to red areas indicate the wears of the cutters. Large wears were observed on the PDC cutters on nose, taper and shoulder of both bits, especially of Bit-A. According to IADC dull grading of fixed cutter bit, inner/outer rows of Bit-A and Bit-B were evaluated as 3/3 and 1/3, respectively. There were not chipped or lost cutters on Bit-A and Bit-B. Although the wears on the primary PDC cutters of Bit-B was smaller than that of Bit-A, many primary cutters on the shoulder of Bit-B appeared to be delaminated. One possible reason for this delamination is that the cutters on the shoulder of Bit-B were exposed to iterative large impact when bumping hard rock strata due to the employment of

ABH system (Lin et al., 1992). Gage losses for both bits were less than 1/32 inches. It means that the goal for gage loss of bit in drilling described in INTRODUCTION is achieved.

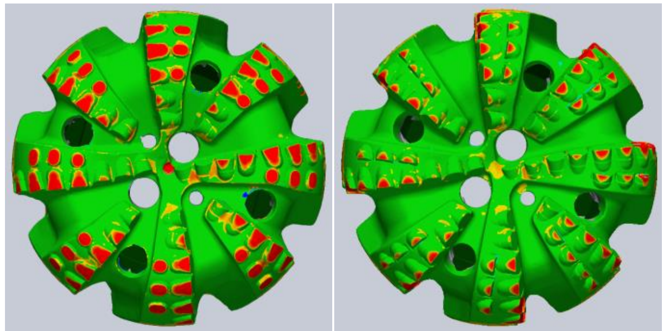


Figure 12: Top-view images of Bit-A (left) and Bit-B (right) after the field experiments.

4.5 Drilling performances of Bit-A and Bit-B after field experiments

To measure the decrease in drilling performances of Bit-A and Bit-B through the field use, they were subjected to the laboratory test again after the field experiment, which is hereafter referred to as “posttest.” The posttest was conducted under the equal conditions with the pretest. The ROP-WOB relationships obtained in the posttest are shown in Fig. 13 by single logarithmic plot to display the results of the pretest concurrently. The ROP of both bits clearly declined due to the progress of wear of the cutters. Note that the ROP of Bit-B was higher than that of Bit-A after field experiment; the magnitude relation of ROP of Bit-A and Bit-B was reversed through the field experiment, which is thought to occur because of the larger wear on the cutters of Bit-A compared with that of Bit-B. As seen in Fig. 13, Bit-B may still keep the potential to drill softer rock such as Emochi Andesite (UCS = 86 MPa) at the ROP of 0.6 m/hr with the WOB of 64 kN.

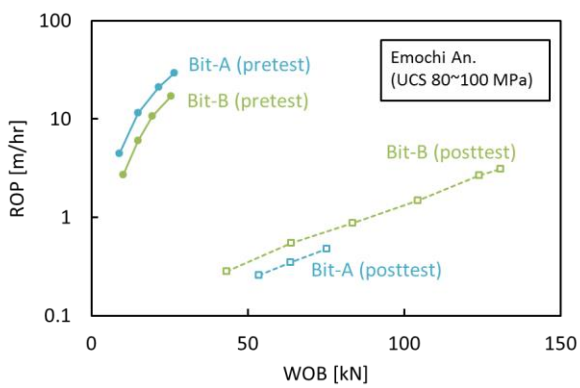


Figure 13: ROP-WOB relationships measured in the posttest using Bit-A and Bit-B.

