

## Single PDC Cutter Studies of Fluid Heat Transfer and Cutter Thermal Mortality in Drilling Fluid

Michael A. Freeman, M-I SWACO, a Schlumberger Company; Yuelin Shen and Youhe Zhang, SmithBits, a Schlumberger Company.

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### Abstract

Many PDC cutters ‘die’ of overheating. In our experience, cutter testing in water does not duplicate field failure patterns and has difficulty distinguishing differences in performance. Using drilling fluids, cutter wear patterns and mortality are more representative. We believe this is because heat transfer is more like that seen downhole. This new method provides a more efficient cutter screening process and challenges current models for heat loss while drilling.

### Introduction

PDC cutters are made by sintering diamond particles onto a tungsten carbide surface under high temperature and pressure. Typically, metallic cobalt is used to catalyze diamond crystal re-arrangements, and to fuse with the sintered tungsten carbide (WC) body below. The most common cutter is cylindrical, with a thin diamond wafer at one end. In use, cutters are set into a drill bit body, arranged with a slight back rake angle to the work. The bit is rotated and large force is applied which causes a narrow arc of the wafer to dig into formation, cutting a rounded groove. .

If the rock fractures, its effective volume expands by the volume of fractures induced. Trapped by the back rake angle and pressure difference between the hydraulic pressure of the drilling fluid and the vacuum within the fractures, the broken rock is forced up and over the diamond face of the cutter. If not invaded and dispersed by fluid, the crushed rock moves as a train of solids onto the body of the bit and into the junk slots.

Diamond cutters are used in this application because diamond has the highest abrasion resistance known. However, the scraping of the cutter against the formation creates friction that rapidly heats the diamond wafer. Because metallic cobalt has about 5 times higher thermal expansivity than diamond at 600 K,<sup>1</sup> it will create mechanical stresses within the matrix that result in fracturing of the wafer. Once broken, the flattened arc section exposes much greater area in contact with and sliding over the rock, resulting in even more heat, higher temperatures, and catastrophic failure of the diamond wafer.

Removing the cobalt by acid leaching provides some relief,<sup>2</sup> and about 80% of PDC cutters are leached to improve performance. Still, temperature is a common cause of cutter failure and, accounting for heat transfer is therefore essential

in the search for new cutter technologies.

### Thermal Mortality of PDC Cutters

One method of testing cutter efficiency is by cutting a large cylinder of granite with a single cutter using a Vertical Turret Lathe (VTL). A 3-ft diameter granite cylinder is rotated about its axis and the cutter is scrolled from the outer radius to an inner radius, rather like a vinyl record player (Figure 1). The cutter is fixed in a holder with a set back rake angle. The depth of cut is controlled by applying force on the cutter perpendicular to the granite surface. Each transit is measured as a single run. Vertical and normal loads are measured, along with cutter temperature.

At the end of the run, the cutter is washed, and another transit made. Periodically, the cutter is removed and a photograph taken of the cutting edge. As wear flats develop, cutter temperatures increase as does the normal load. Cutters fail as temperatures reach 400°C,<sup>3</sup> so a cooling jet is directed onto the face of the cutter (Figure 1). Early work<sup>4</sup> showed water is far more effective than air for cooling. When the normal load increases above a target level, testing is ended and the cutter removed, photographed and characterized for wear.



Fig. 1 – VTL cutting granite with single PDC cutter and drilling fluid coolant.

Typical results are shown in Figure 2. Using water, cutter-type #A in Run #1 cuts a complete disc from the top of the cylinder from Data Point 50 to Data Point 127. Normal force for the new cutter is 50 lb-force (lb<sub>f</sub>). The second pass made from Data Point 130 to 190 shows an increase in normal force as the cutter chips and develops wear flats. With each additional run, the normal force increases in a regular fashion through the 15 runs shown.

The increase in normal force is due to deterioration of the cutting edge. The wear pattern on the edge of the cutter (Figure 3) becomes visible after 5 runs as two separate pits. These continue to grow with each run. After 60 runs in water, they have overlapped but retain separate concavities. This bimodal wear pattern is not seen in cutters returned from the field.

