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Evaluation of Measurement Techniques for Fluid Lubricity in the Laboratory

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Abstract

Lubricant and the lubricity of drilling fluids play an important role in drilling operations, especially with the continued advances in technologies for drilling long horizontal laterals. Lack of lubrication during drilling can result in excessive torque and drag on the drillstring, thus limiting the length of the horizontal wellbore. Therefore, the selection of the appropriate lubricant is critical in the success of drilling operations.

In this paper, we perform a comprehensive study on the measurement techniques to evaluate lubricants and the lubricity of drilling fluids. The surface roughness of the contact bodies is critical in tribological studies. However, it is not controlled when the traditional extreme pressure (EP)/lubricity tester was used. As a result, the measured lubricity does not fall onto the same Stribeck curve. This problem is overcome by the use of a novel dynamic lubricity tester, which utilizes surfaces with controlled roughness for lubricity measurements. In addition, temperature, fluid pressure, rotational speed and the force normal to the surface of contact can be varied on the dynamic lubricity tester to mimic the downhole conditions.

Our tests show that reproducible lubricity results can be obtained when the roughness of the rubbing surfaces is controlled on the dynamic lubricity tester. A lubricant was shown to be effective in friction reduction under downhole conditions when added to a field water-based drilling fluid.

Introduction

The rapid advancements in drilling technologies have enabled the oil and gas industry to drill long horizontal laterals in the subsurface for hydrocarbon production. However, the friction between the downhole tools and the casing or borehole walls has often been a limiting factor for the rate of penetration and the length of the drilled wellbore. As a result, sufficient lubrication is critical especially when directional and horizontal wellbores are drilled. Failure to provide lubrication during drilling can result in problems such as wall-sticking, which in turn will delay the drilling process and incur additional costs for the operators. Successful evaluation of the effectiveness and compatibility of lubricants with drilling fluids can help reduce the excessive friction encountered during drilling.

Friction, wear and lubrication are parts of the science of tribology, which studies the phenomenon of surfaces moving relative to each other (Hironaka, 1984). The word “tribology” derives from the Greek word “tribo”, which means rubbing (Persson, 2000). It was first used in 1964 by British physicist David Tabor and mechanical engineer Peter Jost. In tribological studies, the most frequently referenced and well received theory is the classical Stribeck curve (Figure 1), which relates the friction coefficient, f, with the viscosity of the lubricating oil, η, the load normal to the sliding motion, F_N, and the sliding velocity, v. As shown in Figure 1, three lubrication regions based on the interactions between two rubbing surfaces are captured by the Stribeck curve: 1) boundary lubrication, 2) elastohydrodynamic lubrication and mixed lubrication, and 3) hydrodynamic lubrication. Figure 2 shows the surface interactions of these three lubrication regions. In the boundary lubrication region, the film thickness of the liquid filling up the gap between the two surfaces is much smaller than the surface roughness; in the elastohydrodynamic lubrication and mixed lubrication region, the film thickness is approximately equal to the surface roughness; and in the hydrodynamic lubrication region, the film thickness is larger than the surface roughness.

Variations in surface roughness can lead to substantial differences in friction coefficient measurement when other testing parameters remain constant. The relationship between the friction coefficient and other parameters described by the Stribeck curve is only valid when roughness of the rubbing surfaces remains the same. When the surface roughness varies, the shape and the position of the Stribeck curve will also change. It can be seen from Figure 2 that when the liquid film thickness, sliding speed, normal force and other conditions are the same, surfaces with a greater roughness profile could be well into the boundary lubrication region, while surfaces with a much lower roughness profile could still be in the hydrodynamic lubrication or elastohydrodynamic lubrication and mixed lubrication region. In summary, it is important to ensure that each lubricity measurement starts with consistent roughness of interacting surfaces and this consistency in surface roughness is maintained throughout the measurement.

In this paper, the traditional lubricity measurement technique in the laboratory was evaluated. A novel dynamic lubricity tester that ensures the consistency of surface roughness during measurements is presented. Measured lubricity results show good reproducibility. The lubricity of fluids on steel block and core samples were measured to evaluate the effectiveness of a lubricant in a field water-based drilling fluid.