5. IMPROVEMENT OF PDC BIT

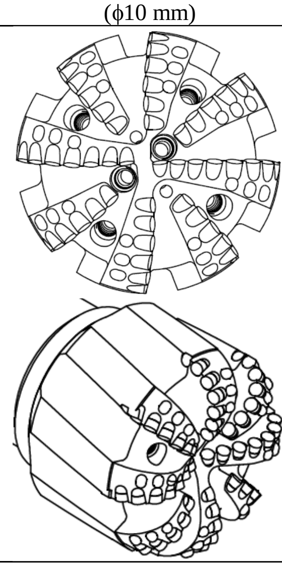
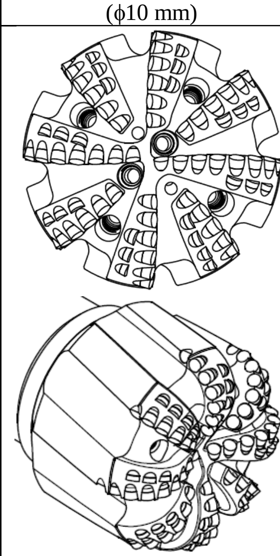
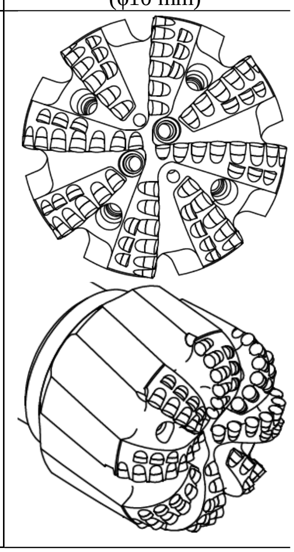
Large damage of the cutters located in nose to shoulder portions of the both bits was observed. Especially some of the primary cutters in shoulder portion of Bit-B were extremely worn, and the diamond layers of several PDC cutters were delaminated. Moreover, the gage losses of the both bits were less than 1/32 inches. As compared to the present goals described previously, target values concerning drilling speed (efficiency) and gage loss have been achieved, while the targeted drilled length (durability) remains unachieved. We need to improve impact toughness of the PDC bit in total, where characteristics of the PDC cutter has to be examined together, though the rock strata encountered in the field experiments seemed to be higher UCS than estimated. We primarily reconsidered the bit specifications to overcome the subjects described above, and three types of PDC bit were fabricated: Bit-C, Bit-D and Bit-E.

Bit-C was adopted almost the same bit design as Bit-A, except that the length of bit gage was 30 mm longer than that of Bit-A, intending to stabilize the bit and then to decrease damage of the bit by impact during well drilling. 50 PDC cutters and 24 arrestors were used. The PDC cutters (a), which had high wear resistance, were installed in nose to shoulder portion of the Bit-C, and the back rake angle of all PDC cutters was set to -15°. Chamfer in width of 0.45 mm was applied to make impact toughness of the cutters higher.

Bit-D was almost the same bit design as Bit-B, except that the length of bit gage was 30 mm longer than that of Bit-B. Bit-D was equipped with 50 primary cutters and 25 backup cutters, which were the same cutting trajectories as the primary ones, and the PDC cutters (a) with high wear resistance were also installed in nose to shoulder portion. The back rake angle of all PDC cutters with chamfer in width of 0.45 mm was -20° to emphasize durability of the bit.

Bit-E was developed based on Bit-C. In order to increase cutting ability in cone portion of the bit, preliminary experiments and structural analyses were carried out to find better cutter arrangement regarding position of PDC cutters and their back rake angles. As a result, the WOB and TOB became smaller when the cutters were arranged as close to center of the bit as possible and their back rake angle was set to -15°. By the structural analyses, we also found that reaction forces on the cutters with back rake angle of -15° were acceptably small even when all the cutters in nose to shoulder portion were arranged so as to decrease the area of each PDC cutter which contribute to the cutting of rock strata. In this design, not only 50 primary cutters but also 25 secondary cutters were expected to work on cutting the rock strata simultaneously and then the load on each primary cutter in nose to shoulder portion of Bit-E was reduced as compared to that of Bit-D. PDC cutters (a) with high wear resistance, which have chamfer of 0.45 mm in width, were installed in nose to shoulder portion, and the length of bit gage was 30 mm longer than that of Bit-A. Specifications of the three PDC bits were summarized in Table 3.

