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Improving TC drill bit's efficiency and resistance to wear by graphene coating

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ABSTRACT

Displaying a two-dimensional pure crystal carbon structure, Graphene is the strongest, yet thinnest substance discovered by scientists. Coating tungsten carbide (TC) drill bits with graphene to evaluate the effect of graphene on the wear, as well as the rate of penetration of the drilling bit was examined in this research. Two evaluation approaches were employed: one with employing ANSYS Software and the second by employing atomic pressure chemical vapor deposition (APCVD synthesis) in the laboratory to produce a monolayer graphene coating. The simultaneous software-based and lab-based testing were performed to increase the credibility of the results and minimize the potential errors. Conducting the simulation using ANSYS, the maximum shear elastic strain, equivalent elastic strain, equivalent (von mises) stress, total deformation and maximum shear stress were investigated prior and after the graphene coating was applied on TC simulated bit. Total deformation was only slightly increased, while the maximum shear elastic strain was almost doubled, reflecting that the bit's wear was significantly reduced after the coating. Lab-based APCVD synthesis results showed 34% increase in compressive strength of the coated bit, in comparison to the uncoated one. The failure occurred for uncoated bit at 35 MPa, where the coated bit experienced failure at 46.9 MPa. The Von Mises stress test conducted on the coated and uncoated samples also indicated that this stress was 41% less for the coated bit, in comparison to the uncoated one. Finally, two small-scale drilling operations, one using a 1inch graphene-coated TC bit and the other using a 1inch non-coated TC bit, were performed on a granite block, to evaluate the performance of the graphene-coated bit in practice. In a chosen 120-min time frame, 27 consecutive holes could be drilled by the graphene-coated TC bit, while 19 consecutive holes could be drilled by the uncoated TC bit, in identical drilling conditions. This implies a 42% increase in ROP.

1. Introduction

The term “Graphene” was first introduced to the literature by Boehm et al. (1986) when they noticed it during the conduction of some lab experiments. Due to its unstable status, graphene was treated as a non-discrete matter and as such its applications in various industries had never been examined in practice before Geim and Novoselov et al. (2005) quite accidentally discovered the unique characteristics of the substance while peeling off layers of graphite from its body using a sticky tape in a lab in University of Manchester. The alluring properties of graphene associated with its sp^2 hybrid (i.e., sigma (σ) and pi (π) bonds within self-carbon atoms); which enables the substance to exhibit metallic behaviours such as high thermal and electric conductivity while simultaneously exhibiting the flexibility of a sheet of paper in bending and curving, has made it the ideal candidate to be employed in various industries.

Following a rapid popularity of graphene due to its surprisingly high strength, light weight and fascinating thermal and electric conductivities, oil and gas industries were no exception among the industries which were attracted significantly to this newly discovered substance with its magnificent properties (Syrett and Patel, 2015; Jamrozik et al., 2017; Liu et al., 2017; Rostami et al., 2017; Jamrozik et al., 2017; Ibrahim et al., 2019). It exhibits

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thermal conductivity of over 5000 [W mK−1], a tensile intrinsic fracture strength of 125 GPa, a Young's modulus of 1 TPa, an optical transmittance of approximately 97%, complete impermeability to any gases (Bunch et al., 2008), and its ability to sustain extremely high densities of electric current, which is a million times higher than copper (Syrett and Patel, 2015; Wang et al., 2019). Another exciting property of graphene is its hydrophobicity, which makes any graphene-coated surface to repel water. High resistance to acids, as well as many forms of mechanical or stress tensions, has given graphene a competitive advantage over similar materials used in various industries (Kudin et al., 2001; Koraktkar, 2013). It is important to note that graphene coats have significantly minimal effect on the intrinsic wettability of surfaces as reported by Rafiee et al. (2012) on tests done on copper gold and silicon except for glass. Dumée et al. (2015), successfully demonstrated growth of 3D networks of graphene nanoflakes throughout micron sized steel fibres. They used Scanning Electron Microscopy (SEM) to confirm 2–4 μm nanopillar formation on single sheet graphene coats.

