

A New Look at Bit Balling Mechanisms, Impacts, and Diagnosis

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Abstract

Bit balling is known to be a major cause of slow penetration rates (ROP) in deep shales drilled using water base mud (WBM). A common expectation is that oil base mud (OBM) prevents balling, but slow ROP is still experienced in deep shales even when drilled with OBM. Single cutter tests on two types of shale drilled with mineral oil, as well as some examples from both full-scale bit lab tests and field drilling with OBM experienced severe balling. Consequently, balling may be a significant cause of slow ROP in OBM as well as WBM.

Single cutter and full-scale drilling tests have been analyzed to see how severe balling develops and to identify diagnostic symptoms of different kinds and severities of balling. In full-scale tests where global balling occurred, four sequential, symptomatic trends were identified that potentially represent different balling behaviors or phases. The initial trend in full-scale tests was similar to the trend in single cutter tests with known cutter balling, which suggests that the global balling was preceded by cutter balling. The force ratio (torque/weight on bit) and specific energy measured during cutter balling increase significantly and define a distinctive trend. However, decreased ROP was observed only in cases where severe "global" balling occurred, and the force ratio decreased. These distinguishable symptoms of cutter balling and global balling may be used to identify the occurrence and type of balling in the field. If cutter balling is identified and a mitigating action can be defined and taken before global balling develops, the negative impact on the ROP might be avoided.

Introduction

Hundreds of wells are drilled annually in U.S. with vertical depths greater than 15,000 ft. Analysis of more than 1000 vertical wells drilled in the United States, mostly after year 2007, indicates that average ROP at depths greater than 15000 ft is 10 ft/hr or less in 73% of these wells. Slow penetration rates experienced in deep shale intervals is a major contributor to this problem.

Shale drilling has been the focus of several studies. Extensive research^{1, 2} conducted on drilling shales during the 90's indicated that bit balling is the major cause of slow penetration rates in shales drilled using water base mud (WBM) under high confining pressure. "Balling is any accumulation of cuttings or rock debris that interferes with effective bit performance."¹ Depending on the significance

and location of accumulated cuttings, balling can be categorized as cutter balling, global balling, and bottomhole balling.

Bottomhole balling occurs when accumulation of broken rock material at the bottom of the hole interferes with the transfer of energy from the bit to the rock beneath. This has been observed in high pressure full-scale laboratory experiments in shales drilled with roller cone bits.² However, the significance of bottomhole balling for drilling with PDC bits is still questionable. Cutter balling is generally defined as accumulation, and possibly adhesion, of cuttings on the face of a PDC cutter (Fig. 1). By movement of the PDC cutter under confining pressure, the cuttings are extruded up and accumulated on the face of cutter. Therefore, energy is spent to overcome frictional forces and deform piled up cuttings.^{3, 4} This phenomenon has also been observed in high permeability rocks such as limestone.⁴ Global balling generally causes the most severe impact. It occurs when a large mass of broken and deformed rock cuttings cover the bit face and/or fill the junk slots and cause significant reduction in ROP. High mechanical specific energy, low force ratio, inability to drill at high ROP, and lack of response in ROP to increased WOB are the major symptoms observed during global balling.

Industry has sought the ways to mitigate global balling due to its severe impact on drilling performance. Use of oil base mud (OBM) or synthetic base mud (SBM) mitigates, but does not eliminate, bit balling, and therefore increases ROP in shales. Full-scale high pressure laboratory experiments have shown that the advantage of synthetic base mud over water base mud is not only reducing the cutting cohesiveness, but also potentially by the smaller cuttings produced.⁵ However, single cutter experiments on Catoosa and Pierre shale show the potential for the occurrence of global balling in OBM.¹ Likewise, global bit balling has been observed in full-scale drilling tests with OBM. Figure 2 shows global balling on 8 1/2" PDC bit that drilled Catoosa shale with 16.5 ppg OBM at 6000 psi bottomhole pressure in a full-scale test.

It is very difficult to reverse global balling after its occurrence in order to return to effective drilling. However, the mechanisms that precede global balling are not well understood, and a reliable early detection method does not exist.^{6, 7} In this paper, single cutter tests have been analyzed and compared with full-scale tests in Catoosa shale representative of global balling to obtain a better understanding of the mechanism of balling. Similar trends in

both groups of the experiments indicate applicability of observations from single cutter tests to understand bit balling behavior. Results from this analysis, accompanied with analytical modeling of cutter-rock interactions under confining pressure⁸, suggest that global balling is the end point of a process of cutting accumulation that can be identified from force trends.

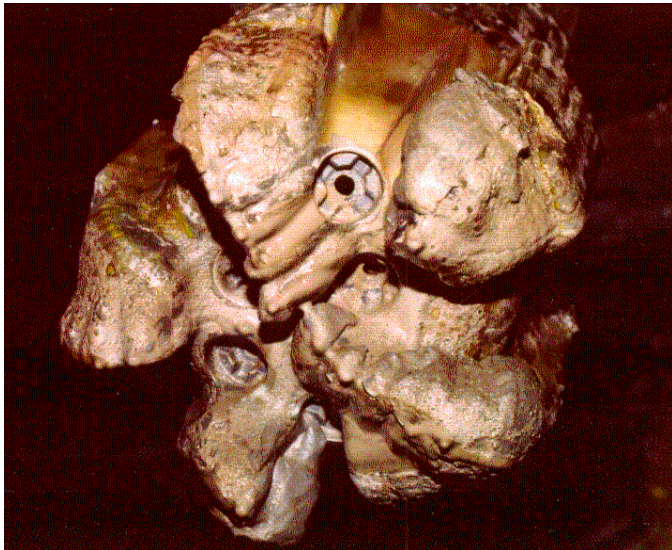


Fig. 1. Cutter balling in WBM in a full-scale drilling test in Catoosa shale¹



Fig. 2. Global balling in OBM in a full-scale drilling test in Catoosa shale (Courtesy of Baker Hughes)

Analysis of Single Cutter Tests

J.R. Smith performed two series of single cutter tests on three different rocks: Catoosa shale, Pierre shale, and Twin Creeks siltstone at 273 rpm under confining pressures as high as 9000 psi. In these tests, both standard and polished cutters with a 45° chamfered edge were used. The majority of these tests were performed using polished cutters, and conclusions here are based on those experiments, unless otherwise indicated.