When the same style cutter is run in a xanthan-based, clear, freshwater drilling fluid, the initial normal force is about 25% higher than when run with water (Figure 2). With each successive run, the normal force remains higher for the drilling fluid until Run 13 where there is a dramatic increase.

When the wear flats for these runs are examined in Figure 3, by Run 5 there more pronounced and uniform wear flats for xanthan drilling fluid than seen with water. By Run 15, the wear flat is well developed and extends more than half way through the diamond wafer. After twenty runs the flat is well into the WC stub, ending the test sequence.

The primary cause for the increased wear when using drilling fluid is heat retention and concomitant increase in temperature. Shown in Figure 4, the cutter temperature recorded for the first run in drilling fluid is 50°C higher than in water. After only 5 passes, this difference is 150°C, and continues to climb dramatically as expected from the increasing wear flat area.

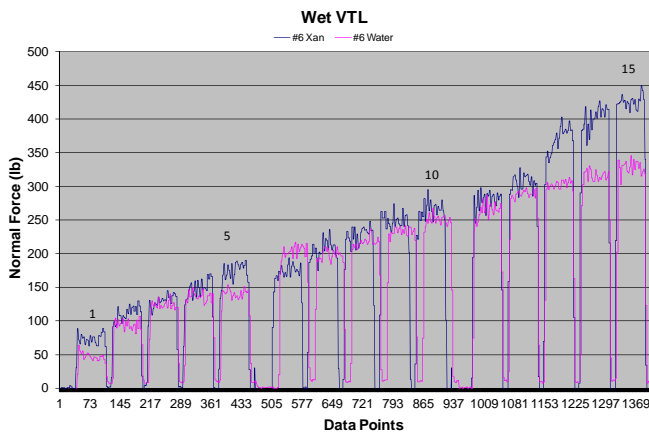


Fig. 2 – Normal force for single type #A PDC cutters using water (pink line) and xanthan-based drilling fluid (blue line).

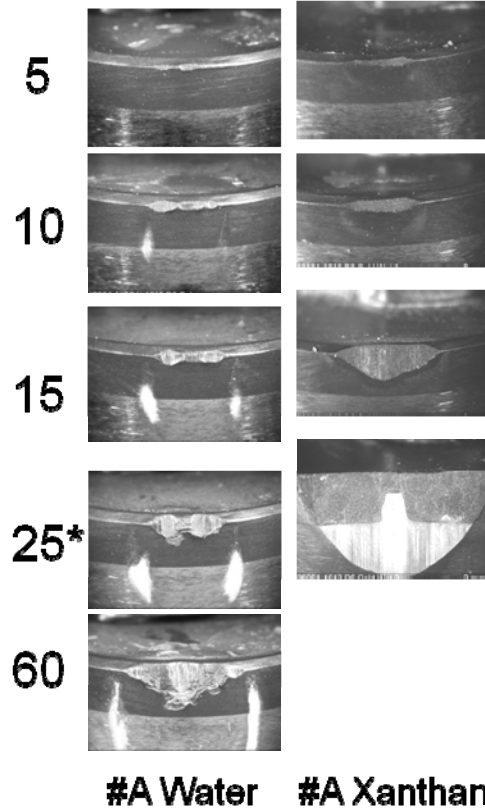


Fig. 3 – Wear patterns of type #A PDC cutters used with water and xanthan drilling fluid coolant.

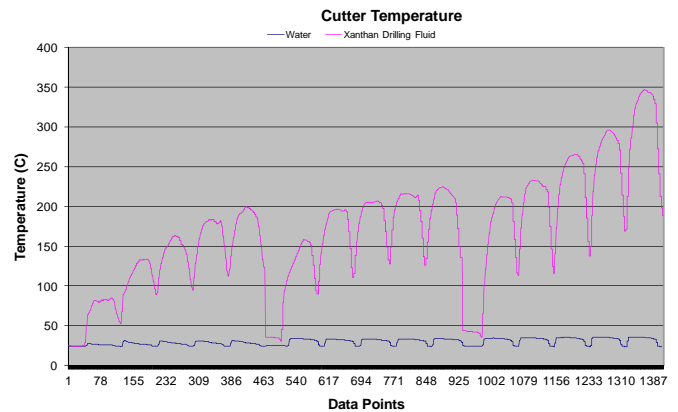


Fig. 4 – Single cutter temperatures corresponding to Fig. 2. Note that in this figure, the blue lines are water and the pink lines are xanthan-based drilling fluid.

