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Potential Application of Nanomaterials in Oil and Gas Field Drilling Tools and Fluids Design

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Abstract: The emerging nanoscience, nanotechnology and nanomaterials can be used for various industrial applications to enhance reliability, performance, stability and functional capability. Their application in the design and development of tools and materials used in oil and gas industry for extreme drilling conditions could overcome the current limitations of conventional tools and the various fluid systems used by the industry. The functional limitations such as poor physio-chemical stability in acid gas environment, frequent mechanical failure and malfunctioning in complex geological environment, thermal degradation in high temperature environment, etc. of currently used conventional tools and fluid systems are associated with extreme operating conditions due to a shift of the drilling operation from low risk to high risk geological environments, onshore to offshore locations, shallow water to deep water environment, etc. The progressive shift to increasingly higher risk operating environments is unavoidable as the energy demand of global community has increased manifold and is expected to increase further in future. Moreover, the probability and likelihood of finding easy oils and gas resources in low risk areas are diminishing quickly. That is why the oil and gas companies are constantly shifting to extremely challenging environments to meet the global energy demand. This is reflected by the expansion of drilling activities in complex geological areas, deep water environments, extreme-HPHT environments, etc. As the current tools and equipment and also the additives and chemicals often fail and/or lose their functional ability due to the detrimental effect of exposure of extremely harsh conditions, the industry needs tools and equipment, chemicals fluid additives that are highly reliable, chemically resistive, thermally and mechanically stable to ensure safe and trouble free drilling operations. It has been demonstrated in several fields of study that nanostructured materials and additives exhibit improved mechanical, chemical, thermal, electrical and tribological properties that can significantly increase the stability and durability of the tools and equipment along with the chemical and thermal stability of additives required for high performance fluid design. This review article captures the recent developments about the application of nanomaterials in the design and development of tools, equipment, additives, chemicals and smart materials to overcome current and future technical challenges of the oil and gas industry. Finally, the conventional of rule of mixtures of composite materials design and the current nanotechnology-based research conducted by various researchers have been highlighted to demonstrate potential of nanotechnology to enhance the physical, mechanical, chemical and thermal property of tools, equipment and various fluid systems used by the oil and gas industry.

Key words: Nanotechnology, drilling, nanocomposites.

1. Introduction

Hydrocarbon has been the main source of energy supply for the global energy market and it will continue to remain the main source of energy over the coming years. Global energy demand has increased significantly over the last few decades but the discovery of new oil and gas resources is diminishing constantly. Moreover, the readily accessible and easily recoverable hydrocarbon basins are declining quickly leading to a significant drop in total oil and gas production. Hence, the oil and gas industry is looking for new reserves of oil and gas in every corner of the earth. As a result, oil and gas industries are moving to more complex and challenging drilling environments such as in deep water and ultra-deep water environments, high temperature and high pressure conditions, tectonically active complex geological environment, etc.

Statistical analyses of various past and present discoveries indicate that the average field size for the new discoveries in traditional onshore and offshore

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fields has been declined significantly from 220 MM BOE per discovery in the 1960s to less than 50 MM BOE in the 1990s [1]. This highlights the need of concentration of exploration in new areas with high potential to make big discoveries. As the ocean occupies three quarters of the earth and has a high prospect of hydrocarbon resources in addition to other valuable marine resources, there are increasing activities in deep and ultra-deep offshore areas to meet the global energy demand [2]. The possibility of discovering giant oil and gas fields in deep water environments is much higher than in onshore and shallow water environments [3]. It is also reported that the reserves at depths approaching a mile or more now represent the biggest single new oil resources for world communities [4]. Published information indicates the presence of more than 20% of the world's proven reserve in complex, troublesome and technically challenging offshore geological structures. According to the future production forecast of hydrocarbon resources, about 40 to 50% of hydrocarbon production will be from offshore fields with challenging drilling and production environments [5].

The extreme operational conditions such as high pressure, high temperature (HPHT), corrosive environment, complex well profile, etc., have a detrimental effect on conventional tools, equipment, seals, elastomers, fluid additives, etc. As for example, the changing complexity of well profiles and increasing horizontal reach require tools and equipment that are physically lighter but mechanically stronger and the extreme and ultra-high HPHT drilling conditions demand tools and equipment that have higher thermal, mechanical and chemical stability to avoid frequent failure in extreme drilling environments. Due to the technical limitations of conventional tools and chemicals, development of extreme environment drilling and production tools and equipment and also the fluid additives using conventional micro-structural materials is rarely possible. Hence, the industry faces a range of materials-related challenges in the design of high performance tools, sensors, fluid additives, seals, etc.

Nanotechnology has received a lot of attention over the last two decades and it has been successfully implemented in several fields especially in bio-medical technology, aeronautical engineering, electronics, coating industry and material composite [6]. The benefit of nanomaterial comes from its nano size, which provides a huge active surface area for a given material. As a result, the performance of the material is improved significantly. The application of nanomaterials in oil and gas industry has also been a subject of frequent study over the past few years and it has been reported to have significantly improved performance [7, 8]. The objective of this paper is to provide a comprehensive review on the applications of nanomaterials in oil and gas industry with a special focus on drilling tools and materials. In addition to that, we made a simple theoretical calculation to estimate the improvement in physical and mechanical properties of tools having nanomaterials and nano-composites incorporated in the design in order for the tools to withstand the extreme drilling environments.