The first group of tests used a standard holder, and the cutter was cantilevered away from the driveshaft to limit global balling effects. These tests are referred to as “cantilever” tests. In another series of tests, the cutter was positioned below a simulated bit face, i.e. an interference plate was installed over the cutter with about 0.34 inches standoff. Consequently, it allowed global balling to occur between the bit face and the rock. Here, these tests are referred to as “interference plate” tests. The apparatus and procedures for both groups of tests are described by J.R. Smith.¹

Cantilever tests

Cantilever single cutter tests were performed in both water and mineral oil. Tests were performed at 0.011” and 0.075” depths of cut at 273 rpm rotation speed, proportional to 15 ft/hr and 102.3 ft/hr, respectively. Nevertheless, due to lower rotation speeds used in field those depths of cut were stated as representing penetration rates of 7 and 50 ft/hr in Smith’s study. The desired penetration rates were achieved in all of the tests with the cantilevered holder. In addition, an increased axial load, equivalent to increased weight on bit (WOB), was required at the higher depth of cut. Consequently, these tests were considered representative of effective drilling. However, the drilling efficiencies during the tests, evaluated with mechanical specific energy (MSE), were different depending on the confining pressure, the surface finish of the cutter, the depth of cut, and the drilling fluid. Mechanical specific energy (MSE) is defined as the amount of energy spent to drill a unit volume of the rock.⁹

Figure 3 shows the test results at high depth of cut (0.075”). The tests were performed using a polished cutter with 10° back rake angle at different confining pressures, as labeled in psi. As can be seen, at 1000 psi confining pressure, both tangential and axial forces are lower in water than in mineral oil. The ratio of tangential force to axial force, defined herein as the force ratio, is consistent for all of these tests except those in water at high confining pressures. The recorded force ratios in mineral oil were 0.99 and 1.07 at 1000 and 9000 psi confining pressures, respectively. Force ratios close to one were also observed in the tests in water at different confining pressures up to 3000 psi. However, the force ratio in water increased to 2.7 and 3.1 at 6000 psi and 9000 psi, respectively. At those pressures, the tangential force is higher and the axial force is significantly lower than expected. MSE is dependent on tangential force, while the impact of axial force in calculation of MSE is less than 5%. Therefore in those cases, the MSE for drilling in water was much greater than in mineral oil. The combination of high force ratio, which is often considered to represent “aggressive” or “effective” drilling, and high MSE, which implies inefficient drilling, point to the need for a better understanding of these symptoms.

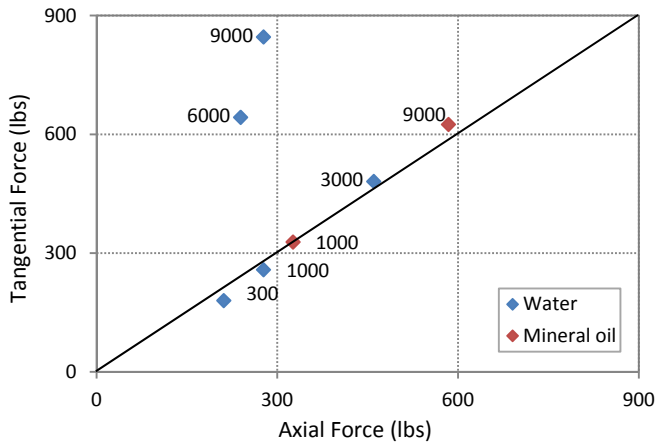


Fig. 3. Single cutter “cantilever” tests with 10° back rake angle polished cutter at 0.075” depth of cut

The thin, ribbon-like cuttings from tests in both water (Fig. 4) and mineral oil (Fig. 5) with one side jagged and one side smooth had a similar appearance to cuttings recovered in the field when drilling with PDC bits in OBM. At 9000 psi, the thicknesses of ribbons were 0.17” and 0.25” in mineral oil and water, respectively. In addition, balls as large as 0.25” x 0.375” composed of accumulated cuttings were observed adhering to the cutter in tests in water at high confining pressures (Fig. 6), while they were not observed in the tests in mineral oil. Similar cutter balling has been observed in full-scale PDC bit tests in water, see Fig. 1.

Analytical modeling of cutting forces indicated that the increase in tangential force, and reduction in axial force, is possibly due to the occurrence of cutter balling.⁸ It was hypothesized that as the size of the cuttings accumulation on the face of cutter increases, more energy is spent to deform and carry the accumulation. This problem is more severe under higher confining pressures and is a likely cause for the higher force ratios recorded in the high pressure tests in water.



Fig. 4. Saw-toothed ribbon shaped cuttings produced in a single cutter test in water at 9000 psi¹



Fig. 5. Saw-toothed ribbon shaped cuttings produced in a single cutter test in mineral oil at 9000 psi¹



Fig. 6. Cutter balling in a single cutter test in water at 6000 psi¹

Figures 7 and 8 show the results from cantilever single cutter tests in mineral oil and water. The cutter advances at a constant rate proportional to 102.3 ft/hr rate of penetration (ROP). However, the actual ROP is less than this value until cutter reaches the desired depth of cut (0.075”). Also, the area of cut only becomes constant below 0.15” depth. After this point, constant cutter forces are expected.

In the test in mineral oil, both axial and tangential forces increase until the desired depth of cut is reached. Also, MSE decreases significantly as depth of cut increases. When the desired depth of cut is reached, cutter forces and MSE remain constant until the end of the test. Also the change in the area of cut (A) or cutting profile does not affect the cutter forces significantly. In contrast for tests in water, tangential force and thus MSE increase significantly even after reaching a constant depth and area of cut, while the axial force is almost constant. Therefore, force ratio in water is much higher than that in mineral oil. The radial force in both tests is significantly lower than the other forces.