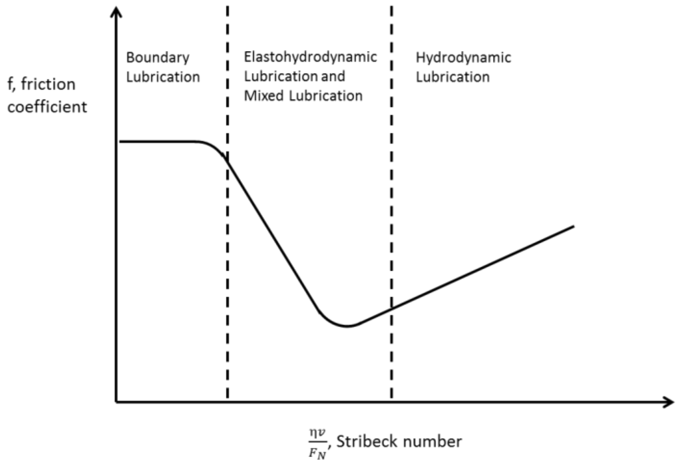

Figure 1: Classical Stribeck curve (modified from Hironaka, 1984).

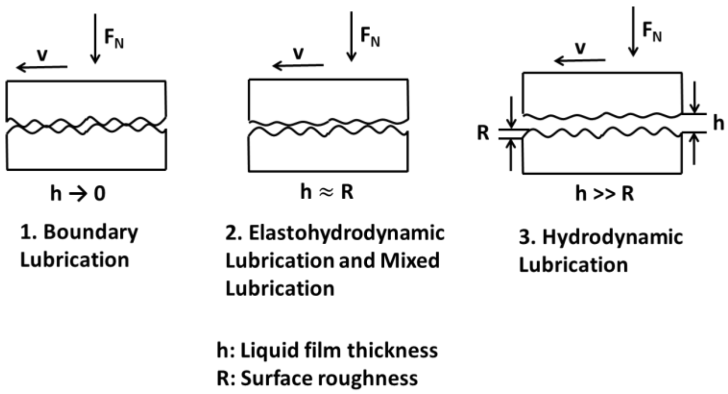

Figure 2: Illustration of different lubrication regions (modified from Hironaka, 1984).

Traditional Lubricity Measurement in the Oilfield

In the oil and gas industry, extreme pressure (EP)/lubricity testers are widely used to determine the lubricity. Lubricity measurements are performed by applying a measured force with a torque arm to a torque-sensitive, rotating bearing cup (Fann Instrument Company, 2007). Specifically, during a typical test, the EP/lubricity tester is first “calibrated” by pushing a block against a rotating ring in distilled water for at least 15 minutes to wear out a rough surface pattern on the block. A friction torque of 150 in-lbs is usually applied. This friction torque is used as a baseline by assuming the friction coefficient of distilled water is 0.34. Further measurements of friction coefficient on real fluid samples are made by comparing the results to the above baseline value (Fann Instrument Company, 2009). In this traditional approach of lubricity measurement, surface roughness is not taken into consideration. The surfaces of the ring and block have already been significantly roughened before the measurement of the lubricity of a test fluid. This results in the measured friction coefficient of water in the boundary lubrication region. Furthermore, there is no control of the surface roughness in the process. Figure 3 shows the ring and the block used in the traditional EP/lubricity tester. It is evident that they have been significantly roughened before the start of any lubricity measurement.

Figure 3: Ring and block used in the traditional EP/lubricity tester.

However, as shown in the previous section, having a rougher surface due to extremely high normal loading will easily move an otherwise mixed lubrication region to the boundary lubrication region, which can potentially lead to doubling the measured friction coefficient. This should explain why consistent results are difficult to obtain in this traditional way of measuring lubricity. Also, even though the friction coefficient of 0.34 with distilled water between two metal blocks is well-documented, metal surfaces should not be roughened just to match this number. As a matter of fact, when two metal surfaces are roughened enough, sticking and galling occur. This further increases the friction factor of water between two metal blocks to a value much higher than 0.34 if surface rubbing continues. Additionally, any trace of impurity in the water sample can reduce the friction coefficient substantially. As a result, even if a friction coefficient of 0.34 is obtained for distilled water, it is hard to determine if this accurately represents the lubricity of water, let alone the accuracy of any subsequent measurement of fluid lubricity. During a typical oilfield lubricity test with water, friction will keep increasing during the “wear-in” or surface roughening process over an extended period of time and does not tend to stabilize after 15 minutes. If an equivalent friction coefficient of 0.34 is ever achieved, the time needed to reach this number varies greatly from test to test. This again demonstrates that the test surfaces are going through uncontrolled changes during the surface roughening process.