2. Limitations of Conventional Tools and Fluids

Table 1 shows the thermal stability limits of various tools and equipment used in current oil and gas industry. Table 2 shows the range of pressures and temperatures likely to be encountered in different drilling environments around the globe. The data presented in Table 1 clearly show that most of the conventional tools and equipment available in the industry will rarely work at temperatures above 450 °F. Analyses of current global drilling reports and activities indicate that the pressure and temperature of extreme drilling environments can exceed 25,000 psi and 500 °F in some onshore and offshore wells. Fig. 1 shows the drilling and completion gaps analysis data described by Tom Proehl [9]. The data clearly show the equipment limit and fluid instability issues in HPHT conditions as some of the

Table 1 Working temperature limits of current tools.

Bottom hole tools	Safe working temperature °F
MWD/LWD	Less than 400
Logging tools	Less than 450
Mud motor	Less than 375
Bridge plug	Less than 450
Packers	Less than 450
Tester valve	Less than 450
Downhole E-gauges	Less than 410
Water based mud	Less than 400

Table 2 Temperature-pressure in different drilling environment.

Drilling environment	Pressure and temperature profile
Normal environment	T < 300 °F; P < 10,000 psi
HPHT environment	T: 300–350 °F; P: 10,000-15,000 psi
Ultra HPHT environment	T: 350-400 °F; P: 15,000-20,000 psi
Extreme HPHT environment	T > 400 °F; P > 20,000 psi

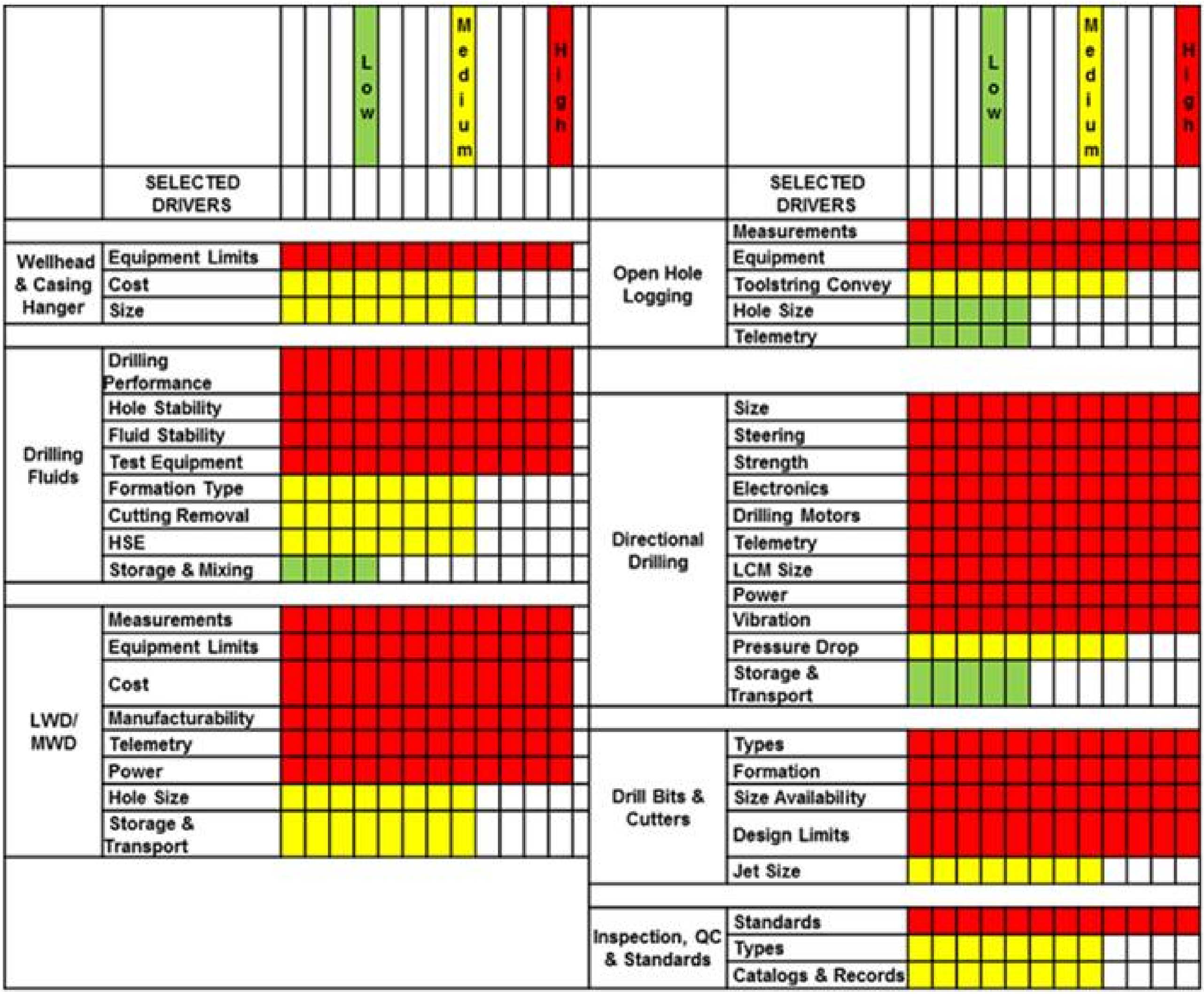

Fig. 1 Drilling and completion gaps in HTHP environment [9].

major technology gaps in safe, economic and trouble free drilling operations in HPHT environment.

Other than pressure and temperatures, factors such as borehole profile, in-situ stress regime, complexity in the subsurface geology, nature of formation related drilling hazards, etc., govern the performance and stability of the tools, equipment and fluid system in extreme drilling environments. Field experience shows that it is often a combination of some of the above factors that control stability and performance of tools, equipment and fluid systems. As a result, the overall stability limit of the conventional tools and equipment is even below the company supplied stability limit.

