World Academy of Science, Engineering and Technology
International Journal of Materials and Metallurgical Engineering
Vol:16, No:11, 2022

Development of an Impregnated Diamond Bit with an Improved Rate of Penetration

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***Abstract*—**Deeper petroleum reservoirs are more challenging to exploit due to the high hardness and abrasive characteristics of the formations. A cutting structure that consists of particulate diamond impregnated in a supporting matrix is found to be effective. Diamond impregnated bits are favored in these applications due to the higher thermal stability of the matrix material. The diamond particles scour or abrade away concentric grooves while the rock formation adjacent to the grooves is fractured and removed. The matrix material supporting the diamond will wear away, leaving the superficial dull diamonds to fall out. The matrix material wear will expose other embedded intact sharp diamonds to continue the operation. Minimizing the erosion effect on the matrix is an important design consideration, as the life of the bit can be extended by preventing early diamond pull-out. A careful balancing of the key parameters, such as diamond concentration, tungsten carbide and metal binder must be considered during development. Described herein is the design of experiment for developing and lab testing 8 unique samples. ASTM B611 wear testing was performed to benchmark the material performance against baseline products, with further scanning electron microscopy and microhardness evaluations. The recipe S5 with diamond 25/35 mesh size, narrow size distribution, high concentration blended with fine tungsten carbide and Co-Cu-Fe-P metal binder has the best performance, which shows 19% improvement in the ASTM B611 wear test compared with the reference material. In the field trial, the rate of penetration (ROP) is measured as 15 m/h, compared to 9.5, 7.8, and 6.8 m/h of other commercial impregnated bits in the same formation. A second round of optimizing recipe S5 for a higher wear resistance is further reported.

***Keywords*—**Diamond containing material, grit hot press insert, impregnated diamond, insert, rate of penetration, ultrahard formation.

I. Introduction

In the oil and gas industry, the share of hydrocarbons produced from the globe's approximately 500 giant fields is in decline. Few giant fields have been discovered since 1960, with most of the largest fields being over 60 years old and in decline [1]. Companies have successfully exploited unconventional and deep hydrocarbon resources to counteract the lack of new giant fields. The deeper wells are challenging to drill due to harder and more abrasive characteristics of the formations. In order to solve this challenge, drilling tools performance is improved through materials, processes, designs and fit-for-need optimizations. In the drilling tool family, each of the tricone drill bits, polycrystalline diamond compact (PDC) bits, hammer bits and impregnated bits have their own advantages and disadvantages, with engineers striving to expand their application windows.

Roller cone bits are efficient and effective for drilling through formation materials that are medium to high hardness. The drilling mechanism is crushing and gouging, which is accomplished by impacting the formation material. The bit compresses the formation beyond its compressive strength, thus achieving penetration. For high hardness formations, the drilling mechanism shifts from crushing and shearing to abrasion, requiring a fixed abrasive element. For PDC cutter bits, hard interbedded formations will cause damage [2]. As a result, unnecessary tripouts are required to replace the bit, adding additional drilling cost and time. A cutting structure that consists of particulate diamond impregnated in a supporting matrix is found to be more effective in these formations [3].

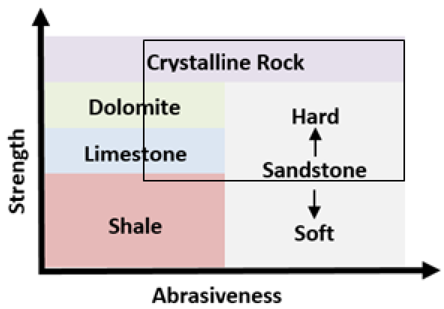

Fig. 1 Plot of the abrasiveness compared to strength for various rock types. The box indicates where impregnated cutter use is optimal

Impregnated bits are widely used in hard and/or abrasive formations. In China, successful exploration has occurred in the Middle Permian Maokou and Qixia Formations located in the Sichuan Basin. Lithologically, the Middle Permian Qixia Formation and Maokou Formation are dominated by a section of stably deposited carbonates. The Qixia Formation consists mainly of limestone with nodular and banded black chert [4]. Drilling the formation frequently results in truncated cutter life due to wear and damage. A higher wear resistance cutter would result in more economical drilling by reduced damage to the bits, allowing for higher ROP and fewer trip outs, thus shortening drilling times.

