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Improved design, matrix materials reduce costs while drilling interbedded formations

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EVEN WITH THE significant developments in polycrystalline diamond compact (PDC) cutter technology over the past decade, bits comprising diamond-grit impregnated working surfaces are still preferred for drilling hard and abrasive formations. Such "impreg" bits may also be required to operate on interbedded formations, including those containing softer and stickier lithologies such as shale. Functionality must be considered on both micro- and macroscopic scales.

Microscopically, impregnated bits operate by providing a balanced wear of the diamonds and surrounding matrix, continuously regenerating the surface through the exposure of new diamonds. Matrix wear rates should not be so high as to limit the useful working life of the diamond. Neither should they be so slow as to limit the protrusion of the diamond and restrict the passage of detritus from the face of the bit. Macroscopically, the inclusion of geometries that promote shearing of softer interbedded formations, whilst contributing to the cleaning and cooling of the diamond metal matrix composite (DMMC) are considered beneficial to improved penetration rates.

A development project was identified; the objective was to increase impregnated drilling efficiency through hard and interbedded formations and to transfer the knowledge and improvement model to other sizes and applications. **Petroleum Development Oman** (PDO) was willing to develop and improve impreg performance. The Saih Rawl and Saih Nihayda fields in Oman were proposed locations, containing interbedded formations. Geological data were available for the intended application. The Oman application also provided the timely return of dull impregnated bits for evaluation.

A project team was created. Materials engineers were responsible for improving the existing manufacturing processes and characterising the wear of the DMMC. The geometric design was created and adapted by the eesign engineer, while the applications engineers provided detailed run and formation information.

Figure 1: Field experience of historic bit designs had shown that an interrupted blade profile as shown here produced increased penetration rates when operating through interbedded shale containing formations.

Developments and improvements were achieved iteratively. From the initial design, subsequent modifications were made continuously.

To fully evaluate the wear modes of the dull impregnated bits, a quantitative analytical technique was developed. The technique has since proven to be valuable in recommending improvement strategies for Oman and other applications. Central to the technique is detailed microscopic examination of the diamonds and the surrounding metal matrix composite (MMC). Outcomes include the applicability of the size, grade, concentration and retention of the diamonds and relative wear rate of the MMC.

OMAN APPLICATION

The Saih Rawl and Saih Nihayda fields are located in northern Oman in the Ghaba Salt Basin. Deep liquefied natural gas (LNG) wells target the two main reservoirs of the Barik and Amin sandstones, both of which are hard, abrasive Palaeozoic sandstone sequences of late Cambrian age. These reservoirs are each capped by sequences of sand and shale. The Ghudun sandstones, Barakat & Mabrouk shale units overlay the Barik sandstone, which then leads into the heavily interbedded Al Bashair carbonate and shale sequence followed by the Miqrat shales and siltstones overlaying the Amin. LNG wells on Saih Nihayda field drill deeper into the Amin as it is a primary LNG reservoir.

The lower formations of the Saih Rawl and Saih Nihayda fields consist of predominantly dense clay, with silt, sand and pebble horizons interbedded. The Barik sequence is dominated by fine-grained sandstones interbbeded with thin red and green shales. The Al-Bashair section contains an interbbeded sequence of fine sandstones, siltstones, shales and limestones. The Miqrat formation is a sequence of red brown shales and siltstones thinly interbbeded with fine sandstones. The final Amin sequence of sandstones with various developed siltstones and conglomerates in the lowermost part. Typically the final 100 m of the Amin interval contains the highest confined compressive strength of the section.

To develop an experimental range of diamond impregnated drill bits, significant

EXCLUSIVE WEB CONTENT
Figure A: Protrusive elements providing shearing and cleaning capabilities in experimental bit. Increased protrusive heights compared with the historical series were introduced to offer an uniform and improved duration of shearing capability.

changes to the processing, materials and design of legacy product were required. These improvements led to unprecedented levels of casting integrity and provided a capability for rapid execution of modifications to the design and materials based on dull evaluations.