Table 3: Specifications of 8-1/2” PDC bits; Bit-C, Bit-D and Bit-E.

Developed 8-1/2” PDC Bit		Bit-C	Bit-D	Bit-E
Number of blades		8	8	8
IADC classification code		M433	M433	M433
PDC cutter	Size	ϕ13.44 mm	ϕ13.44 mm	ϕ13.44 mm
	Number of Primary cutters	50	50	50
	Number of Backup/Secondary cutters	-	25 (Backup cutters)	25 (Secondary cutters)
	Number of Gage cutters	8	8	8
	Total	58	83	83
	Chamfer	exist	exist	exist
Arrestor		exist	none	none
Nozzle	Number of nozzle holes (Nozzle OD)	6 (ϕ20.4 mm)	6 (ϕ20.4 mm)	6 (ϕ20.4 mm)
	Number of water holes (Hole ID)	2 (ϕ10 mm)	2 (ϕ10 mm)	2 (ϕ10 mm)
Bit face				

6. FIELD EXPERIMENTS-2

6.1 Drilling performances of three PDC bits before field experiments

Pretests of Bit-C, Bit-D and Bit-E were performed by using the drilling apparatus in the laboratory to obtain their initial drilling performances. The procedures were the same as those of Bit-A and Bit-B.

Fig. 14 shows the ROP-WOB relationships measured in the posttests. ROP increased linearly with WOB for three bits. ROP of Bit-C reached as high as 28 m/hr when WOB was 25 kN, and the drilling speed was almost comparable with that of Bit-A. Drilling speed of Bit-D was very similar with that of Bit-B, and the ROP was approximately 18 m/hr at WOB of 25 kN. The ROP of Bit-E was higher than that of Bit-D and lower than that of Bit-C, and was 22 m/hr at WOB of 25 kN. The ROP of Bit-C was higher than that of Bit-D, because the back rake angle of Bit-C was steeper than that of Bit-D. The difference in ROP between Bit-C and Bit-E, which have the same back rake angle, may be caused by the number of PDC cutters; 25 PDC cutters were additionally installed on Bit-E as secondary in nose to shoulder portion, while arrestors were put on Bit-C instead of the secondary cutters.

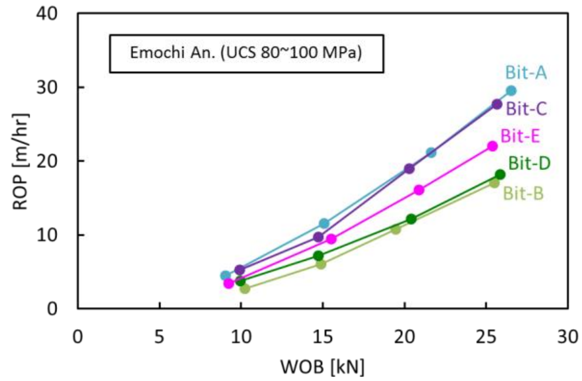


Figure 14: ROP-WOB relationships measured in the pretest using Bit-C, Bit-D and Bit-E.

6.2 Site specifications

Bit-C, Bit-D and Bit-E were installed in three different sites of geothermal development: site-I, site-O and site-K2, respectively. Specifications of the sites are summarized in Table 4. Drilling performance tests were carried out at the hold section in drilling structural boring wells (directional wells). Geological formation of the target well section in site-I consisted of tuffaceous sandstone, lapilli tuff, volcanic conglomerate. The UCS of some rock samples, which were taken from the boring cores of the adjacent well, was 54 MPa on average. Green schist, dacite with mottled quartz were primarily drilled at the target well section of site-O. Some rock samples were taken from the cores obtained in the past geothermal exploration well drilling conducted in neighborhood of site-O, and the UCS ranged from 220 to 400 MPa. Adjustable bent housing (ABH) system was employed at the site-O and the bent angle was set to 1.15°. The target well section of site-K2 was consisted mainly of quartz-rich andesite, dacite and basalt. The UCS was measured by the same procedure as in the case of site-O, and the UCS varied from 150 to 367 MPa. In site-K2, an agitator, which worked to decrease impact on the bit during drilling, was used together with the ABH system which bent angle was set to 0.62°. Note that the UCS described above was all measured directly through the uniaxial compression tests in laboratory, not through the conversion from sonic logging data.