II. Materials and Experiment

Diamond distributed in a hard matrix is progressively exposed as surface diamonds are worn and shed to maintain adequate ROP. In the design of an impregnated cutter, two competing processes must be balanced. If the embedded diamonds are exposed too quickly, the life of the cutter is shortened [5]. If the embedded diamonds are exposed too slowly, the overall ROP will be reduced. These factors are adapted for the demands of the formation and customer. An

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important parameter is what matrix material is used to retain the diamond [6]. Tungsten carbide (WC) particles of varying sizes are used in conjunction with CoCuFeP for the binder. Diamonds are mixed with matrix powder and binder into a paste, which is then loaded into a doser. The paste is extruded into short cylinders that are rolled and dried into irregular granules. The granules are packed into the desired areas of a mold, where they are subjected to a pre-compaction step using a cold press stage prior to hot pressing under an inert atmosphere [7].

The initial batch consisted of a 25/35 diamond mesh, most with a size distribution of ± 5%. The distribution was varied to have a wider diamond size distribution in some formulas. The diamond volume percentage is varied between 17.5% and 27.5%. It is reported as diamond concentration, a 4x multiple of the volume percentage. The diamond granules are consistently distributed to allow a high concentration where the diamonds are not in close proximity. The diamond particle retention is increased as all portions of the diamond are encapsulated by the matrix, which in turn will increase the life of the cutter.

Selection of the matrix material must ensure processing temperatures that will not graphitize or oxidize the diamond. The matrix material must be adequately abrasion resistant so sharp diamonds are not released, impacting cutter life. Further, it must be hard to avoid localized yielding as diamonds push into the formation under high force. Tungsten carbide with a CoCuFeP binder meets these criteria. The size of the tungsten carbide particles range from fine to coarse, and can be fused or spherically cast. Coarser grains are easier to infiltrate with a molten binder during the powder metallurgy processes, whereas fine grains have a higher packing density. Finer grains will have higher hardness, whereas coarser grains will have higher toughness [7].

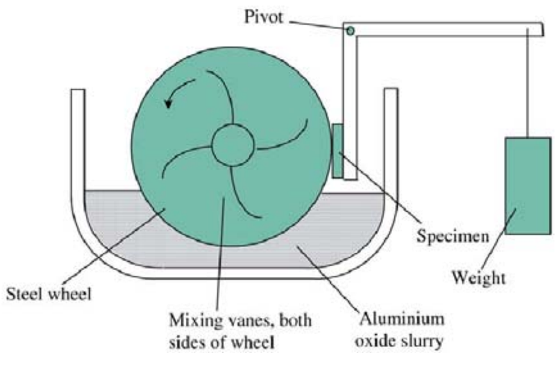

Fig. 2 ASTM B611 Wear Test Figure from standard [8]

Fig. 3 25x75x6mm coupon used for ASTM B611 testing

To ascertain the wear resistance, ASTM B611 testing was performed on 25x75x6 mm coupons in triplicate. ASTM B611 covers the determination of abrasive wear resistance of cemented carbides under high stress abrasive conditions. It is a practical test for comparing the formulas in standardized conditions. A vessel contains abrasive slurry that a wheel rotates in contact with the specimen. The slurry consists of 30 mesh grit in proportion of 4 g to 1 cm^3 of water [8].

TABLE I
THE SAMPLE ID OF THE EIGHT BATCH I FORMULAS ALONG WITH THE REFERENCE

Sample ID	Diamond Size (mesh)	Diamond Concentr.	WC Size	WC Type
S1	25/35 (± 5%)	70	Fine	WC
S2	25/35 (± 5%)	100	Fine	WC
S3	25/35 (± 5%)	70	Medium	WC
S4	25/35 (± 5%)	100	Medium	WC
S5	25/35 (+ 10%, -15%)	100	Fine	WC
S6	25/35 (± 5%)	70	Fine + Medium	WC (fine), spherical cast (medium)
S7	25/35 (proprietary aggregate)	70	Fine + Coarse	WC (fine), fused cast WC
S8	25/35 (70%) +30/40 (30%)	110	Fine	WC
Ref.	Baseline reference material			

The diamond size and mesh are listed in the second column, with diamond concentration in the third column, tungsten carbide size in the fourth, with the type in the final column.

