

Effects of Thermal and Mechanical Loading on PDC Bit Life

D.A. Glowka, SPE, Sandia Natl. Laboratories
C.M. Stone, Sandia Natl. Laboratories

Summary. Results of numerical analyses to determine the effects of thermal and mechanical loading on the integrity of polycrystalline-diamond-compact (PDC) cutters during deep-hole drilling are presented. Cutter-temperature distributions for several drilling environments are combined with the appropriate mechanical cutting loads to predict stress distributions for the study of cutter wear mechanisms. A discussion of wear mechanisms acting on the cutting structure is presented. Suggestions based on these analyses are presented for the operation of PDC bits to increase bit life in hard, abrasive rock drilling. Microstructural design considerations for the cemented carbide that supports the diamond layer are also discussed.

Introduction

In deep drilling for geothermal and fossil fuel resources, rate of penetration (ROP) and bit life are important factors in the determination of well cost. The use of PDC bits in oil and gas drilling can result in substantial well-cost reduction in certain formations. Drilling cost savings of more than \$100,000 have been reported for single PDC bit runs,¹ and total drilling cost savings of 30 to 50% are common in some areas. Generally, such savings result from greatly improved bit life (two- to ten-fold) and smaller improvements (zero to two-fold) in ROP.¹⁻³

In more severe applications, such as geothermal drilling and hard-rock drilling for oil and gas, a reduction in bit life and ROP is experienced. Because of their aggressive nature, however, PDC bits can generally drill as fast as or faster than roller bits in any environment.⁴ Bit life then becomes the primary factor in the determination of the economics of a given bit run, in the absence of other drilling problems. The impacts of ROP and bit life on typical geothermal-well costs have been determined with a well-cost simulator.^{5,6} Results show that if ROP and bit life can be doubled by the use of PDC bits, the total well cost should be reduced by 10 to 15%. If bit life is reduced by 50% as a result of PDC bits, however, savings resulting from improved ROP are cut in half. In particularly severe environments, PDC bits can increase drilling costs because of poor life. Thus, there is an incentive to improve bit life for any potential application of PDC bits to take advantage of the inherently higher ROP's.

Although bit life and ROP are both variables in the determination of drilling costs, the two are actually interrelated. Limited experimental data with hard, abrasive sandstone show that PDC-cutter wear rates increase one to two orders of magnitude when cutter-wearflat temperatures exceed a critical value of about 350°C [660°F].⁷ Yet wearflat temperatures in a given environment are controlled by weight on bit (WOB) and rotary speed. Because these two variables are also the primary controllable factors influencing ROP, the trade-off between ROP and bit life is evident.

This paper examines the effects of controllable drilling variables on PDC bit life. It is an extension of earlier work^{7,8} and is aimed at identifying conditions that lead to rapid cutter wear and uneconomic bit life.

General Wear Considerations

It has been shown that in the absence of thermal effects, the volumetric wear, V_w , of a metal specimen sliding on an abrasive surface is proportional to the load, F , on the specimen and the sliding distance, L_s .⁹

$$V_w \propto FL_s \quad \dots \dots \dots (1)$$

Thus in the absence of thermal effects,

$$\frac{1}{F} \frac{dV_w}{dL_s} = c \quad \dots \dots \dots (2)$$

PDC-cutter-wear data presented in our earlier work⁷ are replotted in Fig. 1 in the form $(1/F)(dV_w/dL_s)$ vs. \bar{T}_w , where V_w is the measured wear volume while cutting hard, abrasive sandstone^{10,11} and \bar{T}_w is the mean temperature across the cutter wearflat.

If thermal effects are not important, Eq. 2 indicates that the data in Fig. 1 should be relatively constant with temperature. Although there is considerable scatter, the data seem to follow a different trend. This trend is consistent with the finding¹² that adhesive wear of cemented carbides in machining steel decreases with sliding speed until a wearflat temperature of 450°C [840°F] is reached, after which wear increases. The decrease is attributed to thermal healing of defects in the microstructure and the increase to general thermal softening at higher temperatures. Although abrasive-wear mechanisms for PDC cutters in rock drilling are different from those for adhesive wear, these general thermal effects are evidently similar, at least qualitatively.