There are four fundamental procedures for graphene synthesis as reported by Park et al. (2009): Chemical Vapor deposition (CVD), epitaxial growth, mechanical exfoliation, and graphene reductio. CVD synthesis is by far the most successful method in preparing large area monolayer graphene films of high structural quality to be coated on metal surfaces (Liu et al., 2017). Carbon precipitation on metals surfaces, known as growth mechanism, is relatively an easy process, due to existence of a very strong interaction between carbon and the metal (Rostami et al, 2017; Zhang et al., 2014). During the subsequent cooling processes, the carbon atoms from the carbon sources, dissolve into the catalyst followed by the deposition at the metal surface to form graphene layers arranged in a honeycomb lattice (Wang et al., 2019). Two approaches of CVD adopted by Park et al. (2009), and Rafiee et al. (2012), use methane gas and/or liquid hexane as a precursor, respectively. The former tends to produce a monolayer of graphene with tendencies of growth suppression at the formation point whereas the latter produces similar results at a lower cost (Park and Ruoff, 2009; Reina et al., 2009).

The use of graphene in oil and gas industry and, in drilling oil wells, has been restricted mainly to studies conducted on the effect of graphene as an additive to the mud composition (Reina et al., 2009; Rostami et al., 2017) or oilfield related applications (Jamrozik and Terpilowski, 2018; Syrett and Patel, 2015). In an interesting study carried out in the Cretaceous Songliao Basin of Northeast China, results indicated that the lubricating properties of drilling fluid significantly improved when adding appropriate amount of graphene oxide rather than sole graphene, which seemed to have minimal effects on the lubricating properties of drilling fluid (Liu et al., 2017). It was also noted in the literature that the newly uncovered applications of graphene have also been expanded to shale stabilization efforts (Arvind, 2016). Das et al. (2016), demonstrated that graphene coating on metal cutting tools improved surface roughness, lifetime, and production efficiency. An earlier study had reported the potential of graphene coating on tips of tools eliminating reliance of coolants that are characterised by smoke, odour, and high costs (Moser et al., 2007).

Drilling bits must be consistently reinvented to conquer the major problems encountered during drilling operation such as drill bits fragility due to the presence of hydrogen sulphide gas, which is abundantly present in oil wells, excessive drill bit temperature increase following continual drilling operation, wear and corrosion of the drill bits teeth, body and cover following interaction with hard formations, and cracking of the bit due to stuck pipe or differential pipe sticking. Graphene presence has been proven as an enhancer with the ability to increase corrosion resistance and electrical conductivity with no effect to the primary structural properties of steel (Zhang et al., 2014). Successful graphene application on novel graphene bits has been used in polycrystalline diamond carbides (PDC) inserts; also, in nanowire applications (Wang et al., 2019). However, insufficient evidence was found in literature, on the study of graphene as the coating substance and tungsten carbide (TC) alloy as the substrate metal. One recent research conducted by Hu et al. (2019), however, studied the effect of graphene on modulus and strength of the wires, when the nanowires were coated by graphene. Tungsten Carbide (TC) drill bits in comparison to diamond bits have higher impact resistance yet suffer from low resistance to wear. This study employs two methods: Simulation by ANSYS software and CVD Synthesis Method to investigate the effectiveness of graphene coating in overcoming the highlighted drilling problems.

2. Methodology

Two distinct approaches were employed in this study in coating a TC drill bit with Graphene. The first approach benefited from the ANSYS software, for which both the TC input characteristics and the graphene coating characteristics, were simultaneously introduced to the software. The second approach incorporated the chemical vapor deposition (CVD), which performed the actual coating practice over the surface of a candidate 1inch TC bit via transferring the generated graphene on cupper substrate. Factors such as temperature, growth time, carbon source (hexane) flow rate and the substrate metal type will affect the CVD process (Zhang et al., 2014). These variables need to be controlled in accordance with the scope and purpose of graphene generation on metals.

Finally, in a pilot scale, two drilling operations in identical conditions, were performed using two TC bits: one coated with graphene and the other without a graphene coating on the substrate TC. The drilling with the graphene-coated drill bit, as expected and supported by the two other approaches, yielded satisfactory results, which will be reported in subsequent sections of this research paper.

2.1. Simulation by ANSYS software

“TC” as the main layer and “Graphene” as the underlying layer, were the two layers of information, the characteristics of which were introduced to the software as inputs as shown in Table 2. The sample TC bit underwent coating, and the coated sample was exposed to applied pressures in five sequences as depicted in Table 1. Maximum shear elastic strain, equivalent elastic strain, equivalent (von mises) stress, total deformation and maximum shear stress were measured prior and after the simulation, the results of which are contained in Figs. 2–5 (see Table 3).