At and above the mechanical, thermal, chemical, etc., stability limit, the equipment shows speedy degradation, frequent failure and loss of functional capability due to severe damage, permanent deformation and rapid wear of tools and equipment, seals and elastomers, piston and liners, etc. The corrosion and erosion of tools and equipment, especially due to the presence of high concentration of acid gases in extreme drilling environments also reduces the lifetime of tools and equipment dramatically. The current additives and chemicals used in the design of various fluid systems degrade very quickly and thus are unable to fulfill their functional tasks. That is why the industry needs a new generation of tools, equipment and additives for fluid systems with superior mechanical, thermal, chemical, etc. stability limits.

Current microstructural composite-based oil and gas field tools and equipment, and also the micro size of drilling and completion fluid additives, often show poor performance in extreme drilling environments such as in ultra and extreme HPHT environment, deep and ultra-deep water depth, in horizontal and extended reach drilling, in high acid gas environments, in areas with complex subsurface geology, etc. Intricate geology containing highly reactive and gumbo shales, tectonically active zones, mobile formations, and extremely abrasive rocks often cause serious damage to conventional tools and equipment due to insufficient strength, material toughness, poor wear resistance of the conventional materials used in the design of oil and gas field tools and equipment.

As the root cause of this limitation is the lack of material characteristics that are required to design tools and equipment, seals and elastomers, drilling and completion fluids, there is a need to improve the conventional material characteristics well above the technical limits that are necessary for fail-safe operation in extreme drilling environments. As a result, the improvement of material characteristics such as strength, strength-to-weight ratio, torsional resistance to failure, fatigue and wear resistance, thermal and chemical stability by the application of emerging nanotechnology and the tiny Nanos with their mighty effect on physical, mechanical, thermal, chemical properties on steel-nanocomposite can provide a viable solution to current and future technical challenges in extreme drilling environments.

3. Application of Nanomaterials in Drilling Fluids

In the recent past, there have been a number of reports pertaining to the application of nanoparticles for oil and gas industry applications [10-16]. A typical water based drilling fluid is formulated using a variety of chemicals such as viscosifier, fluid loss control additive, shale stabilizer, lubricant, H_2S scavenger, oxygen scavenger, biocide, etc. Each of these additives has its own limitations in terms of thermal stability, salt tolerance, acid gas tolerance, solids tolerance, etc. For example, well known and very well utilized viscosifier and fluid loss control additives for water based mud are bio polymers such as xanthum gum and carboxymethyl cellulose with thermal stability up to 250 °F [17, 18]. These chemicals or additives available in the industry are suitable for conventional drilling and HPHT drilling. However, when the bottom hole temperature approaches 350 °F and above, most of these additives will fail to perform their functional tasks due to physical, chemical and thermal degradation. Therefore, additives with improved thermal, chemical and physical stability are required under these drilling conditions. Due to superior physical, chemical and thermal properties of emerging nano-based additives, they are able to withstand much higher temperature, pressure to prevent any thermos-mechanical degradation in harsh drilling environments. Hence, drilling muds formulated using nanomaterials will provide significantly improved physio-mechanical and thermos-chemical properties to maintain their stability and functional ability. Recently published research findings already demonstrated the higher performance of nanomaterials and nanoadditives compared to conventional mud additives due to highly enhanced physical, chemical, thermal and hydrodynamic properties of nanoparticles [19, 20, 21]. According to the authors the nanomaterials have significantly improved the physical, mechanical, thermal and chemical properties compared to equivalent conventional mud additives used by the industry.

Fluid loss control additives are used to minimize the invasion of fluid from drilling mud into the formation in order to minimize formation damage and maintain wellbore stability and integrity. Fluid loss control additives made of iron based and calcium based nanoparticles have shown enhanced fluid loss control properties under HPHT conditions [20]. The authors observed up to around 80% fluid loss reduction as compared to the test carried out without the nanoparticles. Moreover, the required concentration of nanoparticles is as low as 0.5%. This clearly shows the superior functional ability of nanoparticles even at very low concentrations. The less expensive and commercially available non-modified silica nanoparticles have been used as fluid loss control additives in water based mud and proved to reduce the invasion of water into Atoka shale [21]. Therefore, the shale swelling will be minimized significantly, which will help maintain the wellbore integrity. Colloidal silica nanoparticles can also be used as a fluid loss control additive in solids free drill-in fluid when drilling through pay zone [22]. It creates very thin filter cake and causes very low near wellbore formation invasion. Therefore, formation damage has been minimized significantly.

Water absorption and swelling of water sensitive shale is the major cause for borehole instability and collapse. Shale stabilizers are used in drilling fluids to minimize swelling of shale when drilling through shale formation [23]. Shale mainly consists of three types of clays namely montmorillonite, kaolinite and illite with average size of 10-5,000 nm [24]. The average pore throat of shale is found to be 3-100 nm [25]. Conventional shale stabilizers have particle size diameters in the range of 0.1-10 μm as shown in Ref. [26] and as a result, cannot plug the nano pore throat of shale [27]. Incorporating nanoparticles for shale stabilization in drilling mud potentially decrease the water absorption of shale by plugging the pores and minimize the permeability. Silica nanoparticles have also been used as shale stabilizers with significant reduction in swelling of Marcellus shale [28].

Stuck pipe is the major contributor for drilling non-productive time and it often occurs when making a connection as there is no rotation of drill pipe and no circulation of drilling mud. The primary reason to have differential sticking is because of the having a thick mudcake on the borehole wall besides poor hole cleaning and improper bridging of permeable zones. Drilling mud with poor filtration control properties and high solid content will lead to the deposition of thick mudcake. It is extremely important to ensure the deposition of a thin mudcake and proper hole cleaning especially in deviated and horizontal sections. It has been reported that adding 3% silicon nanoparticles to drilling fluid will cause a 34% reduction in mudcake thickness in addition to the improvement of the mud filtrate filtration due to the formation of thin and good quality and low permeable mudcake on the borehole wall [29]. The application of carbon nanotubes in drilling fluids has also been studied and it is demonstrated that the formation of very uniform and extremely thin mudcake could be achieved by using carbon nanotubes in the mud system [19].