TABLE II
KEY PARAMETERS AND VALUES FOR ASTM B611 TESTING

Test Parameter	Value
Wheel Speed	100 (RPM)
Test Duration	1000 revolutions
Abrasive	30 mesh alumina
Normal Force	20 kg (44 pounds)

The matrix hardness was measured using Vickers hardness testing in order to estimate its ability to resist wear and retain the impregnated diamonds.

After testing of the samples, the sample demonstrating the lowest volume loss from ASTM B611 testing was selected for a field trial. A difficult to drill formation, Longtan Formation-top of Hanjiadian Formation, was selected to verify the performance of the developed impregnated diamond cutter. The well is located in southeastern Sichaun Province. The borehole size of the used well section is φ311.2 mm in the target formation.

After the field test, a further formula optimization effort was completed. However, the wear mechanism provided by ASTM B611 may not be the most representative of field conditions, so a modified version was chosen to test the Batch II volume loss [9]. A cylindrical sample was used to grind 20 mm from a class 5 granite wheel. Afterwards, the working surface of the cutter may be inspected to count the number of intact diamonds, flat crushed diamonds, diamond pull outs, polished diamonds, striations, and cleaved diamonds. Testing is more similar to field conditions in how the matrix/metal bond. An insignificant weight and height reduction will occur as the inserts are too wear resistant. A better metric, the cutting efficiency, may be calculated by taking the granite disc mass loss divided by the time.

TABLE III
THE SAMPLE ID OF THE EIGHT BATCH II FORMULAS ALONG WITH THE REFERENCE AND S5

Sample ID	Diamond Size (mesh)	Diamond Concentr.	WC Size	Note
S10	25/35 (+10, -15%)	100	Medium	
S11	25/35 (+10, -15%)	100	Fine	Coarse center diamond
S12	25/35 (+10, -15%)	100	Fine	Fuse cast carbides
S13	25/35 (+10, -15%)	100	Medium	Fuse cast carbides
S14	25/35 (± 5%)	100	Fine	Coarse center diamond, fuse cast carbide
S15	25/35 (+30, -40%)	100	Fine	Coarse center diamond
S16	25/35 (+10, -15%)	100	Medium + Coarse	
S17	25/35 (+30, -40%)	110	Fine	
S5	25/35 (+10, -15%)	100	Fine	S5 from Batch I
Ref.	Baseline reference material			

The diamond size and mesh are listed in the second column, with diamond concentration in the third column, tungsten carbide size in the fourth, with the fifth column a note indicating special parameters.

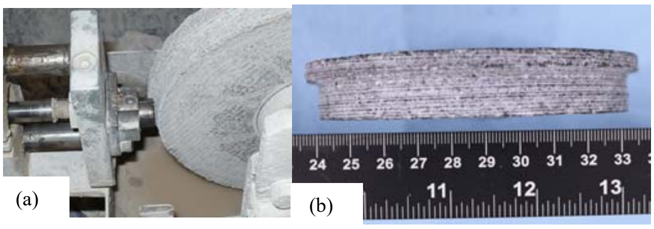

Fig. 3 (a) Modified ASTM B611 test using a Ø13.5x18 mm cylinder. (b) Granite disc after removing 20 mm

III. Result and Discussion

A. Batch I Test Results

The ASTM B611 test results are presented in Fig. 4. Three samples had a smaller volume loss than the reference sample (S2, S5, and S8). All of these formulas had fine grain tungsten carbide. Further, all of these had a diamond concentration of 100 or more. The sample, S1, with fine grains but a diamond concentration of 70, had a higher volume loss, indicating that a higher diamond concentration with all other parameters the same (S2) will result in better volume retention. A wider diamond distribution (S5) over a tight distribution (S2) is beneficial up to a very wide distribution (S8). A very high concentration with a wide distribution (S8) has a diminished performance to a high concentration with a moderate distribution (S5).