2.2. CVD Synthesis Method

CVD processes typically involve two steps: the activation of gaseous reactants and the chemical reaction of forming a stable solid deposit over a suitable substrate (Reina et al., 2009). The

Table 1
Applied sequential pressure intervals.

Sequence	Time (S)	Pressure(psi)
1	0	1000
	1	5000
2	2	7000
3	3	10000
4	4	12000
5	5	15000

Table 2
Input characteristics of Tungsten Carbide (TC) and Graphene, introduced to ANSYS software.

	TC	Graphene
Thickness	5 nm	3.5 nm
Density	15.63 g/cm^3	0.77 mg/cm^3
Tensile Strength	530–700 MPa	130 GPa
Young's Modulus	700 GPa	1100 GPa
Compressive Strength	165 MPa	2 GPa
Mohs Hardness	9	20
Poison's Ratio	0.28	0.16

Table 3
Stress characteristics of Tungsten Carbide (TC) post coating, produced by ANSYS software.

	TC bit post coating
Thickness	7.7 nm
Density	16.12 g/cm^3
Tensile Strength	1900 MPa
Young's Modulus	880 GPa
Compressive Strength	630 MPa
Poison's Ratio	0.19

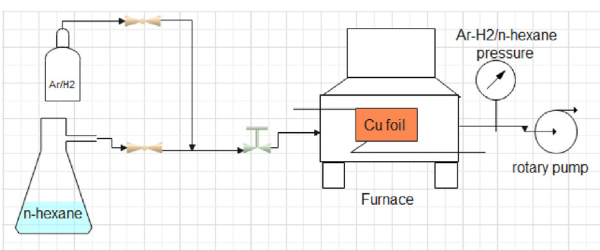

Fig. 1. The schematic diagram of APCVD process for growing graphene films adopted from Srivastava et al. (2010).

metals such as Ni, Co, and mainly Cu, have been reportedly used as the base metals on which graphene monolayer films can land (Reina et al., 2009; Li et al., 2009a; Lee et al., 2010; Bartelt and McCarty, 2012; Liu et al., 2017). Methane (CH4) and Ethyne (C2H2) as gaseous hydrocarbons and Hexane (C6H14) as the liquid precursor, are sources of carbon for graphene film generation purposes due to their abundance and availability (Park et al., 2010).

If the metal substrate on which graphene coating is going to

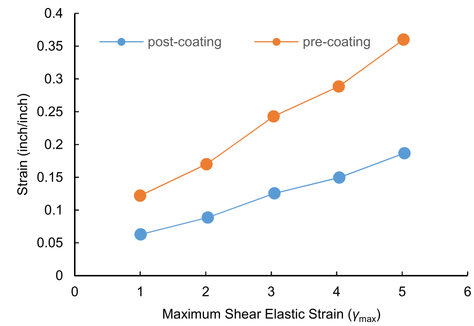

Fig. 3. Maximum shear elastic strain generated by ANSYS, before and after graphene coating, employing ANSYS.

land, is containing a high soluble carbon content (e.g., nickel), the carbon atoms produced by the carbon source cracking are infiltrated into the metal matrix at high temperatures and it will be very challenging to control the carbon deposition on metal's surface, as the solubility of carbon into the metal's matrix increases with temperature increase (Wang et al., 2019). This will result in production of uncontrolled multi-layered graphene, which is lacking the desired strength and uniformity of single layer graphene sheets. Nevertheless, it is evident that on copper foils, CVD consistently produces monolayer graphene (Park et al., 2010; Rostami et al., 2017). Employing gaseous sources of carbon such as Methane for graphene production involves high vacuum to be maintained, as well as accurate control of methane pressure, which are both challenging in nature (Rostami et al., 2017). The challenge was overcome by employing liquid sources of carbon mainly Hexane for CVD growth. The method incorporates cupper foils being loaded into a quartz tube and pumped down to a 10^{-2} Torr vacuum before flowing in Ar/He2 at a pressure of approximately 8–9 Torr with a flow rate of almost 400 sccm (Rostami et al., 2017), as shown on the schematic on Fig. 1. The sample is then heated to 800 °C inside the quartz tube in Ar/He2 ambient. At this temperature, the feed of Ar/He_2 is ceased and, hexane flow into the quartz tube initiates, maintaining a pressure of almost 500 mTorr for approximately 4 min. The hexane flow rate is kept at 4 mL/h. The produced graphene film can then be transferred onto variety of other substrate metals by coating a thin poly methyl methacrylate (PMMA) film onto a graphene/Cu system (Jamrozik et al., 2017). The underlying copper foil is then dissolved in a dilute nitric acid and the graphene/PMMA is transferred onto a substrate of interest (Tungsten Carbide