Table 4: Summary of site specifications, test conditions and results at site-I, site-O and site-K2.

Site specifications			
Site	I	O	K2
Well	Structural boring well (directional well)	Structural boring well (directional well)	Structural boring well (directional well)
Depth of target section (8-1/2" hole diameter)	870-1,100 m (hold section)	1,000-2,000 m (hold section)	1,200-1,700 m (hold section)
Geological formation	Tuffaceous sandstone, lapilli tuff and volcanic conglomerate	Green schist, dacite with mottled quartz, felsic dacite and acidic andesite	Quartz-rich Andesite, dacite and basalt
Uniaxial compressive strength (UCS)	54 MPa (estimated)	220-400 MPa (estimated)	150-367 MPa (estimated)
Test conditions			
Bit	Bit-C	Bit-D	Bit-E
Rotary speed	130-170 rpm (combination of downhole motor and turn table)	160 rpm (combination of downhole motor and turn table)	120-160 rpm (combination of downhole motor and turn table)
ABH angle	–	1.15°	0.62° (Agitator with 6-3/4" was used together)
Test results			
Drilled length (Measured depth)	308.9 m (797.1-1,106 m)	21.0 m (1,001-1,022 m)	20.0 m (1,372-1,392 m)
Drilling time (bit-run time)	93.4 hrs	14.0 hrs	9.0 hrs
Average drilling speed (1 day = 24 hrs)	79.4 m/day	36.0 m/day	53.3 m/day
IADC dull grade (in/out)	0/0	2/5	1/2
Gage loss	< 1/32 in.	< 1/32 in.	< 1/32 in.

6.3 Results

Fig. 15 shows changes in ROP and WOB with drilled length in the site-I where the Bit-C was used. ROP varied largely from 1 to 16 m/hr regardless of the change in WOB until the drilled length of 101 m. Because ROP did not recover in spite of careful WOB operation at the drilled length of 101 m, drilling was interrupted and the wear condition of Bit-C was checked.

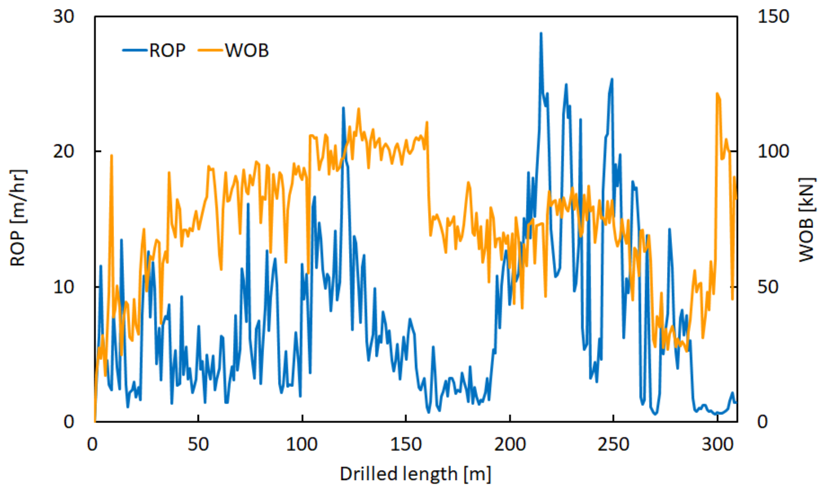


Figure 15: Changes in ROP and WOB in the field experiment for Bit-C in site-I.