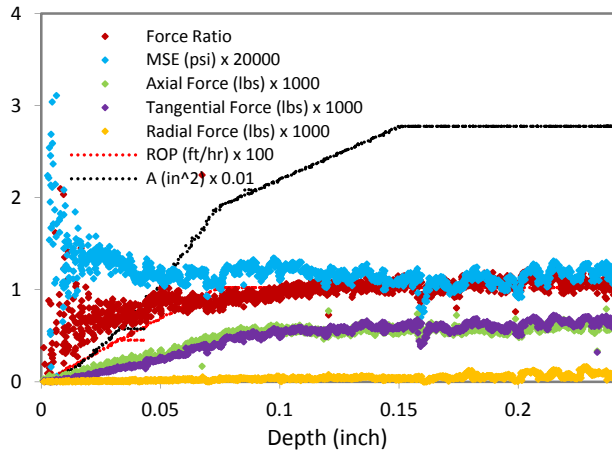


Fig. 7. Single cutter test in mineral oil at 9000 psi with 10° back rake angle polished cutter at 0.075" depth of cut

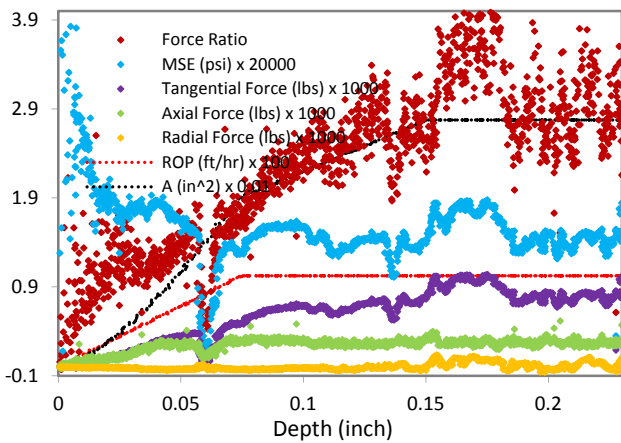


Fig. 8. Single cutter test in water at 9000 psi with 10° back rake angle polished cutter at 0.075" depth of cut

A similar comparison was performed on the tests with a standard cutter, see figures 9 and 10. All of the other test conditions were the same as those performed with polished cutters. However, the forces recorded in these tests were much greater than those with a polished cutter. In addition, the axial forces were higher than tangential forces in both water and mineral oil resulting in force ratios less than one.

In the test of a standard cutter in mineral oil, the force ratio was not significantly different than for the test in water. Nevertheless, the recorded forces in mineral oil were significantly lower than those in water. Also, as expected, the recorded forces in mineral oil were constant after reaching the constant depth and area of cut. The average thickness of ribbons in this test was 0.25", and evidence of cutter balling was not observed during inspection of the cuttings after the test. In contrast, the axial and tangential forces, and thus MSE, increased after reaching constant depth and area of cut in the test in water. This is a symptom that implies a continuing accumulation of cuttings. This was confirmed by the presence of cutter balls as big as 0.625" x 0.875" in the cell after the test. The average thickness of ribbons in this test in water was 0.5".

An additional symptom in these tests relates to the radial force measurements. The radial force in the test in mineral oil was in the order of 100 lbs, whereas it reached 400 lbs in the test in water. This increase in radial force happened after reaching constant depth and area of cut where constant forces are expected. As it is discussed later in this paper, the change in radial force is likely a consequence of cutting accumulation on the side of the cutter and it is mostly seen when global balling, or in this case, significant cutter balling occur.

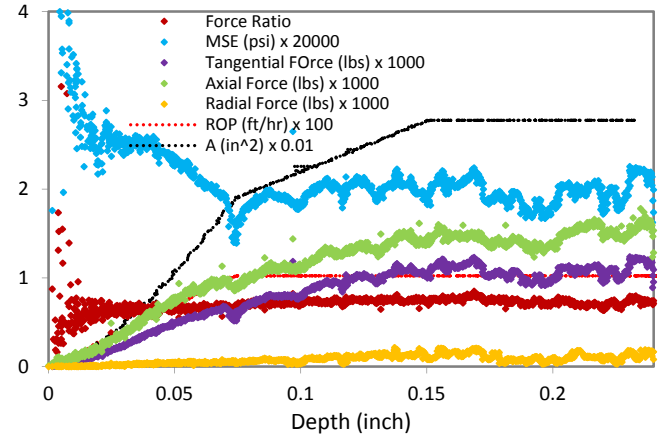


Fig. 9. Single cutter test in mineral oil at 9000 psi with 10° back rake angle standard cutter at 0.075" depth of cut

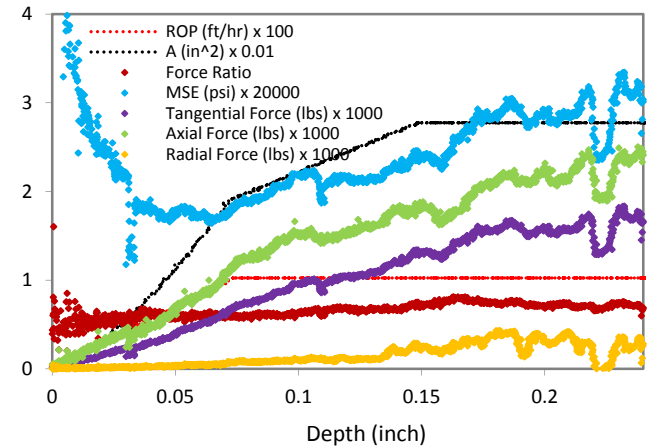


Fig. 10. Single cutter test in water at 9000 psi with 10° back rake angle standard cutter at 0.075" depth of cut

The desired depth of cut was achieved and maintained in all of the tests with the cantilevered cutter holder. Also, symptoms such as low force ratio which are observed in slow ROP shales in field and are indicative of ineffective drilling were not observed. Given that field symptoms for slow ROP shale were not observed in the cantilever tests, the earlier conclusion by Smith¹, based on these same tests, that cutter balling is not the major cause for slow penetration rates experienced in field, was confirmed. However, cutter balling can reduce the cutting efficiency significantly and may be the genesis of the accumulation of cuttings causing global balling.

Interference plate tests

Global balling was observed in tests using an interference plate in water at all of the depths of cut, even as low as 0.006" (Fig. 11). In the tests with mineral oil, however, global balling was observed only at the highest depth of cut (0.075") (Fig. 12). In contrast, at low depths of cut (0.006" and 0.011"), global balling was not observed in mineral oil. This tendency for a mineral oil drilling fluid to suppress balling is likely due to inhibition of cuttings cohesion due to the non-polar nature of the drilling fluid.¹ Figures 13 and 14 show the difference in cutting forces by comparing results from similar tests with and without an interference plate in water and mineral oil. All of these tests were performed with a polished cutter at 9000 psi confining pressure at 0.075" depth of cut. As can be seen, the initial stages of the tests are almost the same. In these interference plate tests, the produced cuttings accumulated on the face of the cutter under the plate, see figures 11 and 12. As the cutting volume increased, the cuttings accumulation interfered with downward advancement of the plate. The resulting increase in axial force (WOB) apparently compacted the cuttings more, which increased the resistance to drilling progress from the cuttings accumulation and eventually caused the machine to halt due to excessive load.