Besides the inconsistency in surface roughness and measured lubricity, the traditional EP/lubricity tester can only be used at ambient conditions. This limits the applicability of relating the laboratory results to field performance at elevated temperature and pressure. In addition, it is well-known in the industry that even though the EP/lubricity tester can demonstrate the effectiveness of a lubricant, it does not work well when evaluating the performance of multiple lubricants, especially in mud samples. A dynamic lubricity tester that maintains the surface roughness during lubricity measurement under controlled temperature and pressure is introduced in the next section. A case study where the instrument was used to evaluate the effectiveness of a lubricant in a field fluid is presented.

Dynamic Lubricity Tester

Figure 4 shows the dynamic lubricity tester that was used in this study. It consists of a sample cell in which the sample fluid can be heated up to 500 °F. Pressure can also be applied to the fluid up to 2000 psi. During a test, the surface of a steel block or an actual core sample is exposed to the testing fluid inside the sample cell. A steel rubbing shoe is screwed onto the rotating shaft on the top. The normal loading can be adjusted by the cylinder underneath the sample cell. Figure 5 shows the configuration of the rubbing shoe and steel block inside the sample cell. A cylindrical core can be used in place of the steel block.

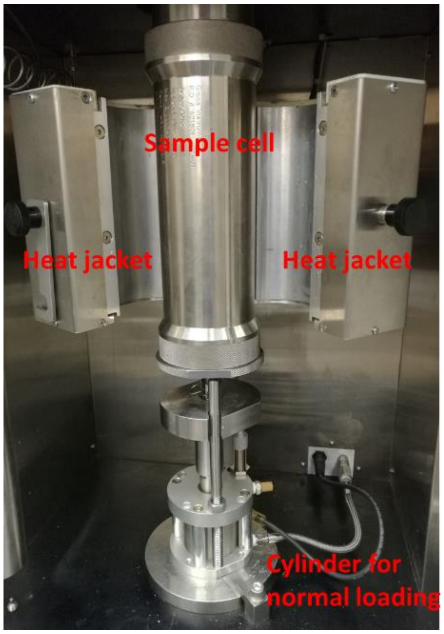

Figure 4: Dynamic lubricity tester.

Figure 5: Configuration of the rubbing shoe and steel block inside the sample cell.

Figure 6 shows the steel block and rubbing shoe before and after a lubricity test. It can be seen that after each lubricity measurement, a visible "ring" was left on the steel block as a result of its surface interactions with the rubbing shoe. To ensure the consistency of surface roughness, resurfacing the steel block and the rubbing shoe using 350 – 400-grit sandpapers is usually performed before the next test. Despite the change in surface conditions, the surface of the steel block remains relatively smooth after each measurement because the instrument is not first "calibrated" with water. This is confirmed by the reproducible friction coefficient measured using the dynamic lubricity tester. Figure 7 shows an Alabama marble core sample before and after the lubricity test. Similar to the steel block, a visible "ring" was left on the core surface after the lubricity test. Since it is very difficult to resurface a core sample to the same condition, the core sample should not be reused.

Figure 6: Metal block and rubbing shoe (a) before and (b) after a lubricity test.

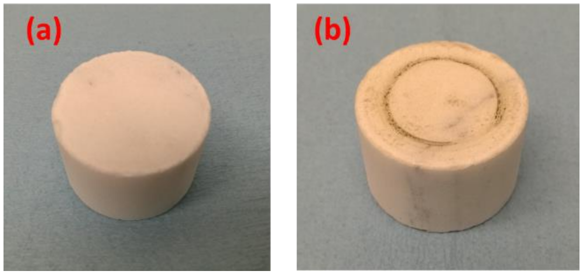

Figure 7: Alabama marble core (a) before and (b) after a lubricity test.