New manufacturing processes developed during the project provided robust, reliable and high integrity product. Infiltration and solidification cycles were optimized through the use of finite element models and validated through sectioning and examination. Improvements in processing provided a more regular diamond distribution and much reduced levels of contamination throughout the MMC compared with historic techniques. In addition to the benefit of improved structural integrity, improved diamond to MMC interfaces were achieved. The adoption of new moulding methods enabled geometric and materials changes to be made quickly.

As a result of research into the wear behaviour of diamond metal matrix composites, a technique was applied to characterise dull bit surfaces. In developing the method, legacy diamond impregnated bits were initially examined, resulting in material improvement opportunities that were immediately transferred to the experimental range. Using a light microscope, the condition of the diamonds and surrounding MMC were assessed quantitatively. Evaluation results revealed the wear behaviour during the final stage of the bit run. The assessment was cognizant of its performance through its last lithology. In particular the predicted rock strengths, abrasivity and final penetration rate formed a basis for recommendations. Understanding the wear mechanism(s) was key to improving performance; examination at different radial locations over the surface of the bit revealed regional differences in wear behaviour of the DMMC. Outcomes from the technique included an assessment of the appropriateness of the diamond grit size, grade and concentration. Cases were also identified when the wear rate of the surrounding material was out of balance compared with diamond breakdown and loss.