It is well established that abrasive wear of metals is a strong function of the relative hardness between the abra-

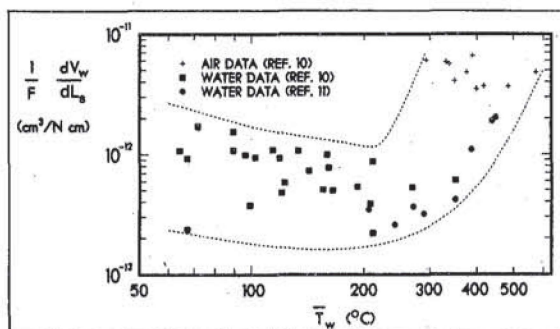


Fig. 1—Experimental cutter wear rate per unit weight on cutter while cutting hard, abrasive sandstone, plotted against computed wearflat temperature for the same conditions.

sive, H_a , and the metal, H_m .¹³ For soft abrasives ($H_a/H_m < 1.2$), the wear rate is relatively low and does not depend greatly on the actual ratio of the hardnesses. As H_a/H_m exceeds 1.2, wear rate increases significantly and becomes very sensitive to the hardness ratio. This effect has been confirmed for several grades of cemented carbides with a variety of abrasives.¹⁴

Quartz and other forms of silica constitute about 20 to 40% of many rock formations and cause most of the abrasive wear of hard metal inserts on mining tools.¹⁵ The room-temperature hardness of quartz lies in the range of 9.8 to 11.3 GPa [1.4×10^6 to 1.6×10^6 psi],¹⁴ while the bulk room-temperature hardness of tungsten carbide/cobalt (WC/Co) mining grades falls in the range of 10 to 15 GPa [1.5×10^6 to 2.2×10^6 psi].¹⁶ Thus quartz would be considered a soft abrasive relative to WC/Co, yet it is known that under certain conditions, wear of mining tools occurs rapidly in a manner consistent with that produced by hard abrasives. This behavior further suggests that thermal effects are important.¹⁶ With increasing temperature, the hardness of WC/Co drops more rapidly than that of quartz, thereby increasing the ratio H_a/H_m . Furthermore, quartz particles may not attain the same temperature as the cutter wearflat because of the limited period of time that individual particles are subjected to frictional heating. On this basis, Perrott¹⁶ concluded that at cutter temperatures below 350 to 400°C [660 to 750°F], WC/Co composites cutting rock experience wear of the type produced by soft abrasives, while at higher temperatures, wear is accelerated and occurs by mechanisms associated with hard abrasives. Our results shown in Fig. 1 for PDC cutters agree with this conclusion.

The Downhole Wear Environment

In addition to its abrasive nature, other factors make drag cutting a severe application for engineering materials. High loads required to cut hard rock impose large mechanical stresses on cutter structures. These high loads also cause significant frictional heating at the cutter/rock interface, leading to elevated cutter temperatures.^{7,8} Furthermore, single-point cutter-test measurements at a fixed depth of cut* show that cutter forces are cyclic because of the discontinuous rock-chipping process. As shown in

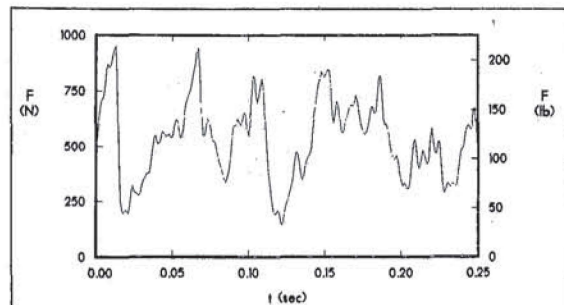


Fig. 2—Transient weight on cutter for a sharp PDC cutter machining Westerly granite; depth of cut = 0.064 cm (0.025 in.)

Fig. 2,* vertical cutter forces fluctuate rapidly under constant cutting conditions. For the conditions used, large-scale fluctuations occur at a frequency of about 10 Hz, with smaller variations occurring at higher frequencies. Horizontal cutting forces behave in a similar manner. After 10 hours of drilling, a PDC cutter under such conditions would accumulate 3.6×10^5 cycles of loading, becoming susceptible to bulk fatigue.