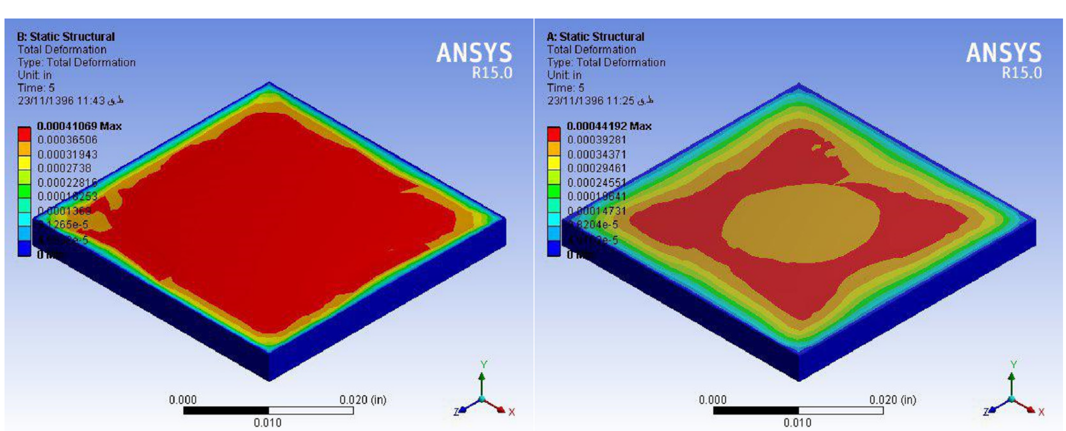

Fig. 2. Total deformation pattern generated by ANSYS, before (left) and after graphene coating.

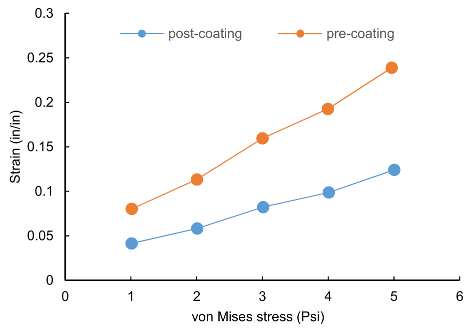

Fig. 4. Von mises stress of the sample bit before and after graphene coating, employing ANSYS.

in the case of this study). Following this transfer, the PPMA film is dissolved away using a hot acetone (Rostami et al., 2017). To have a full coverage deposition of carbon on host metal, Jang et al. (2015) have proposed an oxygen free process, during which all oxidizing impurities were completely removed by pumping before any graphene deposition initiates. The method is well-known in the literature, as atomic pressure chemical vapor deposition (APCVD) method.

This current research made substantial advantage of findings of Kim et al. (2009), Lee et al. (2010) and Jang et al. (2015) and could produce a thin monolayer of graphene over TC bit, following removal of oxygen. Currently, despite the complexity of the CVD method and its associated high energy demands and difficulties involved with performing various stages of the process, it remains one of the most successful methods for large-area graphene sheet production. Although the mechanical exfoliation method, in which graphene layers from the surface of graphite crystals are striped by mechanical force, provides highest quality graphene sheets, it was not considered suitable for this research work, as it suffers from generating large area graphene sheets, due to the difficulties associated in controlling the number of layers and the size of sheets (Kim et al., 2009; Srivastava et al., 2010; Wang et al., 2019). The procedures involved in coating the TC bit with a very thin layer of graphene is briefly reported below. Prior to the commencement of the experiment, the TC bit sample was cleaned thoroughly by Ethanol and subsequently was dried with compressed air. Graphene was then gradually coated on TC bit's surface by means of a tube Lenton furnace employing vacuum chemical vapor deposition process. The used Lenton furnace model was LTF 14/50/450. The sample then was put under 10 MPa pump pressure for 30 min.