Calculation of Friction Coefficient

The friction coefficient is a function of the drag force and the normal loading. The drag force is calculated as:

$$F_D = \tau / r \quad (1)$$

where F_D is the drag force, τ is the torque of the rubbing shoe, and r is the radius of the rubbing shoe. Subsequently, the friction coefficient is calculated as:

$$f = F_D / F_N \quad (2)$$

Verification of Dynamic Lubricity Tester

As mentioned in the above section, distilled water is used to "calibrate" the traditional EP/lubricity tester. Since the surface roughness of the test ring and block is uncontrolled during this "calibration" process, the subsequent measured lubricity of fluids is not reliable and does not offer useful insights for drilling fluids and lubricants evaluation. Figure 8 shows the results from four measurements of water lubricity using the dynamic lubricity tester. A steel block was used in this test. The measurement temperature was 80°F. A normal load of 155 lbs and rotational speed of 60 revolutions per minute (RPM) were also used. It can be seen from Figure 8 that in Measurements #1 and #2, the water friction coefficient reached 0.34 after 15 minutes. However, the continued roughening process kept raising the friction coefficient to almost 0.4 after one hour of test. In comparison, it took only 45 minutes to reach 0.34 in Measurement #3. Measurement #4 did not even produce a friction coefficient of 0.34, probably because the surface of the steel block was not rough enough after 20 minutes of rubbing. It is evident that even though a friction coefficient of 0.34 can be obtained when the surface of the steel block is roughened sufficiently, this surface roughness cannot be controlled during the lubricity measurement of water. Therefore, using water to calibrate any type of lubricity tester is not recommended. The correct practice should be to start with consistent surface roughness/smoothness and continue to ensure this relative smoothness on surface throughout the measurement process of the fluid lubricity.

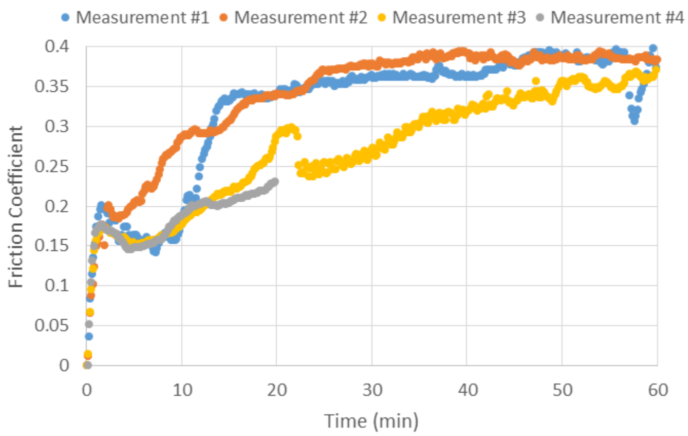

Figure 8: Measurements of the water lubricity using the dynamic lubricity tester.

Figure 9 shows the lubricity of a base oil when the temperature was increased from 150°F to 200°F and then back to 150°F. The normal load was ~260 lbs. At each temperature step, the lubricity of the base oil was measured three times when the rubbing shoe was rotating at 50, 10 and 2 RPM respectively. Each measurement lasted eight minutes. The rubbing shoe and the steel block were disengaged for one minute to allow fresh fluid to enter the space between them.

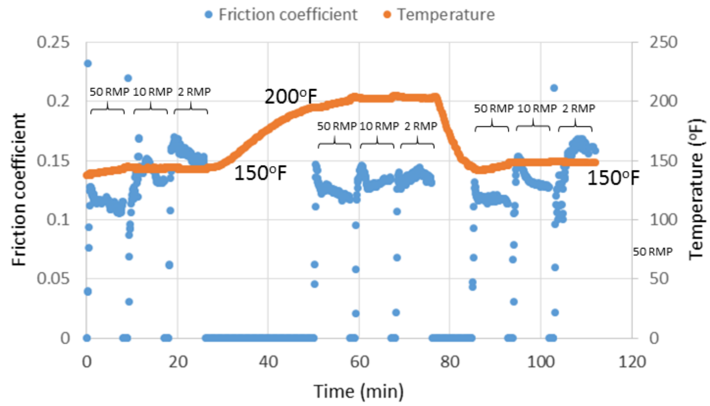

Figure 9: Measurements of the lubricity of a base oil using the dynamic lubricity tester.

Table 1 shows the results of the lubricity of the base oil. It can be seen from the two measurements at 150°F (after heating and after cooling respectively) that the data reproducibility of the instrument was very good, especially when the rotational speed was greater than 10 RPM. A low rotational speed such as 2 RPM might create more data fluctuation. The results also show that the friction coefficient increases with reducing rotational speed of the shoe. This indicates that the measured friction coefficient was in the mixed lubrication region. Table 1 also shows that in general, the friction coefficient increases with temperature. Similar observation was reported by Kaarstad et al. (2009). This can be attributed to the decrease in fluid viscosity when temperature increases. Again, this follows the Stribeck curve in the mixed lubrication region.