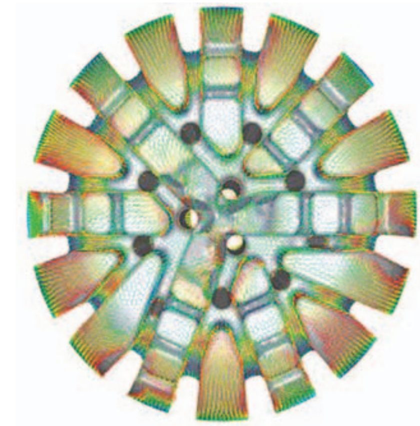
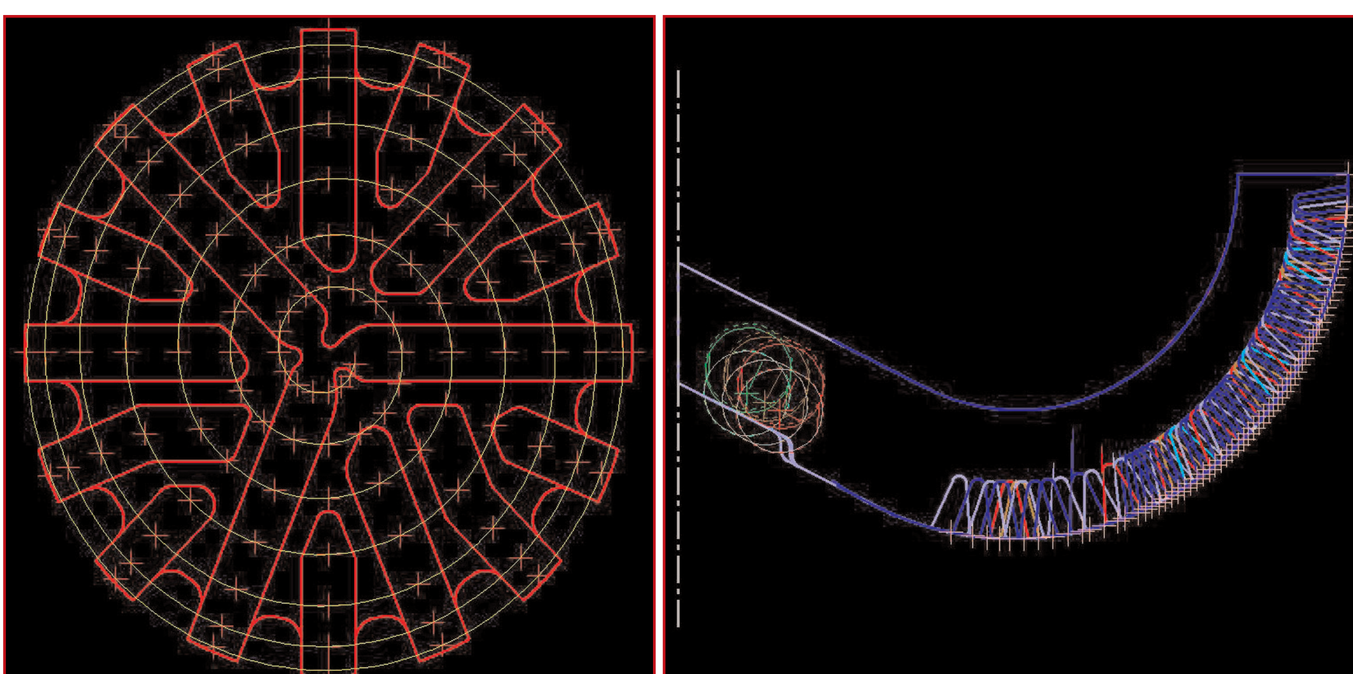
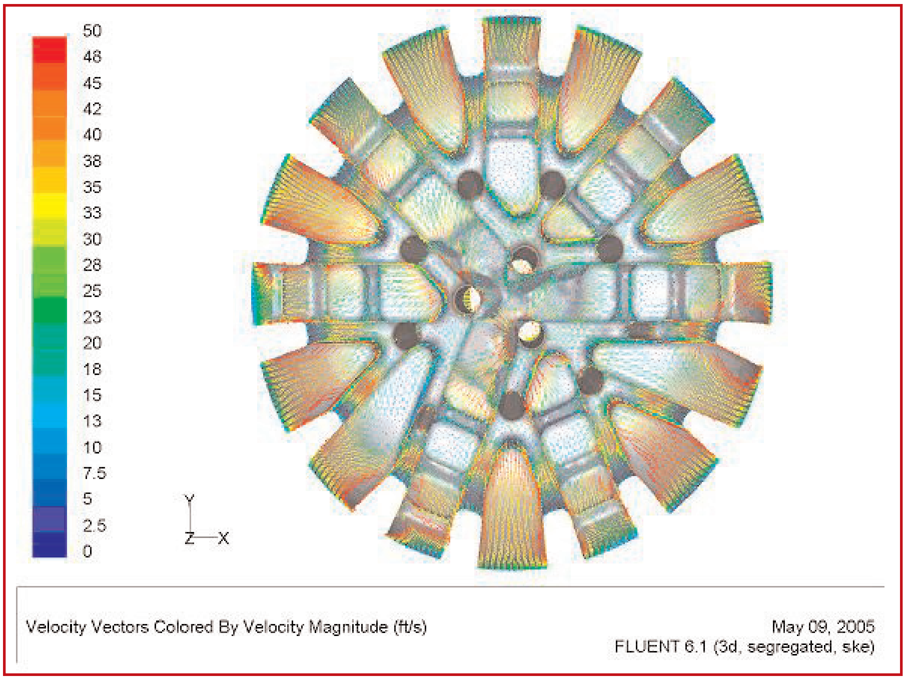


Figure 2: A computer-generated model revealing fluid dynamics of the experimental design.