Following placement of the sample into a ceramic container, a mixture of Argon–Oxygen was then poured onto the tube, with a discharge velocity of 400 cm/min and pressure of 533 Pa for 15 min, to clear the tube of any oxygen residuals left in the tube prior to initiation of the growth processes. The growth time was chosen to be 30 min in a temperature of 800 °C. A volume of 30 cm^3 of hexane with 99.9% purity, was available, as the carbon source. The temperature was adjusted to be over 800 °C as it was evident from the literature review that growth temperatures below 700 °C tend to produce poorly crystalline graphene (Novoselov et al., 2012), which lacks sufficient strength suited for a heavy-duty drill bit. Further reports indicate that foils from normal APCVD at 300 °C produced a non-desirable amorphous and oxidized carbon region (Park and Ruoff, 2009). In addition, lower temperature CVD deteriorates high quality graphene monolayer formation because of micro-sized graphene flakes being produced. Therefore, adapting this procedure for large surfaces possess a crystallization challenge.

The pressure behind the hexane present in the tube was kept at constant level of 533 Pa during the growth process. As the proposed method of graphene growth in this research was the diffusive growth, it is evident that only single-layer graphene will be formed because the feedstock cannot get access to the graphene covered area of catalyst surface (Lee et al., 2008; Wang et al., 2019).

The key criteria of concern in assuring the coating provides the TC drill bit with the maximum possible strength and toughness, relies on the carbon atoms attachment status at the edges of the graphene film layer (Novoselov et al., 2005). Increasing the carbon grain sizes, while simultaneously keeping the thickness of the graphene monolayer as thin and as uniform as possible, was the most challenging part of the growth process, which was successfully overcome during the APCVD test procedures.

3. Results

Because two distinct methodologies were employed in this study, outcomes obtained from both the ANSYS software as well as the results from APCVD procedure, will be reported, accordingly.

3.1. Results from ANSYS software

The followings are the summary of the simulation outcomes returned by ANSYS software.

Total deformation post graphene coating slightly increased, confirming that the elastic physical characteristics of the drill bit

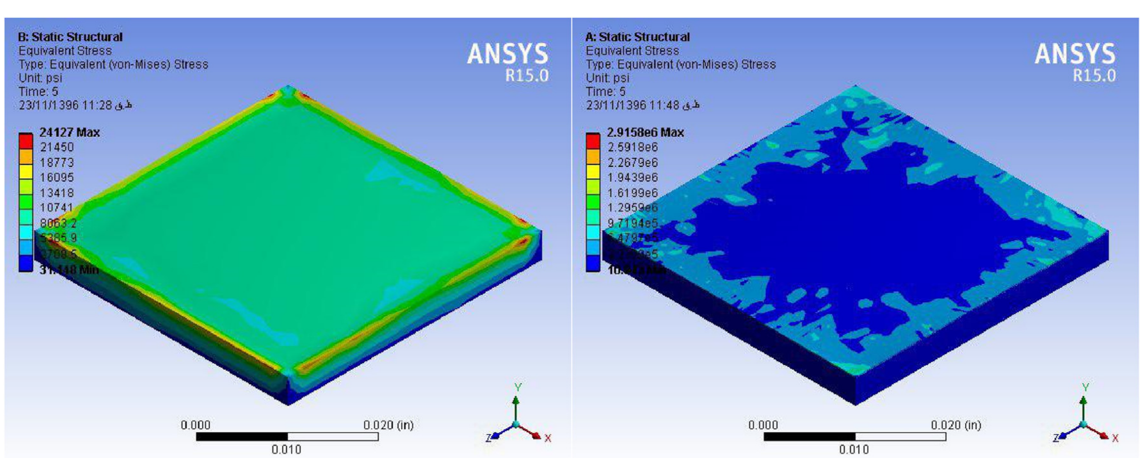

Fig. 5. Equivalent Stress (von Mises) pattern generated by ANSYS pre (left)- and post-graphene coating.

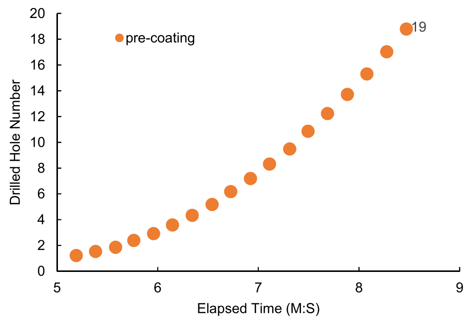

Fig. 6. Drilling time elapsed for the drilling operation, conducted on the sample granite block, performed with an uncoated TC drill bit.