The entry of acid gases into the drilling mud can cause dramatic degradation of water-based mud properties along with a significant degradation of their functional capability. The inefficient neutralization of these acid gases using conventional acid gas scavengers causes quick fouling of drilling mud and serious degradation of downhole tools and equipment with a dramatic reduction of their working life. It is one of the main factors for tools and equipment failure due to a tremendous effect on the durability and stability of conventional oil and gas field tools and equipment. That is why conventional steel tools and equipment often show poor performance in extreme drilling environments containing acid gases. Rapid neutralization of the acid gases using superior scavengers can dramatically improve the durability of tools and equipment for safe and trouble free drilling operation in extreme drilling environment. In case of drilling fluid, rapid neutralization of acid gases will prevent any degradation of the mud components to maintain the functional capability of drilling mud. Therefore, development of very efficient, long lasting and highly durable corrosion inhibitors that are quick to neutralize the acid gases can provide a viable solution to prevent any degradation of water-based mud systems. Due to huge surface area, high interaction potential and quick reaction kinetics of nano-based materials, it is thought to be the material of future to eliminate problem associated with acid gas contamination of drilling mud.

Due to the micro-structural size of conventional acid gas scavengers, the specific surface area available for interactions and neutralization of harmful acid gases is very small. Therefore, the interaction kinetics and the efficiency of neutralization of acid gases are very low. That is why conventional acid gas scavengers often show poor performance in neutralizing acid gases, especially in high acid gas concentration areas. On the other hand, due to huge specific surface area and area of interactions of nano-based materials, nano-based acid gas scavengers can quickly neutralize huge volume of acid gases while drilling and so can provide a safe and hazard free working environment with minimum risk of H_2S exposure in addition to the prevention of any degradation of the water-based mud. Sayyadnejad et al. [30] demonstrated the dramatic effect of nano-size ZnO in neutralizing a huge volume of H_2S within a short period of time (Fig. 2). According to the experimental results described by the authors, the use of conventional ZnO in one experiment showed only 2.5% removal of H_2S in 90 minutes. On the other hand, the use of nano-based ZnO in another experiments showed complete neutralization and removal of acid gases in 15 minutes. The extremely high surface area to volume ratio of nanos compared to micros and macros allows them to incorporate a huge number of functional groups for effective neutralization of acid gases that enter the well while drilling. Therefore, the scavenging action of nano-based additives eliminated the H_2S gas totally and very quickly after its entry into the wellbore with a drastic improvement of the working environment, OHS of workers, chemical stability of drilling mud and mechanical stability of the drilling equipment.

The rheological properties of drilling fluid such as yield point, plastic viscosity and apparent viscosity are the important parameters that determine the quality of the drilling fluid. These properties should be maintained at a certain level depending on the hole section and depth. Bentonite has been used as a viscosifier in water based mud for several decades. A combination of regular bentonite and nano scale bentonite along with minor proportion of other metal oxides such as magnesium oxide, titanium oxide and graphene showed improved properties [31]. The filtration control properties of the system have improved by 35% in addition to the improvement of the yield point of the drilling mud.

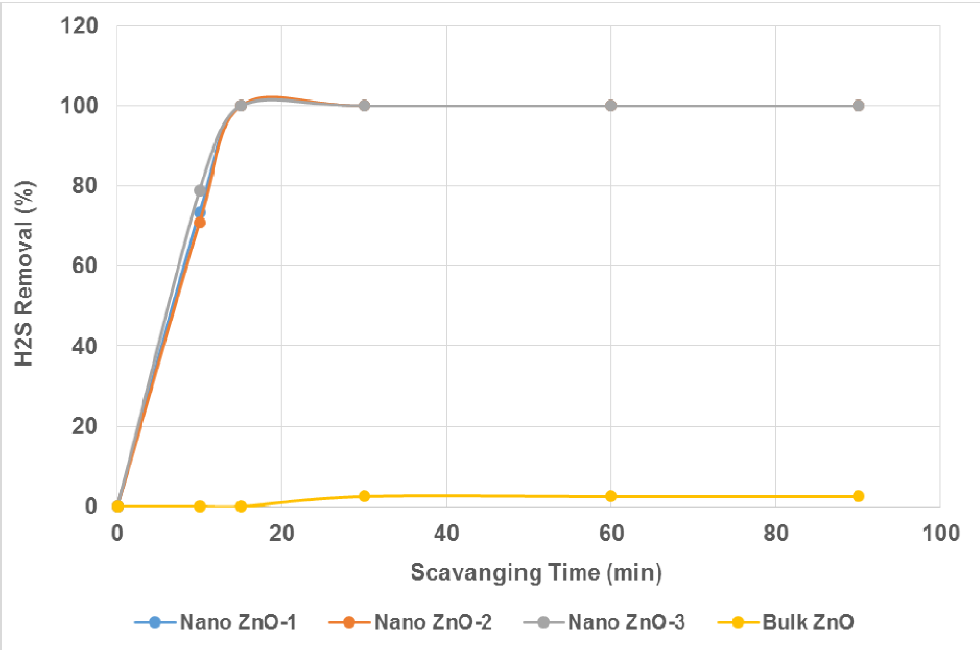

Fig. 2 Comparison of H_2S neutralizing potential of nano and bulk ZnO [30].