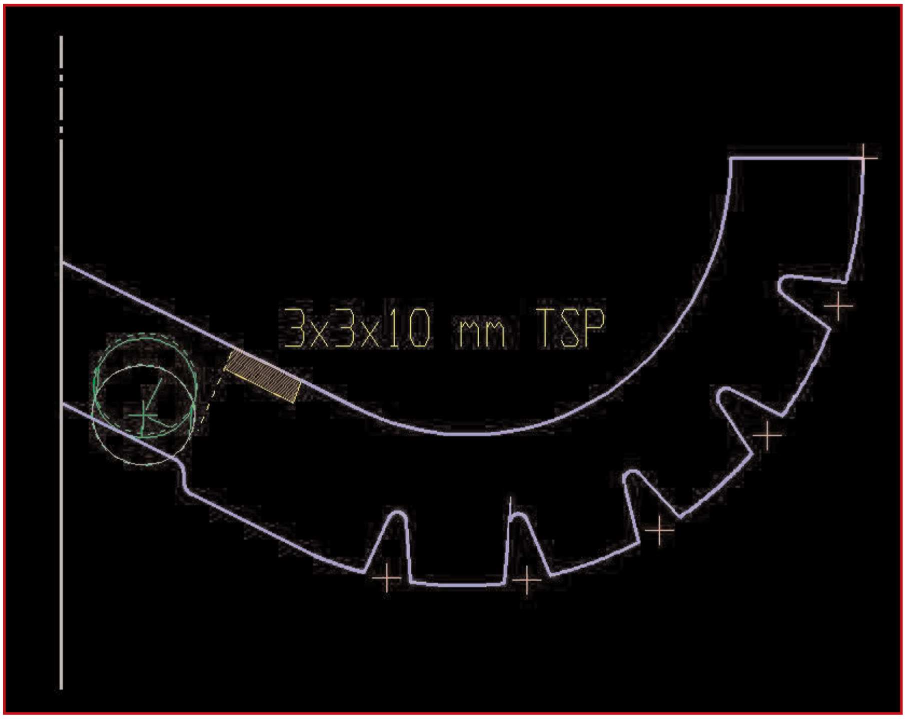
The proposed lithologies were considered in selecting the geometry for the experimental range of impregnated bits. Field experience of our historic bit designs had shown that an interrupted blade profile as shown in Figure 1 pro-



EXCLUSIVE WEB CONTENT Figures B (1 and 2): Spiral location of protrusive shearing elements for the experimental series. The protrusive elements were located in a spiral configuration to further improve the shearing potential and incorporating drag bit cutter location philosophies.



EXCLUSIVE WEB CONTENT Figure C: During the design validation process, computational fluid dynamics models were used to evaluate hydraulic energies and flow paths. Shown here is a typical result.



EXCLUSIVE WEB CONTENT Figure D: In order to avoid coring, but so as to not detract from the free cutting characteristics of the DMMC, sub-surface thermally stable product (TSP) were included in the cone to act as bearing surfaces during the final stage of the bit's life.

duced increased penetration rates when operating through interbedded shale containing formations. The initial advantages of this profile were limited by the height of the interruption, since they wore completely and no further shearing potential was available. Adapted from initial concepts, the new design adopted an interrupted profile for operating through interbedded formations. Increased protrusive heights compared to the historical series were introduced to offer improved duration of shearing capability. To further improve the shearing potential and incorporating drag bit cutter location philosophies, the protrusive elements were located in a spiral configuration. Effective cleaning of the detritus and cooling of the diamonds were important considerations. Ports were positioned to provide effective and uniform hydraulics on all blades. During the design validation process, computational fluid dynamics models were used to evaluate hydraulic energies and flow paths. Figure 2 shows a typical result. Improved cross blade lubrication was promoted by waterways located between the protrusive elements.

The results of comparative field and laboratory data when comparing a new generation of polycrystalline diamond compact (PDC) demonstrated clear superiority in terms of ROP and interval drilled to conventional cutters. Their inclusion has extended the application of drag bits to fields that were not historically PDC drillable. The new generation of PDCs were included within the cone of the experimental bit offering a shearing action, with improved durability and penetration rates compared with conventional cutters. To avoid coring but not detract from the free cutting characteristics of the DMMC, subsurface thermally stable product (TSP) were included in the cone to act as bearing surfaces during the final stage of the bit's life.

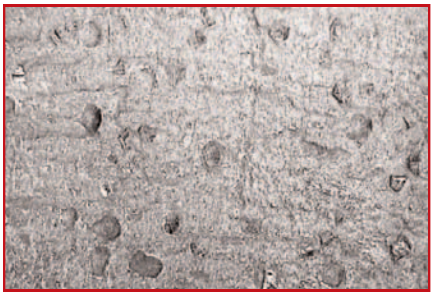
PERFORMANCE CHRONOLOGY

The following reveals the development and improvement process for the experimental range of diamond-impregnated bits. Run data were selected when possible, to provide comparisons between successive iterations. Within the development program, significant geometric changes were identified alphabetically, while alterations to the materials within similar geometries were distinguished numerically.