Fig. 16 indicates a photograph of Bit-C at that time. The cuttings and broken pieces of rocks stuck to most of the waterways. Almost no damage on the PDC cutters was observed and several nozzle holes were blocked. Thus, the drilling performance test by using Bit-C was decided to be continued after bit cleaning. After restart of the test, ROP fluctuated independently of change in WOB. Maximum ROP of 29 m/hr was observed at the drilled length of 220 m, and the ROP gradually decreased with periodical ups and downs. While the ROP was less than 1 m/hr at the drilled length more than 290 m, Bit-C successfully reached predetermined depth and total drilled length of Bit-C was 308.9 m. Drilling time and average speed were 93.4 hrs and 79.4 m/day, respectively.

Figure 16: A photograph of Bit-C after the drilled length of 101 m where the cuttings and broken pieces of rocks stuck to most of the waterways.

Fig. 17 is changes in ROP and WOB with increase of drilled length in site-O where Bit-D was examined. Though WOB was almost constant at 40 kN until the drilled length of 13 m, ROP gradually decreased after reaching 10 m/hr at the drilled length of 3 m. ROP unexpectedly raised to 10 m/hr at the drilled length of 14 m, and rapidly decreased around 1 m/hr although WOB was gradually increased up to 100 kN. Drilling time of Bit-D was 14 hrs, and average drilling speed was estimated to be 36 m/day.

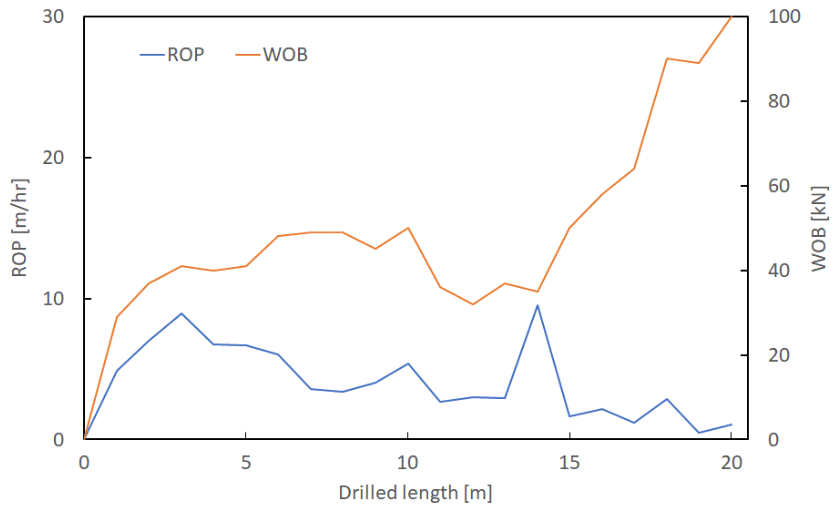


Figure 17: Changes in ROP and WOB in the field experiment for Bit-D in site-O.

Fig. 18 indicates variation of ROP and WOB with increase of the drilled length at site-K2 where Bit-E was tested. ROP slightly fluctuated around 3 m/hr, while WOB was almost constant at 24 kN until the drilled length of 13 m. Though WOB was increased gradually up to 70 kN, change of ROP was not observed obviously. Whole tendency of the change in ROP and WOB of Bit-E was similar to that of Bit-D. Drilled length was 20 m in total, and drilling time was 9 hrs. Namely, the average speed was calculated to be 53.3 m/day.