Besides showing enhancement in their specific applications, incorporation of nanoparticles in drilling fluids also has supplemental benefits such as low friction, improvement in rate of penetration, improvement in cuttings carrying capacity, better hole cleaning, low wear and tear, minimizing formation damage, etc. Therefore, nanoparticles are the choice to go especially in high risk environments and extreme drilling zones to overcome current and future drilling and operational challenges.

4. Application of Nanomaterials in Drilling Tools

The other potential area where nanotechnology definitely has an upper hand is in the design and development superior tools and equipment for oil and gas field applications. Manufacturing tools only by using nanoparticles may seem to be extremely expensive. On the other hand, we can have nanocomposites by dispersing small percentage of nanoparticles in the bulk phase during the manufacturing process in order to achieve significant improvement in properties. That is why nanocomposites have attracted a lot of attention over the last couple of years in tools and equipment design due to their excellent physical, mechanical, chemical and electrical properties [32]. One such example in drill bit tooth design is reported by Zhiqiang et al. [33] to demonstrate the improvement of impact toughness and wear resistance of nanocomposite Al_2O_3/WC-Co hammer bit teeth. The teeth embedded in drill bit shown in Fig. 3 are made of low-carbon alloy steel. Fracture and wear of hammer bit teeth are main mode of failures as shown in Fig. 3. The primary cause of the failure is that the material used to make the bit teeth is cemented carbide YG8 whose impact toughness and wear resistance cannot meet the complicated and tough working condition [34, 35]. Therefore, enhancing the impact toughness and wear resistance of drill bit teeth is key in improving

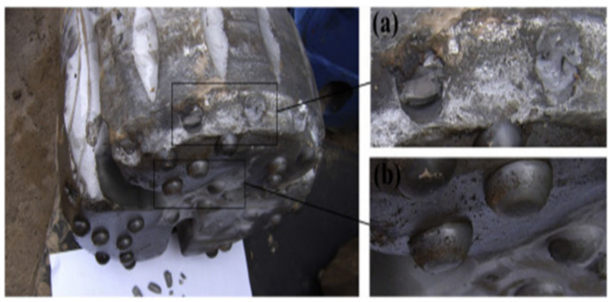

Fig. 3 Failure of hammer bit teeth (a) fracture (b) wear [33].

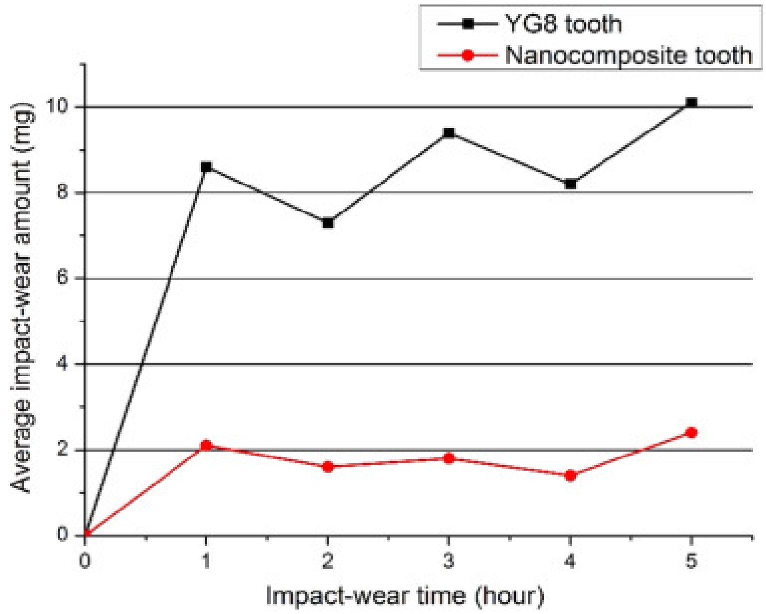

Fig. 4 Average impact-wear amount curves of YG8 tooth and nanocomposite tooth [33].

1.5" Composite 1.5" Steel

Fig. 5 Buckling Failure of Conventional Coiled Tubing under Compressive Force [36].

rock breaking efficiency and prolonging service life, which is also one of the tough technical problems in percussive-rotary drilling.

An impact-wear test carried out by the authors comparing cemented carbide teeth and nanocomposite teeth was carried out using MLD-10 dynamic impact wear tester. Fig. 4 shows the average impact-wear curves of YG8 tooth and nanocomposite tooth. The average wear amount of Al2O3/WC-Co nanocomposite tooth is about 2 mg per hour, whereas it is 7 to 10 mg for YG8 tooth. This indicates that the nanocomposite teeth have 3 to 5 times higher impact toughness and wear resistance than YG8 teeth. Hence, bit designed with nanocomposite material is expected to show much higher performance than conventional drill bits.

Nanocomposite can play an important role in enhancing the mechanical properties of coiled tube used in coiled tubing drilling. Fig. 5 shows an example of a conventional coil tubing failure [36]. Conventional coiled tubing has poor buckling resistance due to insufficient stiffness of the steel alloy used to manufacture the tubing. That is why current coiled tubing has limited performance in horizontal and extended reach drilling operations. Fig. 5 shows the photo of buckling failure of coiled tubing under the action of compressive force due to insufficient material stiffness. Improvement of composite material stiffness by incorporating one or more nano-phase materials will prevent delamination tendency of coiled tubing under the action of bending and compressive forces, which can reduce the buckling failure significantly. The high stiffness of the nanocomposite based coiled tubing will allow a higher push to the BHA while drilling ahead and higher pull in case of a stuck pipe condition without damaging or parting the pipe/coil tubing. Nanocomposite-based coiled tubing with two nano-phase materials can improve the tube stability dramatically due to simultaneous enhancement of compressive and tensile stiffness. As for example, simultaneous incorporation of nano-sized boron fiber and tubular CNTs in a metal matrix, the compressive strength and tensile stiffness of the tube will improve significantly. Hence, the tube will offer very high resistance to tensile, compressive and biaxial loading leading to a dramatic improvement in the coiled tubing stability and performance. More than 50% increase in the stiffness of CNT-steel composite described earlier highlights the application of nanomaterials in enhancing the mechanical properties of coiled tubing.