Well 1-Saih Rawl. A1 Version

The first experimental run of the A1 version was undertaken in the Saih Rawl field, in well 1 through the lower boundary of the Mabrouk and upper Barik formations. The performance of the initial A1 design was considered to have delivered a satisfactory rate of penetration, with no evidence of plugging or balling. The run length was a modest 150 m and the rate of DMMC loss was thought to be high with regions of preferential wear observed, together with an undergauge condition. Microscopic evaluation revealed that a large proportion of the diamonds had been lost prematurely. To provide a reduced DMMC wear rate and produce more preferential wear, the diamond size and concentration were adapted. Methods were proposed to provide improved retention and reduce the amount of missing diamonds. The bit and turbine sleeve gauge contact areas were increased to further improve durability.

To examine the relative performance of future iterations to the A1, the drilling costs per meter were indexed from the A1 run.



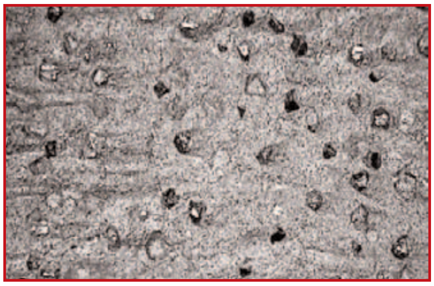
EXCLUSIVE WEB CONTENT

Figure E: High proportion of prematurely lost diamonds on the face of the A1 experimental diamond impregnated bit. In the Saih Rawl field, microscopic evaluation revealed that a large proportion of the diamonds had been lost prematurely.

Well 2-Saih Nihayda A2 Version

The A2 version incorporated improvements made as a result of examination of the A1. It was run in well 2 of the Saih Nihayda field. Compared with the A1, penetration rates were higher, particularly through the Miqrat shale section; dropping significantly on entering the harder Amin consolidated sandstone.

The onset of a ring out was observed in the cone, but the overall the run was twice the interval drilled of the A1 and half the drilling cost. Changes to the diamond selection and incorporation of retention methods had reduced the proportion of prematurely lost diamonds by 50%. Proposed changes for the future iterations, included modification of materials toward the cone of the bit to reduce the propensity for coring. The main objective was to be able to drill at increased ROP and longer intervals through the Amin section. Changes to the diamond size range used were proposed so as to better overcome the fracture strength of sandstone.



EXCLUSIVE WEB CONTENT

Figure F: The A2, run in the Saih Nihayda field, shows a 50% reduction in prematurely lost diamonds compared with the A1 due to changes to the diamond selection and incorporation of retention methods.

Well 3-Saih Nihayda A3, A4 and A5 Versions

The A3, A4 and A5 versions were returned and evaluated collectively after being run in the same well. The A3 was designed primarily for the Miqrat, whilst drilling as far as possible into the Amin formation. Like the A2, it recorded higher penetration rates in the Miqrat before slowing in the Amin and provided 65% of the drilling costs of the A1. Crushed diamonds were observed on the surface of the A3, indicating that they were too weak for the hardest final formation.

Although the A4 indicated increased durability than comparable competitive bits run in the Amin formation of well 2, further improvements were required. The A4 contained an experimental method to provide still further improvement in diamond retention. Since significant diamond crushing was evident, the adequacy of the alternative diamond retention method within the A4 could not be verified.

The A5 was proposed to drill the Amin, where the diamond size and grade would be better suited. Erosive wear of the metal matrix predominated in the A5 before the diamonds could become active with the formation.

Well 4-Saih Nihayda. A6 Version

Incorporating changes made as a result of evaluating previous iterations, the A6 adopted improved gauge protection and material selection to provide increased durability through the hardest sandstone section. Run in well 4, it achieved TD completing the demanding Amin section and part of the shale containing Miqrat formation. Its durability and pentration rate was improved compared to A4 and A5 runs in well 3 and comparable competitive runs through well 1. Allowing for a more arduous formation, drilling costs were 64% of the of the A1 version.