Fig. 11. Global balling in single cutter tests with interference plate in water at 9000 psi and 0.075" depth of cut¹



Fig. 12. Global balling in single cutter tests with interference plate in mineral oil at 9000 psi and 0.075" depth of cut¹

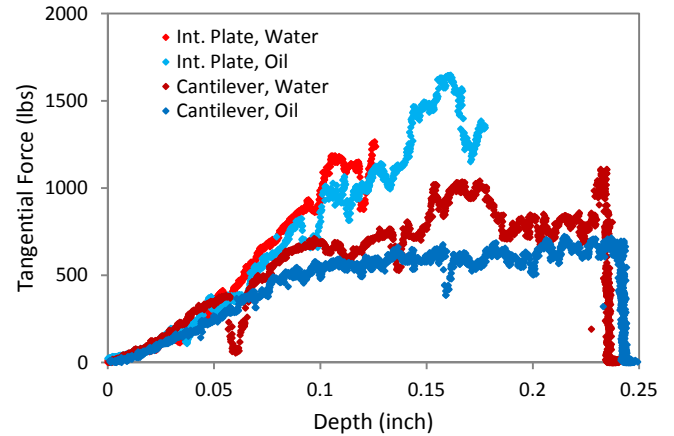


Fig. 13. Measured tangential forces for tests with and without interference plate at 9000 psi

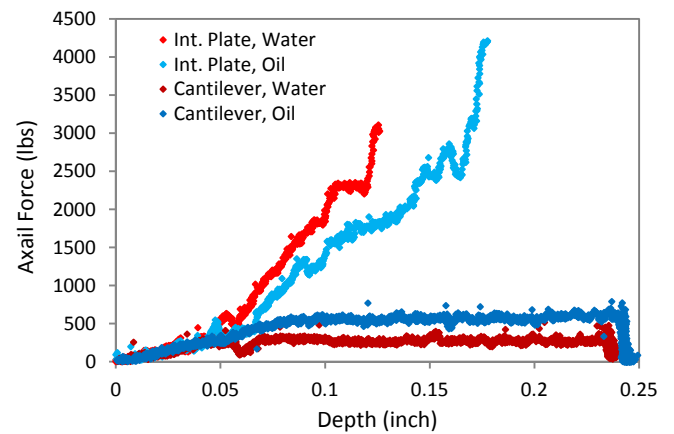


Fig. 14. Measured axial forces for tests with and without interference plate at 9000 psi

The machine drive was halted by overload protection on all of the tests where global balling occurred. Therefore, total depths drilled and volumes of cuttings produced at high depth of cut were generally lower than at low depths of cut (Table 1). In absence of hydraulics, it is expected that the total volume of cuttings plays a major role in occurrence of global balling. However, the impact of global balling was more at high depth of cut. This indicates that factors such as rate of cutting generation and size of produced cuttings can even be more important than cuttings volume in the occurrence of balling. The size of cuttings, and not necessarily the volume of cutting, has already been shown⁵ to be important in occurrence of balling.

Table 1. Total depths drilled (indicative of total cuttings volume) in interference plate tests

Test	Fluid	Depth of cut (inch)	Total drilled depth (inch)
1	Water	0.075	0.13
2	Water	0.011	0.19
3	Water	0.006	0.17
4	Oil	0.075	0.18
5	Oil	0.011	0.30
6	Oil	0.006	0.16

Figures 15 and 16 show the effect of drilling fluid type on occurrence of global balling in single cutter interference plate tests. Both tests were performed with a constant 0.075" depth of cut. Both tests had almost identical trends that lead to global balling. Nevertheless, the total depth that was drilled with water was shorter than mineral oil since global balling apparently developed faster and occurred earlier.

At least two distinguishable trends can be identified in the test in mineral oil (Fig. 15). From the start of the drilling to 0.07" depth of penetration, the force ratio is almost constant. Also, both axial and tangential force shows a gradual increase due to increase in the effective depth of cut. The second phase starts at 0.07" depth of penetration where axial force increases dramatically while tangential force increases gradually at almost the same slope as before. This causes a reduction in force ratio. A reduction in force ratio accompanied with significant increase in MSE is one of the known symptoms of global balling. The test could not be completed due to occurrence of global balling that stalled the cutter drive. The start of the second phase in the test in water (Fig. 16) is between 0.035" to 0.06" depth of penetration. At the former point, the force ratio starts to drop gradually. At the latter point, the rate of drop becomes more significant until the test stalled at a depth of 0.13 inches.

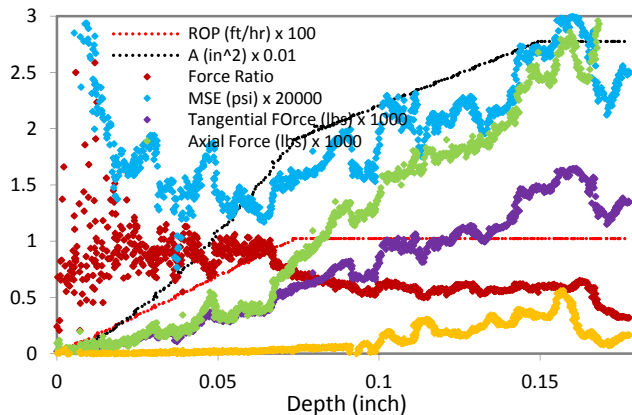


Fig. 15. Single cutter test with interference plate in mineral oil at 9000 psi with 10° back rake angle polished cutter at 0.075" depth of cut

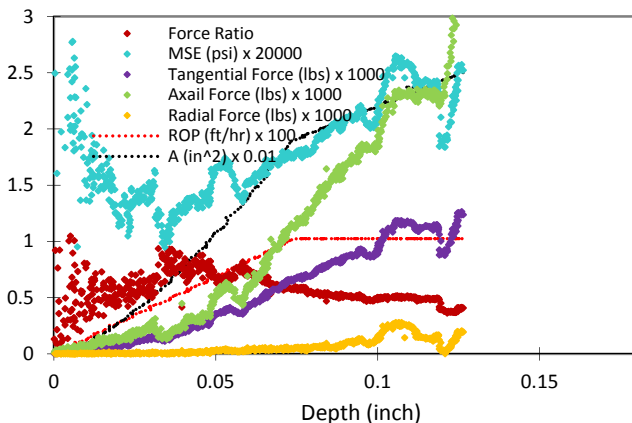


Fig. 16. Single cutter test with interference plate in water at 9000 psi with 10° back rake angle polished cutter at 0.075" depth of cut

The symptom of cutter balling observed in the cantilever tests, e.g. a simultaneous increase in force ratio and MSE, was not observed in either of these tests. Also, the cutting ribbons observed in the cell after cantilever tests were not observed in these tests. This may be because the cuttings interacted with interference plate and caused global balling so quickly that cutter balling never developed or that the symptoms were masked. These possibilities were examined using the test data at a lower depths of cut.