Table 1: Lubricity of a base oil from running the dynamic lubricity test.

Rotational speed	Friction coefficient		
	150°F after heating	200°F	150°F after cooling
50 RPM	0.115	0.117	0.114
10 RPM	0.133	0.136	0.128
2 RPM	0.146	0.131	0.164

Table 2 shows the lubricity of a water-based mud (WBM) sample. The test sequence was similar to that for the base oil. The temperature was increased from 140°F to 200°F and then back to 140°F. The normal load was ~150 lbs. At each temperature step, the lubricity of the mud was measured three times when the rubbing shoe was rotating at 60, 30 and 10 RPM respectively. At each rotational speed, three measurements of eight minutes each were performed. Between each measurement, the shoe and the steel block were disengaged for one minute. The friction coefficient of the third measurement is shown in Table 2.

Similar to the results for the base oil, the two measurements at 140°F show good data reproducibility of the instrument. However, unlike the trend for the base oil, the friction coefficient of the mud increases with decreasing rotational speed. This indicates that the measured friction coefficient was in the hydrodynamic lubrication region. Table 2 also shows that the friction coefficient decreases with temperature, which is also different from that of the base oil. This again shows that the friction coefficient of the fluid was in the hydrodynamic lubrication region on the Stribeck curve, when the fluid viscosity decreases with increasing temperature.

Table 2: Lubricity of a mud sample from running the dynamic lubricity test.

Rotational speed	Friction coefficient		
	140°F after heating	200°F	140°F after cooling
60 RPM	0.117	0.078	0.120
30 RPM	0.088	0.065	0.080
10 RPM	0.080	0.058	0.090

Evaluation of the Lubricity of Water-Based Mud for Field Operations

The dynamic lubricity measurement technique was also employed to evaluate the lubricity of a field WBM. The WBM was planned be used for drilling a deviated well in Colombia. The well was inclined at 50 °. The main lithology in the formation is carbonate.

A lubricant was added at 1% and 2% by volume to the base mud to evaluate its effectiveness. The lubricant used has a high affinity to metal due to the polar type of attractions. It can adhere much more quickly to the metal surface than other surfaces. Table 3 shows the properties of the base WBM without any lubricant.

Table 3: Properties of the water-based mud.

Mud weight, lb/gal	9.05
pH	9.27
θ 600 / θ 300 @ 120°F	100/68
θ 200 / θ 100	52/36
θ 6 / θ 3	11/8
Plastic viscosity, cP	32
Yield point, lb/100 ft²	36
10-sec Gel, lb/100 ft²	9
10-min Gel, lb/100 ft²	12

Since downhole friction involves both metal casings and tool joints as well as rocks for open-hole scenario, both steel block and core samples (Alabama marble) were used in the lubricity measurement. The rotational speed of the rubbing shoe was 60 RPM, and the applied normal loading was ≃150 lbs unless otherwise stated. Sample temperature of ≃200°F was used to mimic the maximum downhole temperature.

Figure 10 shows the friction coefficient of the base WBM with no lubricant on an Alabama marble core. During the first ~30 minutes, the fluid sample was being heated up to 200°F. Each lubricity measurement lasted for 20 minutes, after which the rubbing shoe and the core sample were disengaged for ~10 minutes. The process was repeated to check for data reproducibility. It can be seen from Figure 10 that the friction coefficient was indeed reproducible.

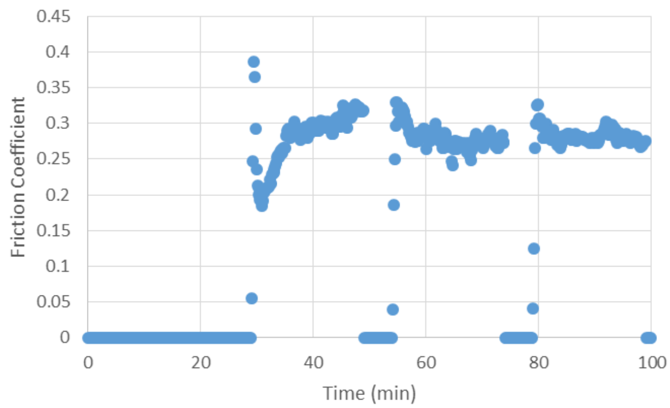

Figure 10: Friction coefficient of the base WBM with no lubricant on an Alabama marble core.