In mining applications where cutters can be changed without significantly interrupting operations, drag cutters are generally constructed of WC/Co cutting tips mounted on WC/Co or steel posts.^{15,17} Wear gradually causes rounding of the tool cutting edge,^{15,18} thereby reducing the stress concentration on the rock surface and degrading performance. In deep drilling, tripping the drillstring to change bits is an expensive operation, so drag bits were used in a limited number of such applications before the invention of PDC bits.¹⁸

PDC's are approximately five times harder than typical WC/Co composites¹⁹ and, therefore, have higher resistance to abrasive wear. A PDC cutting edge stays sharp and continues to cause significant stress concentration at the rock surface, even after considerable wear. PDC's are, however, more brittle than WC/Co and alone cannot withstand the tensile and shear stresses generated at the cutting edge, especially under impact loading. Thus PDC cutters are constructed by sintering polycrystalline diamonds on a base wafer of WC/Co, which provides support to the diamond structure (see Fig. 3).²⁰ The resulting compact either (1) is brazed or diffusion-bonded to a WC/Co or steel support post (stud), which is then pressed into the bit body, or (2) is bonded directly to the bit body (matrix mounted).

The wear of a PDC cutter depends on a symbiotic relationship between its two constituents. The polycrystalline diamond layer, being the leading edge of the cutter, machines larger abrasives off the rock surface, thereby protecting the WC/Co base. The base supports the diamond layer, absorbing shock and preventing gross failure of the diamond layer. Accelerated wear of the WC/Co base reduces support for the diamond cutting edge, leading to increased diamond wear.

The geometry that a PDC cutter assumes as a result of wear seems to depend on the type of rock being cut. In soft, ductile rocks, where cutting forces, particularly impact loads, are relatively small, the relative abrasive-wear resistances of PDC and WC/Co are very important. Be-

*Private communication, J.T. Finger, Sandia Natl. Laboratories, Albuquerque, NM, June 1984.

cause WC/Co inherently wears at a higher rate, a wear angle between the WC/Co and the rock surface develops because of the action of abrasive rock particles sliding beneath the cutter. Examination of field-worn cutters reveals this angle to be generally about 5 to 10°. The effect is to maintain only the diamond face in intimate contact with the rock and, thus, to maintain a relatively small effective wearflat area.

In harder, more brittle rocks, such as Sierra White granite, we have observed that the wearflat on even the WC/Co tends to develop nearly parallel with the rock surface. We conjectured that the higher mean and instantaneous cutting forces required to cut this type of rock effectively remove any unsupported diamond protruding beyond the WC/Co backing. Furthermore, a substantial WC/Co backing is required to support the diamond near the rock interface when the impact loading is higher. Under these conditions, the relative wear of the two materials reaches equilibrium at a smaller wear angle. The result is an effectively larger cutter area in contact with the rock.

Before the wear mechanisms for PDC-cutter materials are examined in more detail, their microstructures should be reviewed. WC/Co composites are made by combining WC and Co powders and sintering at high temperature. The resulting composite consists of a skeleton of WC grains interspersed with thin films of Co.¹² Mining grades contain from 5 to 15 wt% Co. WC grains give the composite strength, while Co gives it ductility; thus these properties depend on the Co content, the size of the WC (1 to 5 μm) and Co (0.1 to 8 μm) grains, and their distributions within the composite.²¹

PDC's are made by sintering synthetic diamond crystals (100 μm) at high temperature/high pressure (HTHP) in the presence of a catalytic binder (primarily Co) that fosters strong diamond bonding.^{20,22} Individual crystals fracture by cleavage along preferred planes; thus the random orientation of crystals in the composite increases strength and ductility on a macroscopic scale. The residual binder after sintering plays a minimal role in the mechanical behavior of the diamond composite,²² except at very high temperatures, as discussed below.

PDC-Cutter Wear Mechanisms

We define "wear" as microscopic or macroscopic removal or fracture of material at the cutter surface—in general, any degradation that reduces bit life. Although both PDC and WC/Co are considered hard, brittle materials, their wear mechanisms in rock drilling are quite different.

Cemented Carbides. The important mechanisms for WC/Co composites may be classified according to the scale of damage they cause.

1. Macroscopic failure includes structural overload and fatigue, impact shock and fatigue, and thermal shock and fatigue.