EXCLUSIVE WEB CONTENT

Figure G: In an alternative application in the Rockies, the first experimental 6 ½-in. A1 produced a satisfactory ROP, but after a modest run (225m) encountered significant blade wear (shown).

Well 5-Saih Nihayda. B2 Version

In order to overcome coring towards the cone encountered on the A versions, an extra row of new generation PDCs were included within the B versions. Material changes were made to the outside diameter and gauge to improve gauge durability. Like the A6, the B2 was able to complete the Amin section but at a higher ROP when run in well 5.

Well 6-Saih Nihayda. C1 and C3 Versions

The C versions included increased blade height, providing increased diamond composite volume and the potential for improved run duration. Blade ends were tapered and the gauge extended to provide increased contact area and volume for improved durability. The C1 runs through the Al Bashir and Barik sandstone and shale formations produced high penetration rates in well 6. Surface examination revealed an optimised diamond size and grade for the application. Evidence of thermally generated damage within the metal matrix composite, combined with a desire to provide still further run lengths resulted in an increase in the diamond concentration in the C3.

The C3 run produced high penetration rates through the Miqrat formation and was able to complete the notoriously difficult Amin. It was run for a second occasion drilling a further 240 m through a sand and shale formation in another field. Allowing for more difficult formations, the cost per meter drilled represents a 60% saving compared with the first A1 version.

EXCLUSIVE WEB CONTENT

Figure H: The dull condition of the experimental 6 ½-in. A2 in the Rockies after 360m.

Summary of Run Performances in Oman

Changes made to the materials and design based on detailed dull evaluation has continuously improved bit performance. Increased penetration rates and interval drilled has been encountered with successive, comparable iterations. The difficulty in completing the Amin section is demonstrated by the number of competitive runs in well 2 and the need for two experimental A4 and A5 bits in well 3. Modifications to the A6 enabled the Amin section to be completed with increased pentration rates, duration and reduced costs compared with the A4 and A5 versions. Changes to the cone of the B2 provided further improvements in ROP compared with the A6. Providing increased available volumes of DMMC, a more durable gauge and materials modifications to the C3 further increased durability compared to the B2 and reduced costs by 60% compared to the first A1 version.

Alternative Applications and Sizes

The knowledge gained in the Oman application and the continuous improvement model, has been applied concurrently to other sizes and applications. Both design and materials have been selected specifically for each application and improvements made iteratively as a result detailed dull evaluation.

In the Rockies, the first A1 version of a 6 ½-in. experimental impreg bit operated through an interbedded section containing sandstones, plastic shales and coal. The first run produced a satisfactory ROP but after a modest run encountered significant blade wear see Figure 12. Detailed post run wear characterisation revealed that preferential blade wear had been encountered as a result erosion of the MMC predominating regionally. Materials and geometric modifications were incorporated into the A2 version to promote even wear and extended run lengths. The A2 run in similar lithologies to the A1 produced similar penetration rates, with even and much reduced blade wear over an increased interval.

In Venezuela, the first run of the experimental 6½-in. version produced a field record for durability and penetration rate. The bit design was selected specifically for the application and completed 280 m at 2.2 m hr-1, providing the lowest cost impregnated bit in the section.

CONCLUSIONS

- Effective teamwork between operator and supplier has reduced drilling costs in Oman for the experimental series of impregnated bits by 60% within a short time scale.
- Modifications to the design and materials have provided an ongoing continuous performance improvement cycle.
- Informed recommendations were made as a result of detailed run information combined with detailed macro and microscopic dull evaluation.
- Improvement to processing provided a high integrity product where design and material modifications could be made quickly.
- Combined materials and geometric changes provided expected performance response.
- Objective of increasing drilling efficiency through interbedded formations has been met.
- Applying design and materials knowledge, together with the teamwork/iterative improvement model has been successfully transferred to other sizes and applications.

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