Figure 17 shows cuttings from a test with the interference plate in water, but at 0.011" depth of cut. The severe global balling that occurred in this test stalled the cutter drive at total depth of 0.19". This was greater than the total depth drilled at a high depth of cut. As can be seen, cutting ribbons were developed in this test. However, they were much shorter than those in cantilever tests. This is likely due to small standoff between cutter and interference plate that did not allow development of long ribbons.



Fig. 17. Cutting ribbons from single cutter tests with interference plate in water at 9000 psi and 0.011" depth of cut¹

Figure 18 shows the force diagram for the same test. The force ratio increases in the 0.075-0.085" depth interval while MSE is almost constant. However, since the area of cut is increasing in this depth interval, a strong conclusion cannot be made regarding the occurrence of cutter balling. Cutter balling was observed in the equivalent test without the interference plate. After occurrence of global balling there is a significant increase in radial force with a magnitude comparable with tangential force. This is possibly due to occurrence of balling that pushes the material to the side of cutter and cause an increase in the radial force.

Global balling did not occur in the interference plate test in mineral oil at 0.011" depth of cut, while evidence of some cuttings accumulation in front of the cutter is evident in the test photos (Figures 19 and 20). A significant increase in tangential force and MSE are observed from 0.085 to 0.13" depth where the area of cut is constant, which is a symptom of cutter balling (Fig. 21). A significant increase in radial force occurs simultaneously. Cuttings adhering to the face and side of the cutter support the hypothesis that the increase in tangential and radial forces is due to occurrence of cuttings accumulation, see Fig. 19. In addition, a cutter ball was

recovered from the test cell at the bottom of the groove, see Fig. 20. It is notable that cutter balling was not observed in the tests with mineral oil when using the cantilevered cutter holder except for one case with a very small accumulation. It is not clear whether the interference plate facilitated a cutter ball-like accumulation in this test or the cutter ball developed independently of the effect of the plate.

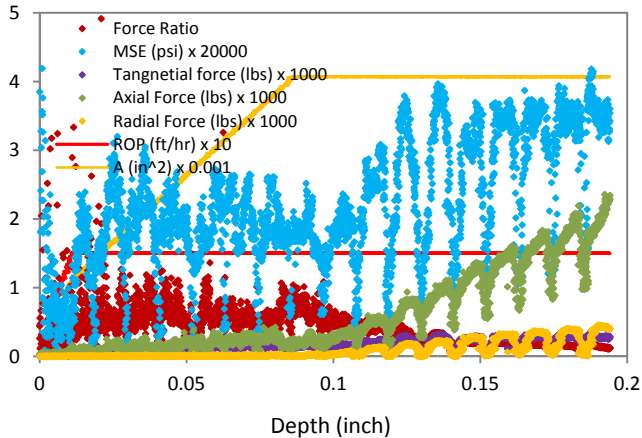


Fig. 18. Single cutter test with interference plate in water at 9000 psi with 10° back rake angle polished cutter and 0.011" depth of cut

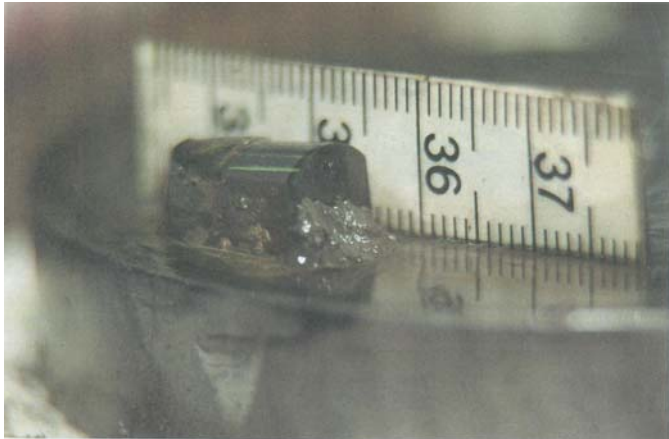


Fig. 19. Balling on the face and the side of cutter in interference plate test in mineral oil at 9000 psi and 0.011" depth of cut¹

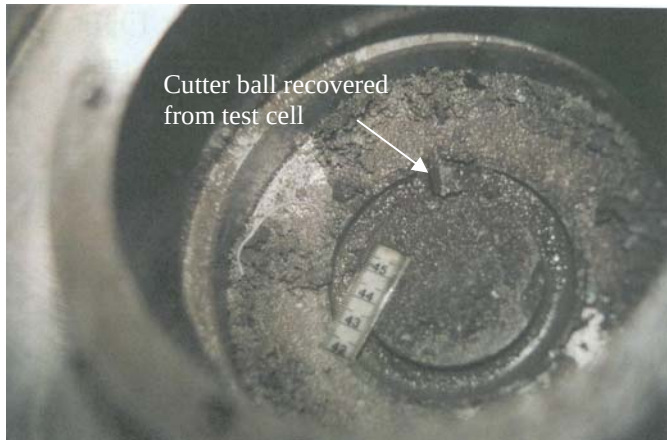


Fig. 20. Test cell of single cutter interference plate test in mineral oil at 9000 psi and 0.011" depth of cut¹