## Heat Transfer and Temperature

Glowka's seminal study of bit hydraulics<sup>5</sup> and thermal loading<sup>6</sup> elaborated the fundamental relations between frictional heat generation and its dissipation into the circulating drilling fluid. However, the need to visualize fluid patterns and other experimental requirements limited the initial studies to water. A partial analysis of heat transfer suggested the non-Newtonian properties of fluids could be ignored. Using the thermal conductivities established in water, further numerical studies were done,<sup>7</sup> predicting that as rock cuttings cover the diamond surface, heat transfer is compromised by up to 13%. However, there were no experimental measurements to verify this prediction.

A later study<sup>8</sup> set out a more complete theoretical analysis of the sources of heat and its dissipation into the circulating fluid. The presence of a chip in front of the cutter face was explicitly included in the analysis. However a critical assumption was that the chip was not held against the cutter surface, and so was free to move, allowing drilling fluid to circulate between it and the diamond surface.

However, cuttings must always be held against the cutting edge if there is any fluid atmosphere. That is, chip hold-down applies to the cuttings on the cutter. As the rock breaks and moves, any fractures created are initially empty. If porous, formation fluid vapor will fill the fracture, if non-porous, vapor from the drilling fluid will fill them. But until these fractures are invaded by fluid in hydraulic communication with the surrounding fluid, the differential pressure must force the cutting against the cutter. When the rock is plastic and does not form visible fractures, this same plasticity seals the edges of the cutting against the cutter face, preventing fluid ingress to the cutter/cutting interface.

For example, consider the flow of crushed carbonate fragments over the cutter as shown in Figure 5. Here, three PDC cutters were mounted in a core barrel and used to cut a 7-in. core from Carthage marble with water circulation. This cutter was canted slightly to the inside of the barrel to cut the OD of the core and provide a small space between core and barrel for fluid flow. Thus, only a portion of the cutter arc actually cut rock.



Fig. 5 – Three-cutter core barrel used to cut core in Carthage marble.

With only a differential pressure of ~7 inches of water (0.3 psi, 2 kPa), the broken rock chips clearly flow across the cutter face and on to the body of the coring tool until they are finally dispersed. On a smaller scale, this observation reproduces<sup>9</sup> work done at high pressure, showing that cuttings trail from the cutter and to avoid balling, bits must be designed in a way to avoid convergence of these trails. Similarly, a recent correlation of ROP with drilling fluid parameters found differential pressure to be the most significant.<sup>10</sup>

Under the conditions of the VTL measurements, the impact of a water jet on the cutter serves to cool the diamond face (Figure 6). Because of the back rake angle, the jet is forced down the face of the cutter and onto the work surface, where it separates into two streams that flow around the cutter. Clear water is able to penetrate and disperse the cuttings. While nominal in laminar flow, there is a chaotic 'dead zone' near the center of the cutter where the downward stream splits in two. This bifurcation may be the source of the two pits.

When viscosified (as with the xanthan-based drilling fluid), the fluid from the cooling jet flows in a much more laminar fashion. The static layer upon the cutter surface is correspondingly thicker and the ability of the fluid to penetrate and disperse the cuttings is markedly reduced. This results in a significant buildup of insulating solids across the face of the cutter. At the high temperatures seen at the end of the cutter test life, the heat evaporates water from the fluid, leaving a crust as a solid barrier (Figure 7).

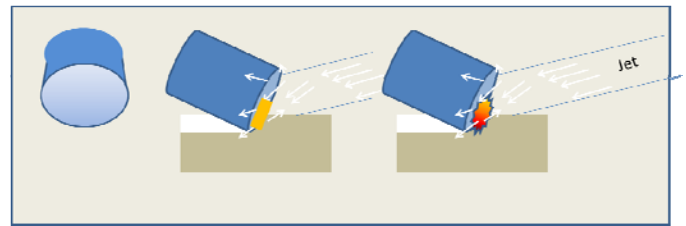


Fig. 6 – Drawing illustrating the interaction of a single cutter, cutting model with solid chip and cutting model with crushed rock.