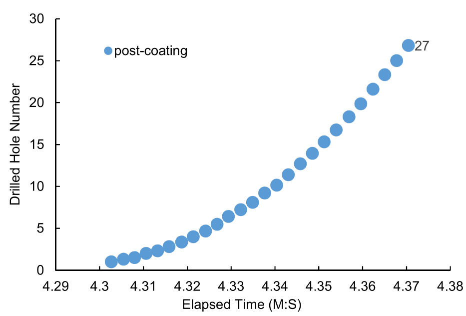

Fig. 7. Drilling time elapsed for the drilling operation, conducted on the sample granite block with identical drilling conditions, with the graphene-coated TC bit.

continued to increase after coating as shown on Table 1. This property is of great value to a bit's functionality in drilling through hard materials. Fig. 2 contains the total deformation pattern generated by ANSYS software before and after the graphene was coated on TC bit.

As reflected on Fig. 2, for pre-coating (left) image, the corresponding total deformation was dominated by the red zone (0.00036506–0.00041069 inch), and by very large margins, followed by orange (0.00031943–0.00036506), yellow (0.00027380–0.00031943), and light green (0.00022816–0.00027380) zones, which are extremely small compared to the red zone.

However, for the post-coating (right) image, due to the impact of graphene coating on the total deformation, the dominance of the red zone, having the highest total deformation, is highly influenced and almost half of its area is now replaced by the orange colour (lower total deformation), as well as the relative expansions of the previous minority zones of orange, yellow, and light green. It is further noticed that the new zones of green and light blue colours, which were initially absent in the pre-coating image, have now been introduced in very small portions, adjacent to the edges. This implies that due to the coating of the bit with graphene, the total deformation is now reduced further, and as it could be visually assessed using Fig. 2, it has reached the boarder of the light blue zone (0.00014731 inch). In fact, the zones have been pushed further down towards the lower total deformation zones. Although in terms of magnitude of the total deformation change, the observed changes are not considered major, only as one of the multiple parameters, it still affects the durability of the graphene-coated bits, accordingly.

The second outcome delivered by employing ANSYS, was that the TC bit's tolerance against tension almost doubled. This is a direct implication of the strain reduction post coating as illustrated in Fig. 3. Another interesting outcome was that the von Mises stress was almost halved after coating with graphene as reflected on Figs. 4 and 5. This reduction is greatly associated with an increased distance between Von Mises stress and the failure force because of increased tolerance to failure stresses on the TC bit.

As reflected on Fig. 5, for pre-coating (left) image, the corresponding von Mises stress was dominated by the green zone (8063.2–10741 psi), and by very large margins, followed by light green (10741–16095 psi), yellow and orange straps (16095–21450 psi), and some pockets of red zones (21450–24127 psi) at the 4-corners, which are almost negligible. However, for the post-coating (right) image, due to the impact of graphene coating on von Mises stress, the dominance of the green zone, having a relatively low von Mises stress level, is highly influenced and almost replaced by the dark blue colour (lower von Mises), followed by blue, light blue and green zones, which were considered the minority zones in the pre-coating image. Absolutely no red, orange, yellow or light green zones were present for the post-coating stage. This implies that the maximum van Mises value for the post-coating stage was achieved and all the other values are below this value, for the graphene-coated TC bit.

It is further noticed that the new zones of green and light blue colours, which were abundantly present in the graphene-free model, have now been introduced in relatively large portions, extended from the edges towards the centre in irregular patterns. However, they did not diffuse extensively and stopped the spread at the very early stages of diffusion. The irregular pattern is produced since the software tries to turn the von Mises stresses, calculated at various points into equivalents as the program is progressing with the calculations. The equivalent von Mises stress was reduced to the very minimum value of categorized in dark blue, indicating that maximum von Mises stress reduction has been achieved.

3.2. Results from APCVD synthesis

Two sections of both graphene coated, and non-coated TC bit (2.5cm each) were cut as samples to conduct various mechanical tests and assess the bits' stress and strain responses prior and post coating. The achieved results are summarised below. A 34% increase in compressive strength was observed in the graphene coated TC bit. Failure for the uncoated bit occurred at 35 MPa compared to 46.9 MPa for the graphene coated bit.