Figure 11 shows the friction coefficient of the WBM with and without lubricant when steel block and Alabama marble core were used in the lubricity measurement. Table 3 shows the percentage reduction in friction of the base WBM after lubricant was added. It can be seen that the friction of the base mud was greater on the Alabama marble than on the steel block. This is probably due to the surface of the marble sample being rougher than that of the polished steel block. The lubricant was also shown to be effective in reducing the friction between the rubbing shoe and both the steel block and the marble sample. ~50% and more than 65% of the friction were reduced when the rubbing shoe was rotating against the steel block and the marble sample in the WBM with 1% lubricant respectively. When 2% lubricant was added to the WBM, the friction reduction was more than 70% in both cases. Clearly, this lubricant is very effective in the friction reduction for both cased and open holes when used in water-based drilling fluids.

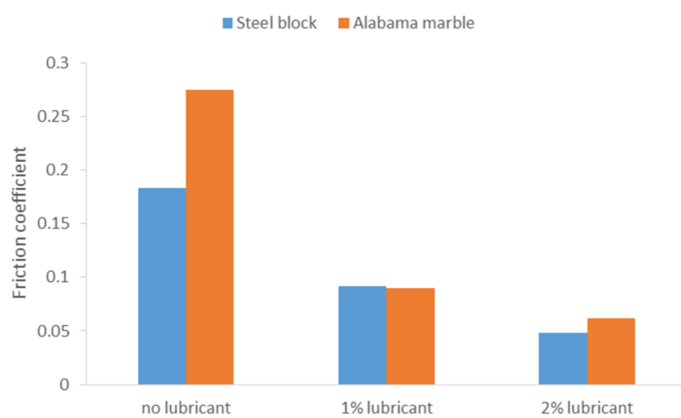

Figure 11: Friction coefficient of the WBM with and without lubricant when steel block and Alabama marble core were used in the lubricity measurement.

Table 4: Reduction in the friction of the base WBM after lubricant was added.

	% reduction in friction	
	Steel block	Alabama marble
1% lubricant	49.7%	67.3%
2% lubricant	73.8%	77.5%

After the laboratory tests, the WBM was used to drill a section of the well of ~5,800 ft long in Colombia. The first ~3,900 ft was drilled from 5,900 ft MD with the base WBM without adding any lubricant. The next ~500 ft was drilled with the WBM with 1% lubricant. The remaining ~1,400 ft was drilled with the WBM with 2% lubricant.

The lubricity of the fluids in the field was also measured using the EP/lubricity tester. The results show that the lubricity coefficient was 0.17 – 0.18 for the base WBM without lubricant, 0.12 for the WBM with 1% lubricant, and 0.09 – 0.13 for the WBM with 2% lubricant. The results using the EP/lubricity tester also show that the lubricant was effective in reducing the friction when added to the WBM. However, all the measurements were performed at ambient conditions. The friction of the WBM was reduced by about 30% and 25% – 50% when 1% and 2% lubricant were added to the fluid. This lubricity reduction was smaller than what is shown in Table 3. Factors such as pressure and temperature can affect the difference in the observed friction reduction. The variation in the lubricity coefficient of the WBM with 2% lubricant might be due to the contamination in the mud system during the drilling process. However, the uncontrolled conditions on the surface of the ring and the rotating block are definitely contributing to the variation in the measured fluid lubricity as well.

Conclusions

In this paper, we evaluated the traditional lubricity measurement technique in the laboratory and found that the surface roughness of rubbing bodies was not controlled during the measuring process. This lack of surface roughness control can result in the measured lubricity not in the same lubrication region on the Stribeck curve, which makes the evaluation of fluids and lubricants difficult. This problem is overcome by the use of a novel dynamic lubricity tester, which utilizes surfaces with controlled roughness and ensures this roughness consistency throughout the measurement. Measured lubricity results show good data reproducibility of the instrument. Results from a lubricity measurement on a base oil indicate that the friction coefficient was in the mixed lubrication region, while the friction coefficient of a mud sample was shown to be in the hydrodynamic lubrication region. The effectiveness of a lubricant in a WBM was examined using the dynamic lubricity tester. Results show that the lubricant was very effective at 200°F when both a steel block and a marble core was rotated against a rubbing shoe.

Acknowledgments

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Nomenclature

f = Friction coefficient
F_N = Normal load
F_D = Drag force
v = Sliding velocity
η = Viscosity of fluid
τ = Torque

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