Fig. 7 – Severely worn cutter with shroud of dried cuttings.

**Fluid Rheology and Heat Transfer**

The effect of fluid viscosity was probed by comparing drilling fluid prepared with hydroxyethyl cellulose (HEC) with the xanthan viscosified fluid. Xanthan produces a shear-thinning, non-Newtonian fluid with high viscosity at low shear rates. With the same viscosity at high shear rate, HEC produces much lower viscosity at low shear rate. Product loadings of xanthan and HEC were adjusted to yield a 40 Dial Reading at 600 rpm on Fann 35 viscometer (Figure 8). This produces about the same effective viscosity of 20 cP at the jet velocity at impact point on the cutter.

As shown in Figure 9, for each of five different cutter types, the HEC fluid consistently provided longer cutter life than xanthan fluid. We believe this occurred because as the coolant jets slows and flows across and around the cutter, the higher effective viscosity of the xanthan fluid results in thicker, static fluid layers and in slower penetration and dispersal of the cuttings. As a result, more heat is held in the cutter, shortening its life. The dramatic differences in cutter life seen for the 3 cutter types studied is what makes the use of drilling fluid so useful. As shown in Figure 10, when tested in water these 5 types show very similar lifetimes. Indeed, the average of several runs must often be made to discriminate between them. In the field, the acid-leached cutter type #ADL shows much better drilling performance at high temperatures than the others do. Cutter type #125 is less effective and the unleached type #A shows the poorest resistance. When tested in drilling fluid, the relative performance of the cutters is now much easier to determine. Indeed this technique identified

superior cutters that have recently been commercialized. PDC bits dressed with these cutters are achieving step-change performance worldwide.

Further, with this new insight, several bits were redesigned for more cooling of cutters with high work rate. Traditionally, fluid paths emphasize cuttings cleaning and bit ball reduction. Cooling has previously been a secondary concern, undifferentiated by cutter. Preliminary results show these redesigned bits drill faster than offsets due to slower development of wear flats. More bits are being revamped to confirm the concept in the field.