When drilling through abrasive formations, a quick wear of conventional drill bit, stabilizer, reamer, drill pipes, etc., leading to frequent replacement of torn out bits, stabilizers and/or reamers can dramatically reduce the drilling performance. The potential solution to this problem is the improvement of wear resistance of these tools. Manjunath et al. [37] demonstrated that the incorporation of a nano-phase material into the bulk phase of a metal matrix can improve the material toughness significantly leading to a significant increase in wear resistance (Fig. 6). According to the experimental data presented by the authors and shown in Fig. 6, incorporation of only 0.5% MWCNT into the bulk matrix can improve hardness and wear resistance significantly.

As vibration is one of the issues causing failure of drill string, the improvement of vibration dampening characteristics of the elements of the drilling string can eliminate or reduce the failure or damage associated with axial, torsional or lateral vibration of the drill string while making a borehole. It is one of the major critical factors of failure of downhole tools and equipment in extreme drilling environments. This is due to the fact that the conventional oil and gas field tools and equipment have poor vibration dampening characteristics.

Incorporation of shock absorbing nano-phase material in the tools and equipment design can improve the vibration dampening characteristics and working life of these tools, equipment, seals, elastomers, etc., significantly. Misra et al. [38] demonstrated the effect of shock absorbing CNT in vibration dampening of a polymer-CNT assembly shown in Fig. 7. According to the authors, the CNT-polymer assembly has at least three times larger shock absorbing capacity than the natural and synthetic cellular foam materials of comparable densities. Other than CNTs, inorganic fullerene, fullerene boron, silicon carbides, or other shock absorbing nanomaterials can be used in improving the vibration dampening characteristics of tools and equipment.

Conventional seals, rubbers and elastomers rarely survive the detrimental effect of extreme condition critical factors such as temperature, pressure, acid gases, etc. Extreme HPHT environments create tremendous thermal and mechanical stress on any elastomeric material leading to permanent deformation, structural

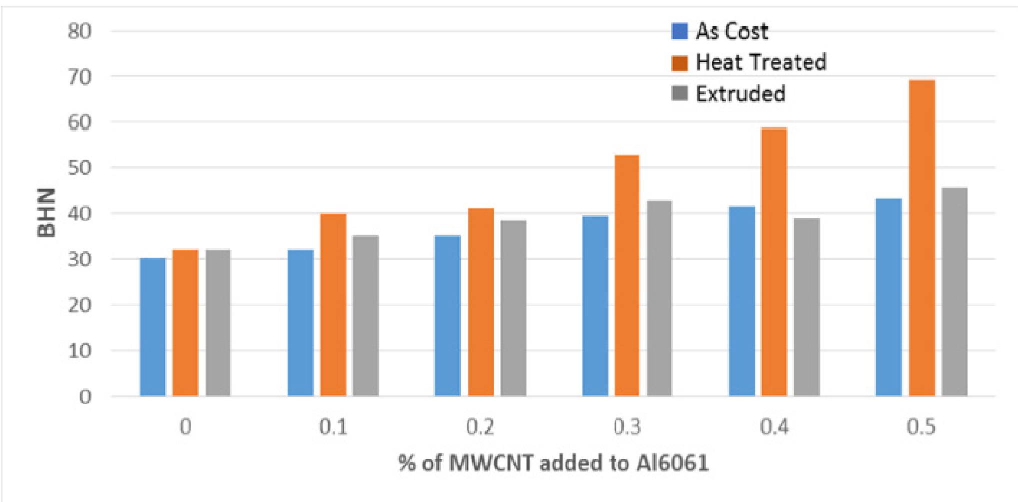

Fig. 6 Hardness improvement by the addition of MWCNT to Al6061 Nanocomposite [37].

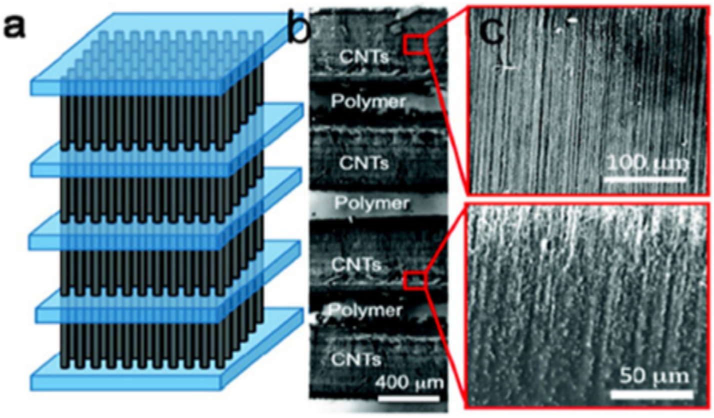

Fig. 7 Multilayer CNT-Polymer assembly. (a) Schematic of four-layer carbon nanotube–polymer structure; (b) Optical image of carbon nanotube–polymer structure; (c) SEM image of the CNT array [38].