The matrix hardness measured by Vickers microhardness is presented in Fig. 5. S1, S2, S5, S7, and S8 all had higher matrix hardnesses than the reference material. S2 and S8 were very close to the reference. All of the tungsten carbide matrixes with similar or higher hardness were fine grain. However, S7 did use a combination of mostly fine and some coarse grains. The harder fine grains increase the wear resistance and thus performance of the cutter.

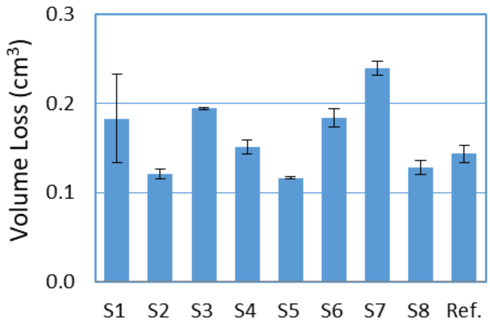

Fig. 4 Volume loss results of Batch I ASTM B611 testing. The average and standard deviation for each formula are presented in the plot

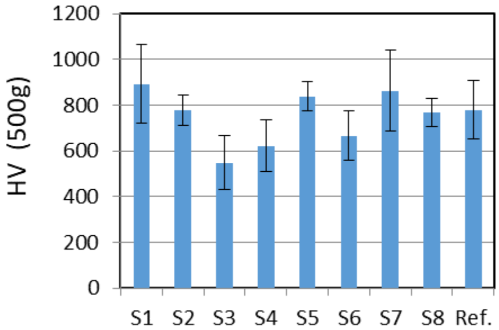

Fig. 5 Microhardness of Batch I samples. The average and standard deviation for each formula are presented in the plot

S5 was chosen as the candidate formula for the field test as it displayed a high matrix hardness and 20% reduction in volume loss. S5 impregnated cutters were manufactured and shipped to the field location.

B. S5 Field Testing

Field testing was conducted to verify the performance of the developed S5 impregnated diamond cutter in difficult-to-drill formations. The selected well was located in the southeast of the Sichuan Basin. Three adjacent wells in the same section were drilled with commercial bits. The results are presented in Table IV.

TABLE IV
TABULATED PARAMETERS OF THE DRILLING RESULTS COMPARED TO ADJACENT WELLS

Bit	Well Section (m)	Drilling Length (m)	Drilling Time (h)	ROP (m/h)
CNPC S5	887-1316	429	28.35	15.13
Offset	780-1230	450	66.02	6.83
Offset	780-1217	437	45.87	9.55
Offset	785-1201	426	53.55	7.79

429 m (887-1316 m) of Longtan Formation-Qixia Section was completed with a total drilling time of 28.35 hours. The average ROP of this section was 15.13 m/h. The bit was tripped out as the intermediate section was completed. The newness of the drill bit was 70% with 5 PDC cutters spalled. It was observed that the rear impregnated cutters were slightly worn in addition to 3 gauge cutters spalled. The blades were intact, the nozzles were not plugged, and there was no balling issue. The

use of the S5 cutters significantly improved average ROP compared to the commercial bits used on the adjacent platforms.

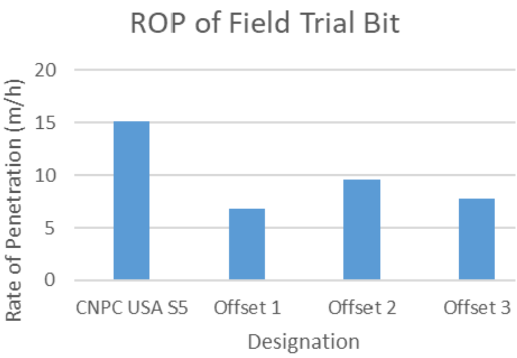

Fig. 6 Average ROP of formula S5 compared to adjacent platforms

Fig. 7 Photos after the drill bit was tripped out of the well

Results from the field trial indicated that the impregnated bits needed improved wear resistance, particularly as a function of ROP. A focus on using coarse center diamonds with distribution of smaller diamonds to protect the larger diamonds was theorized to increase wear resistance.