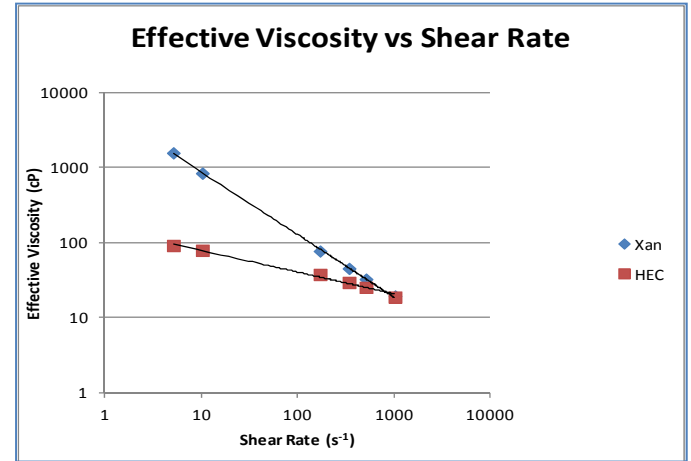


Figure 8. Viscosity of drilling fluids vs shear rate for drilling fluids

**Wearflat Area vs VTL Passes to Failure for VTL Cutters Test with Xan and HEC Fluids**

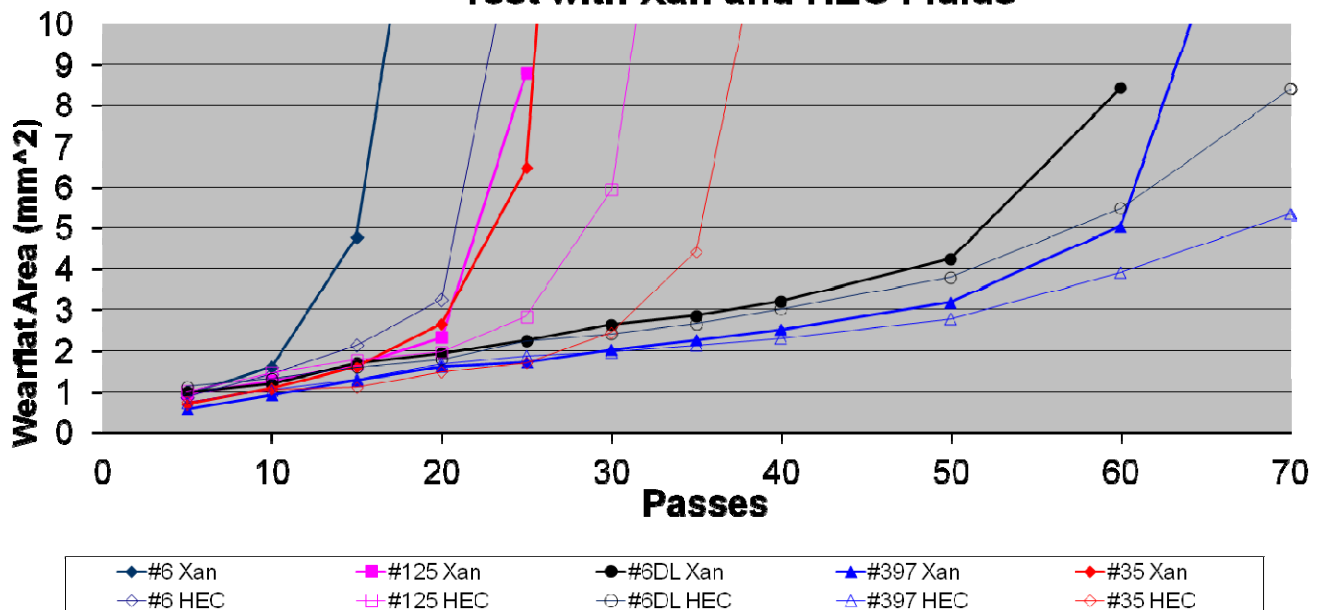


Figure 9. Comparison of wearflat area with xanthan and HEC drilling fluids.

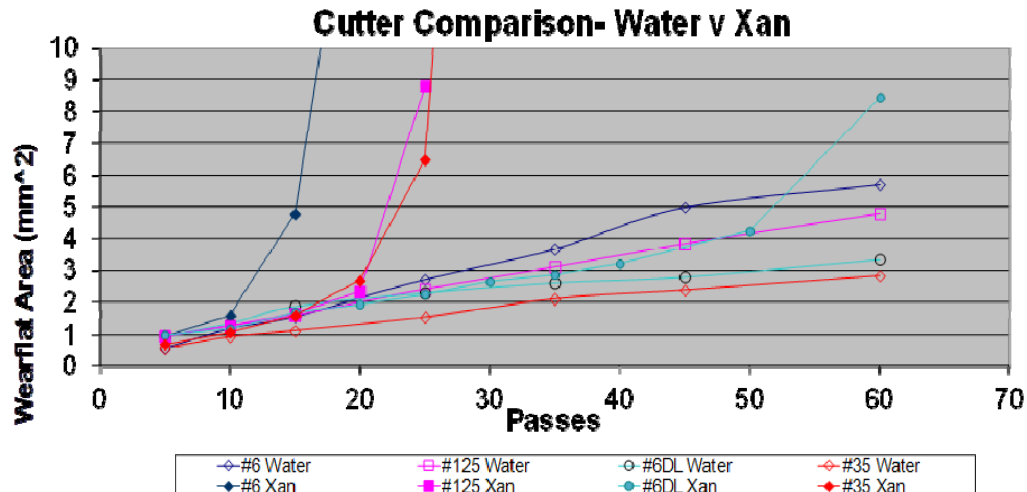


Figure 10. Comparison of cutter performance for 5 cutter types using drilling fluid and water as coolants.

## Conclusions

1. Xanthan-based drilling fluid provides a thermal environment for cutter testing that more closely resembles the environment cutters see in the field.
2. The buildup of thicker static fluid layers and cuttings on the face and around the body of the cutter reduce heat transfer.
3. Published models for heat transfer may not give enough weight to the thermal blanketing effects of cuttings.
4. Increasing the flow of drilling fluid to the hottest cutters can increase bit life.
5. Increasing drilling fluid spurt loss and reducing viscosity can extend cutter life and improve ROP.

## Acknowledgments

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