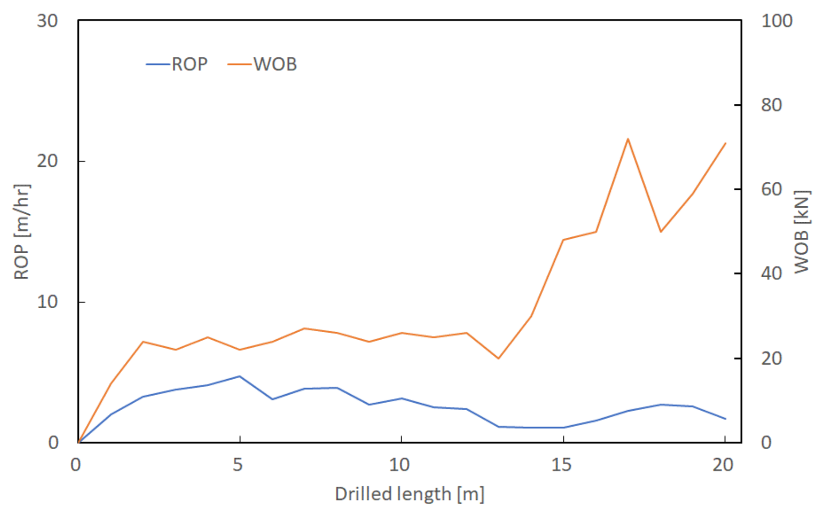


Figure 18: Changes in ROP and WOB in the field experiment for Bit-E in site-K2.

6.4 Wear observation

Though we could not observe any wears of the PDC cutters from cone to shoulder portion and the arrestors on Bit-C at the drilled length of 101 m in site-I, there were delamination on three cutters located at the gage portion. By the wear evaluation after finishing drilling the well, any wears from cone to shoulder portion and the arrestors were not observed. Therefore, the wear degree of inner/outer cutters of Bit-C by IADC dull grading was evaluated 0/0. However, an additional delamination occurred at the gage portion during the successive test. Shavings of the matrix body just behind the PDC cutters, washout, were found, probably because that the drilling mud flowed around the PDC cutters unexpectedly faster than ordinary situation that no blockings of the nozzle hole occurred.

Fig. 19 shows an image generated by 3D scanning and a photograph of Bit-C after the field experiment. Red areas in the image indicate the part where wear down more than 1 mm was observed from the initial shape of Bit-C. The delaminated PDC cutters were indicated by the dotted circles. As for such cutters, the diamond layers more than 1 mm were thought to be dropped out, while other cutters seemed to have no damages on their PDC layers. In addition, the shavings of the matrix body also reached to 1 mm or more in maximum.

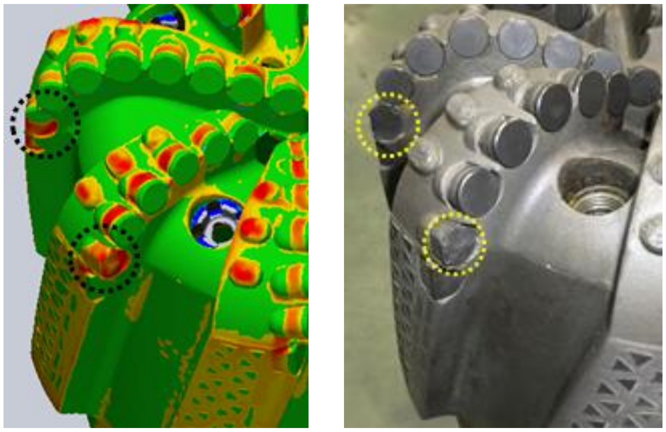


Figure 19: Delaminated PDC cutters (dotted circles) in gage portion of Bit-C after the field experiment.

After drilling 21 m in length by Bit-D at site-O, there were severe wears of the PDC cutters observed, and we also found delamination and chipping. Especially, intense wears occurred in the shoulder portion, and the wear degree of inner/outer cutters of Bit-D by IADC dull grading was 2/5. The number of delaminated and chipped PDC cutters were eleven and seven, respectively. Though slight scratch caused by the friction between borehole wall and Bit-D was found on the bit gage, no cutter was lost.