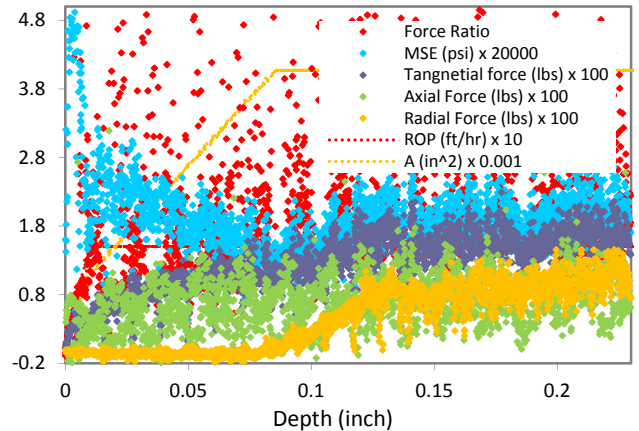


Fig. 21. Single cutter test with interference plate in mineral oil at 9000 psi with 10° back rake angle polished cutter at 0.011" depth of cut

An increase in radial force, as seen in the test at 0.011" depth of cut in mineral oil, was also observed in the tests at 0.006" depth of cut in both water and mineral oil. Global balling occurred at the former test, but it did not occur at the latter test. It is assumed that the accumulation of cuttings in front, and especially to the side, of the cutter in all of these tests resulted in increased radial forces. Figure 22 shows the loosely packed accumulation of cuttings recovered from the interference plate test in mineral oil at 0.006" depth of cut. The accumulation can be seen at both the bottom and the side of the groove.



Fig. 22. Test cell of single cutter interference plate test in mineral oil at 9000 psi and 0.006" depth of cut¹

Single Cutter vs. Full-scale Drilling Tests

Single cutter laboratory test observations were compared with typical full-scale laboratory tests that experienced global balling in water to develop a hypothesis for the process that causes the accumulation of cuttings necessary for global balling to occur. Comparison of these two groups of tests shows some similarities and some dissimilarities.

Figure 23 shows full-scale test results using 8 1/2" PDC bit for drilling Catoosa shale at 6000 psi, where global balling has been observed at the end of the test. μ is friction coefficient which is similar to force ratio but for full-scale tests.¹⁰ Trends

of MSE and force ratio in this test are similar to those for the interference plate single cutter tests. However, trends in axial and tangential forces expose some differences between the two types of the tests. These differences may be because of the difference in the number and geometry of the cutters, the bit body design, and/or the test conditions. In the single cutter tests, severe balling developed very quickly probably due to the small standoff between cutter and interference plate and the absence of hydraulics. In addition, the depth of cut was kept constant during the test. However, the longer duration of full-scale tests allows variation in weight on bit, and potentially in other input parameters, to investigate balling symptoms under circumstances more representative of field operations and practices. Four distinctive trends can be identified in the full-scale test plot shown in Figure 23.

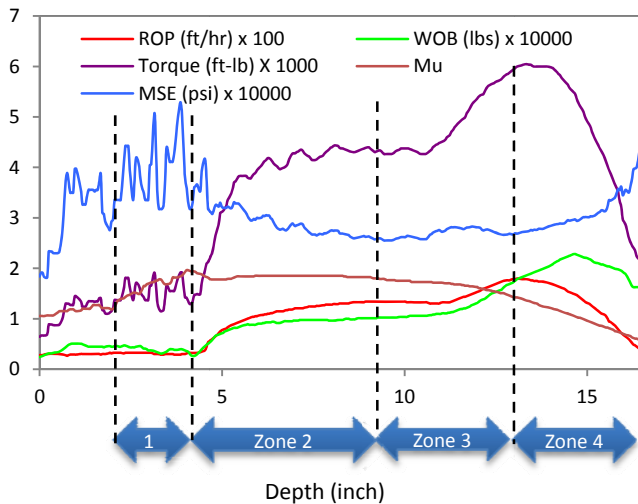


Fig. 23. Typical full-scale test showing the occurrence of global balling (Test A)¹¹

- Zone 1:** The drilling parameter trends from the start of drilling through the end of zone 1 are very similar to those for cantilever single cutter tests in water with a polished cutter (Fig. 8): ROP is constant, WOB is increasing, until profile of cut is almost constant, and then decreasing, torque is increasing, and therefore both friction coefficient, Mu which is equivalent to force ratio, and MSE are increasing. As already discussed, the change in depth and area of cut determines the force behavior at initial stage of the test. Therefore, to eliminate those effects, the first two inches of drilling were excluded. The nearly identical force symptoms to cantilever tests with cutter balling suggest the occurrence of cutter balling in zone 1. Similar trends were observed at interference plate single cutter test in mineral oil at 0.011" depth of cut from 0.085 to 0.13" depth, see Fig 21. It is noteworthy that high force ratio in general is often desired as a symptom of effective or aggressive drilling. However, given a constant area of cut if the MSE is also increasing, then these trends are probably due to the occurrence of cutter balling. As noted previously,

cutter balling does not prevent using increased WOB to increase ROP as evidenced by the response observed in Zone 2.

- Zone 2:** In this zone, ROP, and consequently torque, are responsive to an increase in WOB. Mu is essentially constant and MSE decreases and stabilizes at a minimum value once the operating conditions are stabilized. This would appear to be effective drilling, and the ROP greater than 100 fph would be considered good for similar operating conditions in the field. Although it seems likely that there is some cutter balling occurring based on behavior in Zone 1, it is not interfering significantly with the bit's performance, similar to the single cutter performance after 0.18 and 0.13 inch depths in Figures 8 and 21, respectively.
- Zone 3:** This zone begins with a small decrease in ROP although WOB is almost constant, actually increasing slightly, and there is no apparent reason for a change in system behavior. The Mu subsequently starts to decrease and MSE to increase gradually. Most notably, an increase in WOB causes a more rapid increase in MSE and decrease in Mu. These are the exact symptoms of the onset of global balling observed in the single cutter tests with an interference plate as shown in Figures 15, 16, and 18. Figure 24 shows a similar full-scale test where the change in the slope of force ratio versus depth, at 10" depth, can be used as a symptom of transition from zone 2 to zone 3. Apparently, this zone evidences the symptoms of the onset of a cuttings accumulation to become severe and cause global balling. The initiating mechanisms in these cases are not clear. It may be that this much drilling, which was less than a foot with this specific system, was required to accumulate a sufficient volume of cuttings to cause interference with the bit's performance. It may be that some other factor caused the accumulation to increase.
- Zone 4:** This zone is considered representative of the fully dysfunctional behavior associated with global bit balling. The ROP begins to decline while WOB is still increasing. The symptoms in this zone between 13" and 14" are similar to those in single cutter tests when global balling occurs. Torque is somewhat higher than expected for the ROP, and WOB increases while ROP is constant or decreasing. Consequently, Mu decreases and MSE increases. This is probably due to accumulation of cuttings between the bit body and the bottom of the hole that impedes downward advancement of the bit and causes WOB to increase in trying to maintain ROP and depth of cut as also seen in single cutter tests. Eventually, the torque drops as the ROP drops. In this case, the WOB was subsequently reduced beginning at a depth of 14.7", but ROP continued to drop rapidly as MSE increased and Mu decreased. These symptoms could not be observed in