2. Microscopic failure includes abrasive wear (both abrasion and impact shock and fatigue) and thermal fatigue.

It is likely in any given situation that all or several of these mechanisms occur simultaneously to a certain degree. All depend on the initiation and propagation of fractures to induce failure because WC/Co is extremely brittle.¹⁵

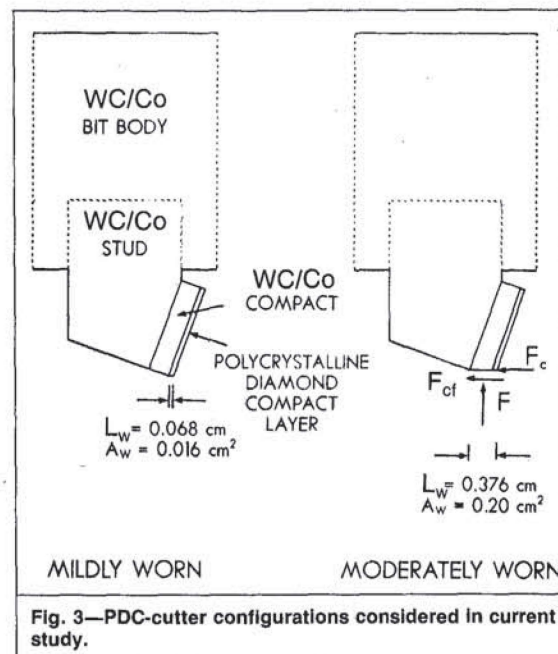


Fig. 3—PDC-cutter configurations considered in current study.

Macroscopic Failure. Structural overload and fatigue refer to macroscopic failure or degradation of the cutting structure caused by stresses induced in the bulk material. In static stress tests of WC/Co specimens, it has been found that apparent strength drops as the size of the specimen increases.²¹ This is attributed to the increased probability of encountering and activating fracture-initiation sites as the volume of material subjected to a given stress level increases. Voids or flaws in the material serve as fracture-initiation sites because of stress concentrations that occur there. In WC/Co composites, such voids can result from inherent porosity resulting from incomplete densification during the sintering process,²³ or they can form during service as a result of the stress history of the tool.²⁴ Because porosity can be virtually eliminated by proper sintering techniques,²³ we restrict further discussion to voids that develop during service.

In the presence of shear stresses, such as those caused by friction at the wearflat, microscopic voids can nucleate at WC grain boundaries because of separation of the WC grains from the Co binder and other WC grains.^{24,25} High compressive stresses can be induced in the cutter by mechanical loads caused by interaction with the rock and thermal loads caused by differential thermal expansion in the presence of steep thermal gradients near the wearflat.⁷ Under high compressive stresses, and especially at elevated temperatures, plastic deformation of WC and Co grains occurs by slip,^{26,27} which is the lateral displacement of one plane of atoms relative to an adjacent plane. Microvoids and cracks are created during the slip process. Inelastic deformation can also occur in WC/Co by creep at stresses well below the yield strength of the composite.²⁸

Upon unloading, compressive plastic deformation leads to the development of residual tensile stresses,²⁹ which cause initiation of fractures at voids, inclusions, and coarse WC grains.²⁷ Tests have shown that a small amount of precompression (0.02%) leads to increased crack lengths

in response to indentation.³⁰ Since creep increases²⁸ and compressive yield strength decreases²¹ with temperature, one should expect initiation of fractures to increase at elevated temperatures.

Once initiated, unstable fractures, which propagate in response to a static or single-impact load, tend to follow rather straight lines through the material in an intragranular fashion.²⁷ Stable fractures, which propagate during cyclic loading, tend to follow grain boundaries in an intergranular manner. Fracture toughness, which is a measure of fracture-propagation tendencies, is substantially reduced at elevated temperatures.³¹

The effects of cyclic loading on the strength of cemented carbides have also been studied. Tests³² with WC/nickel composites have shown that fatigue accrues in the binder phase after 10^6 cycles of compressive loading, even at relatively low load amplitudes. The density of dislocations (crystal imperfections) in the binder was found to increase one to two orders of magnitude because of fatigue, and it was concluded that fatigue constitutes a source of incipient defects and a means of stable flaw propagation.

A significant reduction in strength was found for various WC/Co grades subjected to cyclic loading in compression.³³ Compressive stresses required for failure were reduced from the static levels by 25% after 10^5 cycles and nearly 40% after 10^8 cycles. Because of the reduction in fracture toughness with temperature,³¹ WC/Co composites may exhibit a larger reduction in strength during cyclic loading at elevated temperatures.