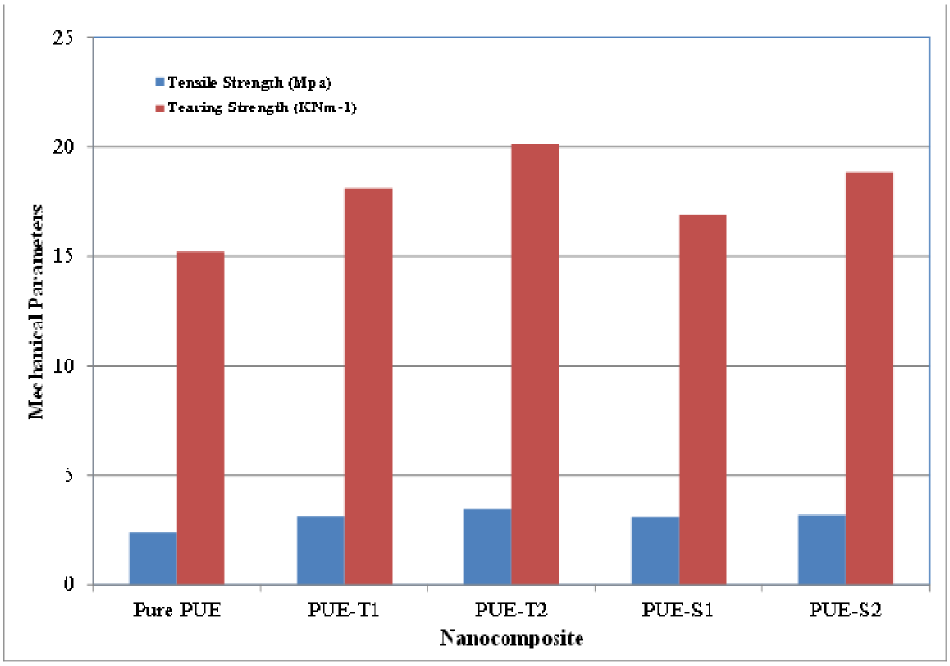

Fig. 8 Comparisons of Pure Polyurethane and Nano-composite Polyurethane Properties [39]

distortion, decrease in ductility and increase in brittleness due to poor thermal, physical and mechanical stability of conventional seals and elastomers. By virtue of the superior physical, mechanical, thermal, and chemical properties of nano-based materials, incorporation of nano-phase material in the bulk matrix of seals, rubbers, or elastomers can dramatically improve the technical limit of these elements and thus can provide a viable avenue to overcome the current and future operational challenges faced by the industry.

Jianming et al. [39] described the improvement of flame retardant performance and mechanical properties of polyurethane elastomer due to the surface modification of the elastomer by incorporating TiO_2 and SiO_2 nanoparticles. According to the authors, the surface modification of the polyurethane by nano-phase materials has enhanced the thermal and flame retardant characteristics of the elastomers significantly. The authors further highlighted the improvement of the mechanical properties of the composite due to the dual effects of uniform dispersion of nanoparticles and the hydrogen bonding between nanoparticles and polyurethane (Fig. 8).

5. Application of Rule of Mixtures

The current research findings discussed above demonstrated the importance and application of nanotechnology, nanomaterials and nano-based fluid additives in fluids, tools and equipment design to enhance their stability and functional capability. To further substantiate the potential of nanotechnology and nanomaterials in surface and subsurface tools and equipment design, we have used the convention rule of mixture for theoretical design of nano-based composite materials to demonstrate the excellent benefits of incorporating even a small proportion of nanomaterials in the tools and equipment design for significant improvement in weight reduction, strength enhancement and stiffness augmentation. Table 3 shows the density, tensile strength and Young's modulus of some conventional and nano-based materials. Application of the rule of mixture to prepare various theoretical blends of conventional steel and the single wall carbon nanotube (SWCNT) indicate significant changes in the physical and mechanical properties of the nano-composite material compared to steel. The rule of mixtures is a method of approximate calculation of composite material properties based on the assumption that a composite property is the volume of weighted average of the matrix and dispersed phases. Appropriate equations of composite mixing rules were used to calculate the density, tensile strength and Young's modulus of elasticity and then the % reduction in weight or % enhancement of tensile strength and the Young's modulus.

Tables 4-6 show the selected dispersed phase weight and volume in the theoretical nanocomposite along with the nanocomposite density and weight reduction (Table 4), the tensile strength and strength enhancement (Table 5) and Young's modulus and stiffness enhancement (Table 6) due to the incorporation of tiny nanomaterial into the bulk steel matrix. Mass concentrations of nanomaterial ranging from 5% to 25% were used in predicting the changes in the physical and mechanical properties of the nanocomposite compared to the original physical and mechanical properties of the matrix phase material. Here, steel has been used as the matrix phase material and SWCNT as the dispersed phase materials to demonstrate the effect of the nanoparticles in enhancing the technical properties of future generation of oil and gas field equipment.

Table 3 shows the densities of two nanomaterials and several conventional materials. The data indicate the second lowest density for SWCNT compared to the densities of other materials shown in Table 3. Due to the lower density of SWCNT compared to MWCNT, it was used in the theoretical blending of different weight percentages of SWCNTs with steel to prepare several hypothetical nano-composites.

Conventional mixing rule, theory and equation on composite density calculation was used to determine the reduction in density due to the incorporation of a particular percentage of nanoparticles into the bulk matrix of the steel.

6. Weight Reduction

Table 4 shows the percentage weight reduction of nanocomposite with respect to the weight of pure steel phase material. The data clearly show that the blending of different percentages of SWCNTS with steel can dramatically reduce the composite density and so can provide an avenue of manufacturing lightweight equipment, tools and tubular for oil and gas field applications, especially for long horizontal extreme drilling environments that require lighter but stronger tools and equipment.