single cutter tests because the depth of cut is designed to be constant, and the machine delivers the cutter forces required to maintain the depth of cut. Therefore, when global balling occurs, which could affect the depth of cut, the machine automatically increases the cutter forces until they exceed its load capacity and cutter drive stalls. Zone 4 is interpreted as representing a globally balled up bit, where a further increase in WOB makes the effect of the balling more severe. Global balling on the bit was observed after completion of the tests in Figures 23, 24 and 25.

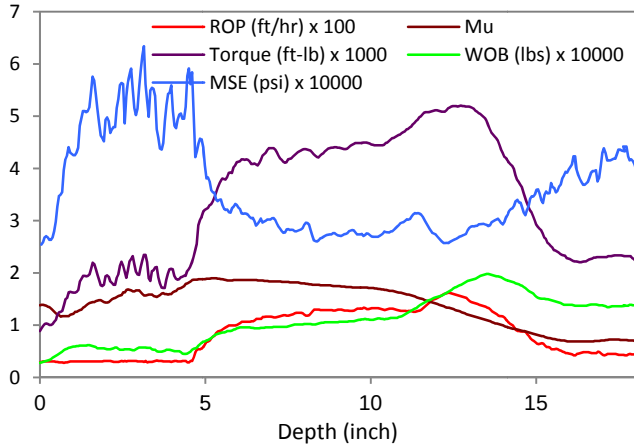


Fig. 24. Typical full-scale test showing the occurrence of global balling (Test B)¹¹

Due to rapid development of global balling, and the uncertainty regarding the mechanism causing cuttings to accumulate, it is sometimes very difficult to predict the onset of its occurrence. Figure 25 shows a full-scale test in Catoosa shale with the essentially the same operating conditions as the previous two tests. In this case, there is again some evidence of zone 1 behavior at the beginning of the test up to a depth of about 5". A constant Mu and MSE decreasing and stabilizing at a constant value over the interval from 6 to 12" of depth appear to be typical symptoms of zone 2. The constant Mu and MSE as WOB and ROP increase to a depth of 12.5" continue to represent zone 2 behavior. At this depth, Mu drops suddenly and MSE begins increasing gradually as in zone 3 or 4. Within about half an inch in addition to these trends becoming more severe, the ROP begins decreasing despite further increase in WOB. These are strong indications of zone 4 behavior and severe global balling. This rapid change from a seemingly normal, responsive drilling condition demonstrates the difficulty in predicting whether a change in operating conditions may cause balling.

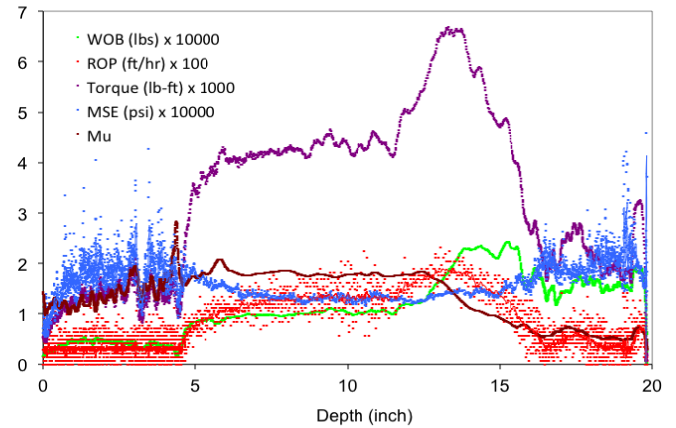


Fig. 25. Typical full-scale test showing the occurrence of global balling (Test C)¹²

Diagnostic Method to Identify Balling

If the onset of balling can be identified and a successful mitigating action defined and taken before global balling develops, the negative impact on the ROP might be avoided. Aghassi¹² and Solano¹³ identified diagnostic symptoms that could potentially predict the onset of global balling but were not successful in defining a reliable diagnostic technique for field application. A particular difficulty was the fast development of global balling as seen in Test C. However, sometimes the development of global balling, as seen in tests A and B, is slower. Also, penetration rates experienced in field are normally lower than full-scale drilling tests shown here. This could also result in global balling developing more slowly and providing more time for the diagnosis and response to the onset of global balling.

The drilling parameters recorded during the separate zones observed in test A were compared using approaches similar to those proposed and used by Aghassi and Solano. These comparisons were used to investigate the potential for identifying distinctive trends that might identify the transition from one zone to a subsequent zone.

ROP vs. WOB

Plotting ROP vs. WOB is probably the most common way to diagnose balling. Figure 26 shows changes in the trend of ROP vs. WOB in the four zones identified in Figure 23 for the full-scale drilling test A. In zone 1, ROP is constant while there is a small decrease in WOB. In zones 2 and 3 ROP increases versus WOB. However, in zone 3 the trend is less steep. Due to occurrence of global balling in zone 4 there is a significant reduction in ROP as WOB is increased. This was followed by a reduction in WOB as an attempt to control balling. The resulting slope was similar to that in zone 2, but the ratio of ROP to WOB is much less than before occurrence of global balling.

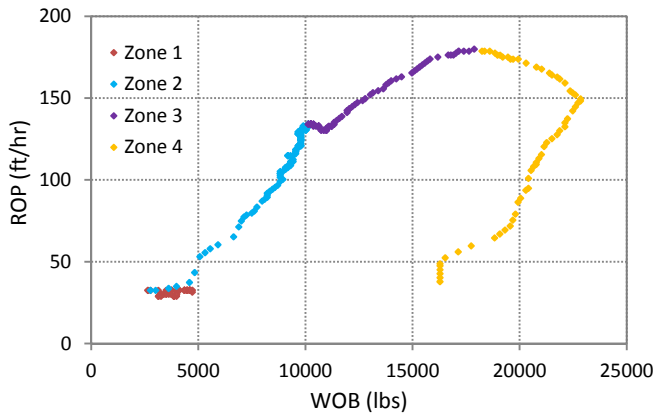


Fig. 26. Trend of ROP vs. WOB in different zones (Test A)

Force Ratio vs. ROP

Figure 27 shows that in zone 1, there is a significant increase in force ratio versus ROP over time. In zone two, force ratio is almost constant while ROP increases. In zone 3, force ratio decreases gradually as the penetration rate increases. In zone 4, both force ratio and ROP decrease regardless of whether WOB was increasing or decreasing. At least for this test, these trends appear to have distinctive differences.