The Von Mises stress test was performed in the lab on the cut sections of the coated and uncoated bits, and it was observed that this stress was 41% less for the coated bit, in comparison to the uncoated bit. This agrees with the results obtained from ANYSIS.

3.3. Results from the pilot drilling replica

Two granite blocks of 160 × 80 × 80 cm^3 dimension, were drilled through by two drill bits: one by simulated small-scale TC bit which was graphene-coated and the other by a normal simulated small-scale uncoated TC bit and the drilling operation was in progress to penetrate through both granite blocks. The time frame of 120 min was selected, based on the last hole, which was drilled with the coated bit. Another hole initiated to be drilled at 2 h and 3 min, but the bit was too dull to be able to penetrate the rock except for 5 mm, after which the continuous drilling operation was completely halted. The 2-h time schedule was then selected as a base, to evaluate the effect of temperature on the coated bit and its functionality.

During the 2 h continuous drilling, 27 holes with identical length equal to the width of the granite block (80cm) were drilled by the graphene-coated TC bit (Fig. 6), while 19 holes could be drilled in a 2-h time frame with the uncoated TC bit (Fig. 7) at identical drilling conditions. This translates to a 42% increase in drilling speed employing graphene coated TC bits. For each of the drilled holes in both blocks, rate of penetration (ROP) was measured. it was observed that for the uncoated one, the ROP is not constant and gradually decreases, in accordance with the length drilled. The observed decrease, as reflected on Fig. 6, is following almost a linear pattern, which is a norm for majority of the drilling operations, except for ultradeep drilling conditions. However, it was observed that for the graphene-coated bit, the rate of penetration throughout the entire drilling operation was almost constant for all the wells drilled, with a very minor increase of 7 s per 80cm each, for the last 4 holes drilled. This was rather a strange behaviour exhibited by the graphene coated bit, since it was expected that ROP either continued its constant trend, or at least decreased for those last 4-wells, instead of an increase. This was followed by an observation for the graphene coated bit, as compared to uncoated TC bit, that the graphene coated one showed a sudden and abrupt last-minute increase in penetration rates, as opposed to the uncoated ones. A general pattern observed for the drilling rate declines, in the uncoated bit, follow almost a linear pattern, as depicted in Fig. 6. As a unique behaviour observed in bit dulling processes, for the coated bits, the bit becomes dull abruptly and without showing any prior clues, as opposed to the uncoated TC bits, in which we can observe a gradual dulling process. As it can be noted, the drilling rate was almost constant but experienced a sudden but minor increase while drilling the last 4 wells. In fact, drilling of the 28th hole started, but the bit was completely dull and couldn't start the penetration except for 5 mm. Sharply at 2 h and 3 min time, when the 28th hole started to be drilled, the bit was completely dull and the rock couldn't be penetrated through except for 5 mm, after which the drilling operation couldn't be continued and had to stop due to a completely dulled drill bit. About the thermal behaviours exhibited by graphene, there is nothing about abnormalities observed on graphene's thermal behaviour under any specific thermal conditions.

4. Discussion

The following discussions are noticed and acknowledged in this research. Some of the addressed discussions are planned to be further investigated in future research activities and some, which are assumed to have negligible effects on the overall credibility of the outcomes, have been accepted, as they are.

The graphene growth was performed in $800^{o}{}_{C}$ with 30 min growth time. Lower temperatures could be exercised, which would have resulted in coarser but weaker multilayered graphene production (Novoselov et al., 2012). The success rate of a graphene sheet production is measured by consistency and uniformity of the produced monolayered graphene sheet, which will eventually affect the drilling ROP. Successful application of single graphene layers is dependent on CVD schedule and environmental conditions (Wang et al., 2019). The growth duration was chosen to be 30 min, because this was the minimum time allowed for large area coverage (Novoselov et al., 2012) when production of monolayer graphene was concerned. However, as PACVD was employed in this research, which is not time-dependant in multilayer graphene production, a shorter growth time could also be exercised. This is not recommended, due to the quality of the produced coating, as the bonding strength is time-dependant (Park and Ruoff, 2009; Li et al., 2009b; Park et al., 2010). An increased ROP as shown in Fig. 7 confirms the success of the coating.

The carbon source (hexane) flow rate (ccm/s) was set to 4 mL/h in this study, because the area to be covered by graphene is relatively small and excess flow rate may affect the uniformity and consistency of the coating (Zhang et al., 2014). While transferring the produced graphene from the cupper foil to the TC surface, due to gradual temperature drops, the paste of the transfer is of great importance. A delayed transfer may result in poor bonding to form between the newly generated graphene sheet and the substrate alloy, which is the TC bit, within the context of this research work.