Intense wears on the PDC cutters were also found after the test by Bit-E in the site-K2, and the wear degree of inner/outer cutters by IADC dull grading was evaluated 1/2. Delamination in shoulder portion was remarkable, and the number of delaminated primary and secondary cutters was seven and eight, respectively. Gage losses for the three PDC bits were less than 1/32 inches.

It is considered that several cutters were delaminated in the tests at site-O and -K2 in the same way as at site-K1. Namely, since the rock strata at site-O and site-K2 were extremely hard in UCS, Bit-D and Bit-E may be exposed to unbearably large impact due to iterative bumps against the borehole wall by introduction of the ABH systems. In order to evaluate the efficiency of agitator, it is required to obtain additional data through field experiments or laboratory tests.

6.5 Drilling performances of three PDC bits after field experiments

Drilling performances in posttests of Bit-C, Bit-D and Bit-E were measured in the same procedures as those of Bit-A and Bit-B. ROP-WOB relationships measured were indicated by broken lines with square symbols in Fig. 20. The ROP of Bit-C in posttest was as high as those of all bits in pretests, indicating that the drilling ability of Bit-C was still kept high and degradation of the performance was very small even after the drilling more than 300 m. It is estimated that Bit-C could continue drilling the strata with UCS of 54 MPa on average at site-I much further. The relationship between ROP and WOB of Bit-D was almost the same as that of Bit-B, indicating that Bit-D still had potential to drill softer rocks even though the cutters suffered severe wears. The ROP of Bit-E after the field experiment at site-K2 was higher than that of Bit-D, and it is considered that Bit-E could continue drilling at acceptable ROP, if the UCS of the rock strata to be drilled was around 100 MPa.

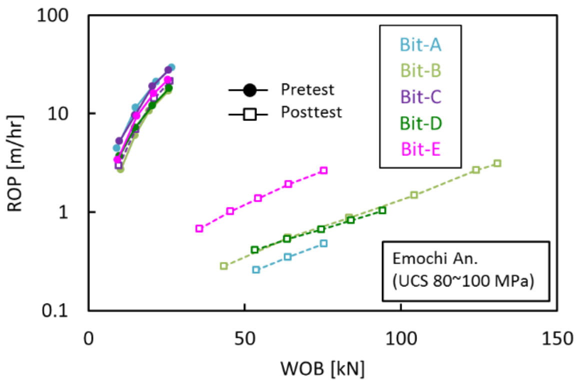


Figure 20: ROP-WOB relationships measured in the posttest using Bit-C, Bit-D and Bit-E.

7. FURTHER IMPROVEMENT OF PDC BIT

In order to achieve the drilled length targeted in one of the project goals, we developed new PDC bits in which impact resistance was improved by the design and specifications of the bits, and made field experiments at three geothermal developing sites using those bits. Consequently, the targeted drilled length had not been achieved yet. We observed many delamination and severe wears on the cutters primarily in the nose to shoulder portion. These suggested that we needed to make the PDC bit more tolerant against the impact and abrasion even when drilling hard rocks and/or employing ABH system. Therefore, we newly developed PDC bits in which both impact resistance and wear resistance was enhanced by reconsiderations of PDC cutter, bit design and the specifications.

7.1 Development of new PDC cutter

Based on PDC (b) with high impact toughness, we made improvement of the PDC regarding both impact toughness and wear resistance by means of making the diamond-bonding stronger. Fig. 21 plots characteristics of PDC (c) newly developed and compares to those of both PDCs (a) and (b). It was found that the wear resistance of PDC (c) was improved remarkably and 3.5 times larger than PDC cutter (b). Though the impact toughness was smaller than PDC cutter (b), that was 1.4 times larger than PDC (a), which was high wear resistance type.