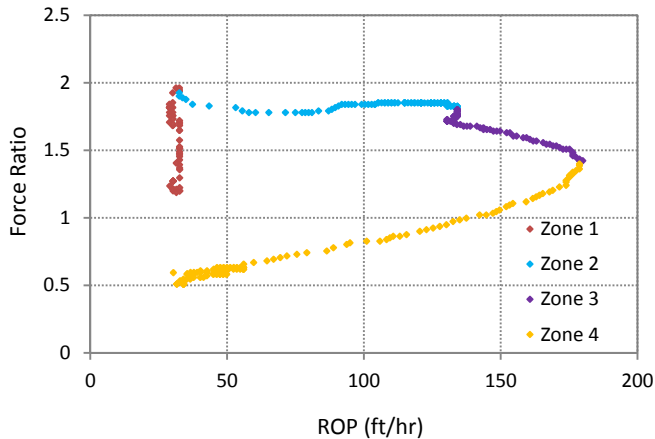


Fig. 27. Trend of Force Ratio vs. ROP in different zones (Test A)

Force Ratio vs. MSE

The plot of force ratio (μ) versus MSE for data in zone 1 is very scattered (Fig. 28). However, the overall trends between these two parameters are as described in the previous section based on review of Figure 23. Both MSE and force ratio increased despite a constant ROP and decreasing WOB in zone 1. In zone 2, MSE decreases and reaches a minimum value while force ratio is constant. Higher WOB in zone 3 increases MSE slightly while there is a gradual decrease in force ratio. In zone 4, force ratio drops more rapidly and MSE increases significantly with both trends becoming more severe over time, presumably because global balling is becoming more severe.

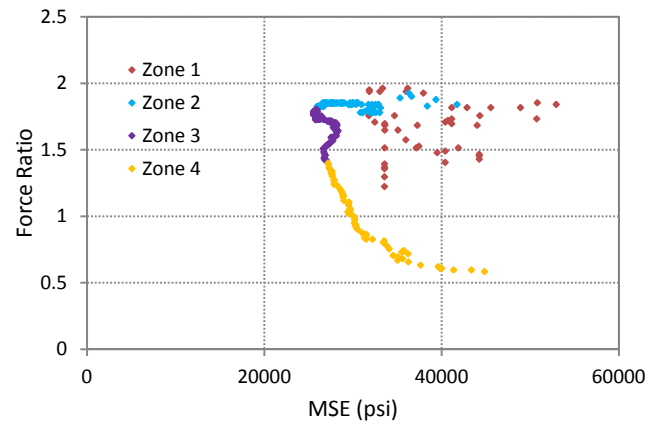


Fig. 28. Trend of Force Ratio vs. MSE in different zones (Test A)

ROP/WOB vs. MSE

Figure 29 is similar to previous plot except in zone 2. In this zone ROP/WOB increase with a decrease in MSE. Given that the trend is for this increase to also occur versus time, the reversal of data along this trend, as seen in zone 3, may give a warning to the operator of the onset of significant balling. Therefore, a mitigating action is taken before it develops more and leads to zone 4.

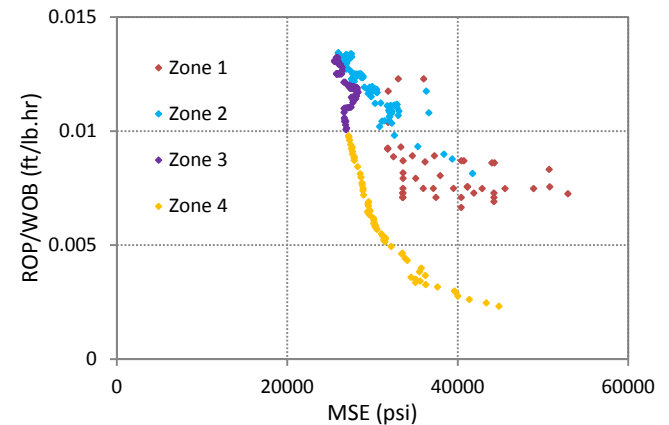


Fig. 29. Trend of ROP/WOB vs. MSE in different zones (Test A)

Conclusions

- A simultaneous increase in force ratio and MSE is likely due to the development of cutter balling as observed in single cutter cantilever tests. It is expected that given the same rock, cutter, wellbore fluid, and drilling conditions in a test with an interference plate, that cutter balls would also form. Consequently, the global balling observed in single cutter tests with water using an interference plate was probably preceded by cutter balling. However, the symptoms of cutter balling were not observed, possibly due to rapid nature of the accumulation of cuttings under the interference plate.
- The same increase in force ratio (μ) and MSE was observed in the early stage (zone 1) of the full-scale drilling tests that later experienced global balling. Therefore, it is likely that cutter balling provides a

mechanism for the accumulation of cuttings that can lead to global balling.

- Evidence of cuttings accumulation ahead of the cutter were also observed in single cutter tests conducted with the interference plate at low depths of cut in mineral oil although tests with the cantilever holder and mineral oil did not experience cutting balling except for one case with a very small accumulation. The full implications of this difference are not clear. Specifically, it is unknown whether the accumulations on the tests with the interference plate originated as a growing accumulation on the face of the cutter or as cuttings being partially trapped by the interference plate.
- Global balling was observed in oil-base fluids in both a full-scale test and in a single cutter test at a high depth of cut with an interference plate. Nevertheless, it did not occur at low depths of cut in mineral oil with the interference plate. Factors such as rate of cutting accumulation and size of cuttings were hypothesized to cause this difference whereas the difference from balling in water was concluded to be a result of the oil suppressing cohesion between the cuttings.
- Four distinctive zones of force trends were identified in typical full-scale tests that experienced global balling. The different symptoms in these zones potentially represent different balling behaviors. A diagnostic technique based on these symptoms may provide a means to identify the types and severity of balling in the field.

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