7. Strength Enhancement

Table 3 shows the tensile strength of two nanomaterials and several conventional materials including steel. The data indicate highest tensile strength for SWCNT and MWCNT compared to the tensile strength of other materials shown in Table 3. To maintain the consistency in theoretical nanocomposite preparation for nano-phase effect analyses, SWCNTs were used in the theoretical composite metal preparation. Different weight percentages of SWCNTs were used in the theoretical blending of the nanomaterial with continuous steel phase to prepare the hypothetical nanocomposite samples, and evaluate the effect of resulting CNT-steel nanocomposite. In this case, the mixing rule theory and equation on composite tensile strength calculation was used to determine the enhancement in tensile strength due to the incorporation of a particular percentage of nano-phase material into the bulk matrix of the steel.

Table 5 shows the percentage enhancement of nanocomposite tensile strength with respect to the tensile strength of pure steel phase material. The data clearly show that the blending of different percentages of SWCNTS with steel can dramatically improve the tensile strength of the nanocomposite material and so can provide an avenue for manufacturing of very high strength equipment, tools and tubular for oil and gas field applications, especially for extreme drilling environments that require robust and stronger tools and equipment.

Table 3 Various properties of several conventional and nano-based material.

	Density (g/cc)	Tensile strength (GPa)	Young's modulus (GPa)
SWCNT	1.8	30	800
MWCNT	2.6	30	800
Diamond	3.52	20	1,140
Graphite	2.25	0.2	8
Steel	7.8	0.4	208
Wood	0.6	0.008	16

Table 4 Weight reduction based on weight (%) of dispersed phase in the matrix phase.

Parameters	Dispersed phase weight (gm)	Dispersed phase volume (cc)	Nano composite density (gm/cc)	Weight reduction (%)
Steel-SWCNT 100:0	0	0.00	7.8	0
Steel-SWCNT 95:5	5	2.78	6.69	14.29
Steel-SWCNT 90:10	10	5.56	5.85	25.00
Steel-SWCNT 85:15	15	8.33	5.20	33.33
Steel-SWCNT 80:20	20	11.11	4.68	40.00
Steel-SWCNT 75:25	25	13.89	4.25	45.45

Table 5 Tensile strength enhancement based on weight (%) of dispersed phase in the matrix phase.

Parameters	Dispersed phase weight (gm)	Dispersed phase volume (cc)	Nano-composite Tensile strength (GA)	Strength enhancement (%)
Steel-SWCNT	0	0	0.4	0
Steel-SWCNT	5	2.78	5.90	1,374
Steel-SWCNT	10	5.56	10.02	2,405
Steel-SWCNT	15	8.33	13.23	3,207
Steel-SWCNT	20	11.11	15.79	3,848
Steel-SWCNT	25	13.89	17.89	4,373

Table 6 Stiffness enhancement based on weight (%) of dispersed phase in the matrix phase.

Parameters	Dispersed phase weight (gm)	Dispersed phase volume (gm)	Nanocomposite Young's modulus (GA)	Stiffness enhancement (%)
Steel-SWCNT	0	0	208	0
Steel-SWCNT	5	2.78	317.94	52.86
Steel-SWCNT	10	5.56	400.40	92.50
Steel-SWCNT	15	8.33	464.53	123.33
Steel-SWCNT	20	11.11	515.84	148.00
Steel-SWCNT	25	13.89	557.82	168.18

8. Stiffness Enhancement

Table 3 shows Young's Modulus of two nanomaterials and several conventional materials including steel. The data indicate nearly four times higher Young's modulus for single wall and multi-wall CNTs, compared to the Young's modulus of steel shown in Table 3. As before, SWCNT was considered in theoretical nanocomposite preparation for nano-phase effect analyses on material stiffness. Different weight percentages of SWCNTs were used in the theoretical blending of the nanomaterial with continuous steel phase to prepare hypothetical nanocomposite samples and evaluate the effect on the steel phase behavior. Mixing rule theory and equation on composite Young's modulus calculation was used to determine the enhancement of material stiffness due to the incorporation of a particular percentage of nano-phase material into the bulk matrix of the steel.

Table 6 shows the percentage enhancement of nanocomposite Young's modulus with respect to the Young's modulus of pure steel phase material.

The data clearly show that the blending of different percentages of SWCNTs with the continuous steel can dramatically improve the stiffness of the nanocomposite material and so can provide an avenue for manufacturing very high stiffness pipes, tools, coiled tubing and other tubular products for oil and gas field applications, especially for extreme drilling environment that requires very stiff material to resist the detrimental effect of critical factors of extreme drilling environments.

9. Recommendation

Although, nanotechnology has been widely applied in many different disciplines, it is still at the early stage of development when it comes to oil and gas industry applications. One of the reasons could be the high cost of nanomaterials and lack of bulk manufacturing process for preparation of nano-composite materials to meet the oil and gas industry demand. Development of a fit-for-purpose and efficient bulk manufacturing process is essential to produce high quality nanocomposites and bring the cost down. It may be emphasized that the higher cost of nano-composite-based tools, equipment and fluid additives can be justified by the supplemental benefits of incorporation of nanocomposites and nano-based additives in the design of tools, equipment and fluids by their ability to enhance ROP, improve hole cleaning, prevent differential sticking, improve borehole stability etc. Potential applications to overcome specific challenges such as fluid and tools instability in HTHP environment, weight reduction and strength enhancement to increase the reach of extended reach wells, improvement of wear resistance of bits and stabilizers to drill abrasive formations, etc can have a dramatic effect in reducing the probability and likelihood of equipment failures and thus the operational risk in extreme drilling environments and also the reduction high non-productive time associated with conventional tools and fluid systems.

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