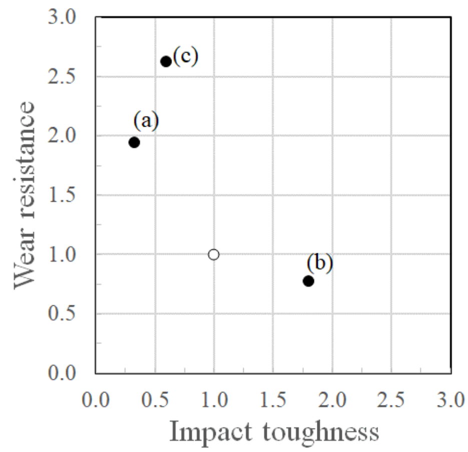


Figure 21: Characteristics of PDC (c) newly developed and comparison to those of both PDC (a) and PDC (b).

7.2 Reconsideration of bit specifications

Two PDC bits equipped with PDC cutters (c) in their nose to shoulder portion were newly fabricated. Bit-F were designed based on Bit-E to keep the drilling ability with adopting the back rake angle of -15°, while all the cutters in nose to shoulder portion were arranged so as to decrease the area of each PDC cutter which contribute to the cutting of rock strata and then to decrease the load on each primary cutter. Thus, the secondary cutters were expected to work with the primary ones on Bit-F simultaneously. In Bit-G, the same number of the PDC cutters as Bit-F was used. However, the secondary cutters of Bit-G were put in the same cutting trajectories as primary ones, and the back rake angles of the cutters were adjusted strategically to mitigate the impacts to the bits, aiming at both drilling ability and bit durability. Several arrestors were additionally installed between the shoulder and gage portion of Bit-F and Bit-G, in order to compete with unexpected impacts during drilling.

7.3 Drilling performances of Bit-F and Bit-G in laboratory test

Pretest by using Bit-F and Bit-G was conducted in the same procedures as previous ones. Relationships between ROP and WOB measured are indicated in Fig. 22. ROPs of Bit-F and Bit-G increased linearly together with increasing WOB. The ROP of Bit-G was slightly larger than that of Bit-F probably because of difference of back rake angle.

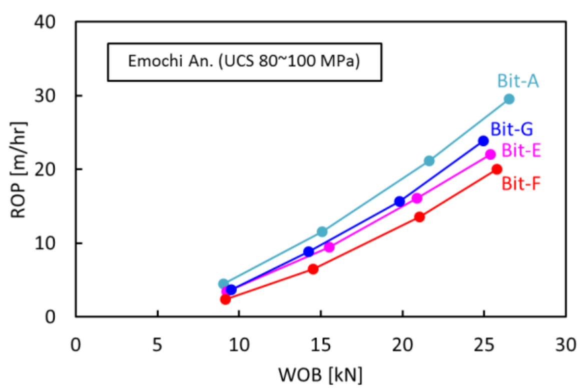


Figure 22: ROP-WOB relationships measured in the pretest using Bit-F and Bit-G.

8. CONCLUSIONS

For the purpose of developing PDC bit for drilling geothermal wells, manufacturing technique of PDC cutters having wear resistance together with impact toughness was established, and PDC bits equipped with basic specifications for the purpose were fabricated. Five types of PDC bits in total were applied to the drilling in five different geothermal developing sites respectively, and the drilling performance of each PDC bit was measured. Targeted goals regarding drilling speed and gage loss were achieved, while that of drilled length remained unachieved. Severe wears and delamination on the PDC cutters were observed especially in drilling hard rock strata, and therefore it was suggested that mitigation of excess impact to the PDC bit or PDC cutters were essential to improve the bit durability. PDC cutter with enhanced both of wear resistance and impact toughness was developed, and Bit-F and Bit-G were fabricated after primarily reconsidering arrangement of the PDC cutters. It was shown in the pretest that drilling performance of both PDC bits was still high as compared to the other ones. Field experiments using Bit-F and Bit-G has already planned, and the targeted drilled length is expected to be achieved in the experiments.

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