C. Batch II Test Results

Generally in Batch II, the diamond size was 25/35 with a distribution +10, -15% based off of the success of S5. Coarse center diamonds were added to the S5 baseline to create S11. Fuse cast carbides demonstrated a higher hardness which had potential for a more wear resistant matrix. S12 and S13 were created to investigate whether the wear resistance could be increased using fuse cast carbides. S14 combined coarse center diamonds with a fuse cast carbide matrix. S15 was formulated to test coarse center diamonds with a wide distribution of protective finer diamonds that could minimize the protrusion of the larger diamond. S16 was created to understand the possible gain in wear resistance from medium and coarse tungsten carbide comingled matrixes. S17 was tested as a reference to S15 without the coarse center diamond and a higher diamond concentration.

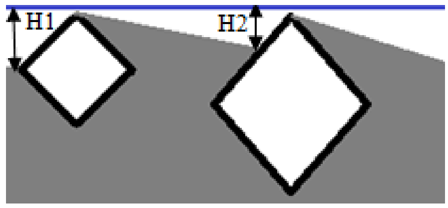

Fig. 8 Fine diamond preventing protrusion of a larger diamond

TABLE V
SUMMARY OF THE MEASURED CUTTER WEIGHT LOSS, HEIGHT LOSS, AND ROP MEASURED FROM THE GRANITE DISC

Sample ID	Avg Weight Loss (g)	Avg Height Loss (mm)	ROP (g/min)
S10	0.27	0.1015	27.8
S11	0.25	0.019	18.1
S12	0.28	0.0395	17.3
S13	0.52	0.019	20.3
S14	0.155	0.032	18.8
S15	0.19	0.034	29.0
S16	0.75	0.043	13.5
S17	0.17	0.08	19.9
S5	0.305	0.0255	20.8
Ref	0.35	0.0495	17.9

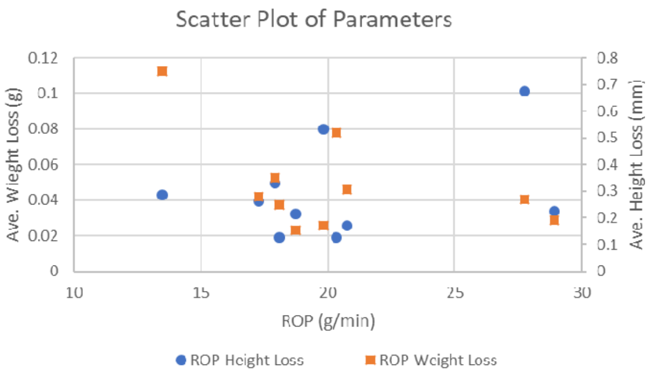

Fig. 9 Scatterplot of the weight loss and height to the ROP. No clear trend emerges from the plot

In the modified ASTM B611 testing, S5 outperformed the reference ROP by 15%. This is in line with results from Batch I. Generally, the new Batch II samples showed less weight loss than the reference and S5. Only S11 and S13 outperformed S5 on height loss. S10 and S15 demonstrated a superior ROP to S5. A comparative scatterplot of ROP to height loss and ROP to weight loss did not indicate a clear trend. Testing was on average 60 minutes in duration, which is not enough to measure a major height loss. The weight loss was also low due to the duration of the test. The ROP is the best indication of performance as it shows how efficiently the granite is removed. S15 demonstrates a 40% improvement over S5 and a 61% improvement over the reference. The ROP is higher than the reported values in literature [10]. The coarse center diamond with a wide range of diamond sizes enhanced the cutting efficiency. A possible explanation is the finer grit diamonds will hinder the full protrusion of the larger, coarser diamonds while creating more protrusion surface area.

IV. Conclusion

An impregnated cutter was developed for field testing after coupon evaluation of 8 formulas by ASTM B611. The best performing formula in lab testing had 20% less mass loss than the reference. Field testing of the S5 formula demonstrated a ROP 58% higher than the next highest value from commercially available impregnated cutters. In order to improve the wear resistance, S15 from a final optimization batch of 8 formulas yielded a 40% improvement over S5 in a modified ASTM B611 test. The use of fine grain tungsten carbide was superior to coarser grains. Diamond concentrations of 100 were optimal. A diamond mesh with a moderate distribution was superior to tight or wide distributions when no coarse center diamond was used. When a coarse center diamond was used, a wider diamond distribution is preferable. S15 ROP and wear resistance will likely outperform both the reference and S5 in a similar difficult-to-drill formation.

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