Concerning the abrupt increase while drilling the last 4 wells, with the current available data, retrieved from this research work, a potential hypothesis could be that this phenomenon might be associated with an intrinsic behaviour of graphene, which has a great potential for further investigations. In the author's opinion, when the graphene's maximum tolerable temperature was approaching, it is showing an abnormally high energy within a few seconds before it is fully discharged. This hypothesis is reinforced when the bit becomes completely dull in a matter of seconds. However, as mentioned earlier, more research work is required for this hypothesis to be further developed, since graphene and its unique applications are still being explored at the time when this transcript was produced.

The drilling operation on the replica was performed continuously and almost non-stop, to evaluate the wear resistance of the graphene coated bit under the extreme temperature conditions. If the physical and chemical changes that the graphene coated bit was undergoing during the 2-h period was to be assessed, then some hold points should have been designed, for instance after every 4-holes drilled. However, this would have affected the continuity and consistency of the drilling operation, which would have reflected on the amount of heat the bit was eventually exposed to. Moreover, it would also have affected the required continuous drilling operation to evaluate the effectiveness of the graphene coating in the context of the length drilled. However, it is strongly recommended to halt the continuous drilling operation on some selected hold points and conduct tensile strength tests, compression tests or any other tests to evaluate the physical status of the coated bit, in a separate study where the continuity and consistency of the drilling operation would not be incorporated in evaluation of the drilling efficiency, as part of the overall project objectives. The chemical properties of the graphene coated bits at those intervals could also be evaluated at those hold points.

5. Conclusions

In summary, we successfully coated one-inch TC bit with a uniform monolayer graphene film using hexane as the liquid precursor. The graphene coated TC bit was used to drill holes in outcrop rock samples for 2 h where a 42% increase in the number of holes was observed. Simulation of conditions in ANSYS software produced very similar results while demonstrating almost double increase in bits tolerance and confirming that the elastic physical characteristics of the drill bit continued to increase after coating.

The uncoated TC bit was used to drill holes while analysing drilling efficiency, whereas the graphene coated TC was simply to monitor the rate of penetration. It is evident that drilling efficiency is directly proportional to the drilling cost and, the rate of penetration, among other factors such as fewer trips to change the bit due to corrosion and wearing, is a factor that sustains drilling efficiency. By reducing wear and corrosion while increasing tolerance, the rate of penetration improved considerably and was almost doubled when graphene-coated TC bits were used in the given drilling operation. Consequently, there is a great potential for reducing the cost of the drilling operation by great margins, due to consumption of fewer TC drill bits for identical drilling conditions. This excludes the advantages attached to reducing maintenance costs, associated with drill bit maintenance, as one of the main contributors to the allocated drilling time and consequently saving a considerable amount of the valuable time. Increased tolerance implies that harder rock formations can be drilled through more conveniently resulting in drastic improvements in effectiveness and efficiency of the drilling operation.

Total deformation of the graphene coated bit, in comparison to the uncoated one, was noticed to be slightly reduced when ANSYS was consulted. This was then verified by the number of the holes drilled with the coated bit, which is incorporated with the reduced wear, as initially suggested by the software. This was further verified by the examination of maximum shear elastic strain which increased considerably, suggesting the corresponding resistance to wear. Both the relatively small magnitude of the total deformation of the coated bit, as well as the considerably high magnitude of the observed maximum shear elastic strain, as two of the main parameters, among the others investigated in this research, reflect their corresponding effects on the durability of the graphene-coated bits, accordingly. The continuity of the drilling operation and the cooling of the bit due to the experiment conductions, will undoubtedly be affected by the contributing parameters, stated above. It would also affect the wear time and penetration rates, which would certainly be increased in comparison to the current situation in which those properties were measured under the extreme experimental conditions involved in non-stop drilling conditions.

A new window for potential research to be conducted on the sequential deformation of physical and chemical properties of the coated bit, while the drilling operation is in progress, has become available by the outcomes of the current research. Potential research is reserved for new insights to be developed in finding the optimum length of drilling before the coated bit approaches its critical efficiency as far as the heat effects on the durability of the coated bit is concerned.

Declaration of competing interest

☐ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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