The above discussion pertains to cyclic loading in which contact with the loading surface is made slowly or maintained at all times. In highly fractured formations, or if bit bounce occurs, PDC cutters can be subjected to impact shock and fatigue, which can be far more destructive. Under these conditions, compressive shock waves in the cutter are generated at the impact surface.³⁴ These waves travel through the cutter and reflect from free surfaces as tensile waves, which have more destructive power and cause secondary cracks to develop. Cracks propagate according to the fracture toughness of the material and the impact energy involved. High-velocity impacts cause fractures to branch readily, leading to increased damage. Single low-velocity impacts may not have sufficient energy to propagate fractures to the failure point. In this case, cyclic impact can cause failure by stable crack propagation.

The WC/Co portions of PDC cutters are also susceptible to macroscopic damage by thermal shock and fatigue,³⁵ both of which leave a cracked and crazed surface and are commonly called heat-checking or heat-cracking. Failure in both cases is caused by thermal stresses that develop as a result of steep thermal gradients near the cutter wearflat.³⁶ Thermal shock in the present context refers to the stress state developed when a hot cutter wearflat is suddenly quenched with cooling fluid, as happens, for instance, whenever a PDC bit is suddenly lifted off bottom to add a length of drillpipe. Because rapid temperature reduction proceeds from the cutter surface into the bulk material, differential thermal expansion early in the cooling period results in the development of tensile stresses at the surface. The magnitude of these stresses depends on the temperature of the cutter before quenching, the fluid temperature, the cooling rate, thermal and

mechanical properties of the cutter material, and the previous stress history of the cutter.

Tests to determine the critical prequench temperature at which cracking of the surface occurs have been reported for a variety of grades of WC/6%Co.³⁷ The results indicate that the critical temperature lies between 520 and 700°C [970 and 1,290°F] for thin (2.3-mm [0.09-in.]) specimens, depending on the material grade. Thicker specimens crack when quenched from lower temperatures. Cracks induced by thermal shock tend to propagate in an unstable, brittle fashion.^{38,39}

Thermal fatigue has also been found to be an important macroscopic wear mechanism for WC/Co composites in metal-cutting^{36,38,40} and rock-cutting¹⁵ operations. As seen in Fig. 2, forces acting on a PDC cutter undergo large fluctuations with time, even under nominally constant cutting conditions. Our earlier work⁷ showed that mean wearflat temperatures respond quickly and almost proportionally to changes in cutter weight. Therefore, we should expect even larger fluctuations in local temperatures as various regions of the wearflat respond to changes in local contact pressure caused by the uneven rock surface. Variation of temperature in time and space parallel and perpendicular to the wearflat leads to rapidly fluctuating thermal gradients and, hence, conditions conducive to thermal fatigue if temperature levels are high enough.

Thermal fatigue of WC/Co composites is most noticeable in nonabrasive rocks because reduced abrasive wear preserves more visual evidence of thermal cracks.²³ These cracks penetrate deeply into the bulk of the material, run in an intergranular fashion, and branch readily.¹⁵ Fractures intersect, removing large flakes of material and forming relatively steep, angular craters. The surfaces of these craters contain many incipient cracks that are also free to propagate. Once this process has started, the cutter rapidly becomes useless for rock cutting.

A final macroscopic failure mechanism that seems to be a common problem⁴¹ is debonding of the PDC/WC/Co compact from the WC/Co stud. Brazing and diffusion-bonding techniques have been developed that produce adequate bond strengths to at least 350°C [660°F].⁴² Bond failures at low temperatures are usually caused by bond defects. Such failures downhole can be prevented by rigorous testing of bond strength before bit use. No data exist at higher temperatures, but it is conceivable that thermal softening of the bond and increased failure could occur above 350°C [660°F].

Microscopic Failure. Abrasive wear is defined as the displacement of material from a solid surface by hard particles or hard protuberances sliding along the surface. It occurs by microscopic mechanisms involving surface layers, but eventually becomes evident on a macroscopic scale. With WC/Co composites, abrasive wear in rock cutting occurs in a two-stage process: (1) abrasion, where hard rock particles remove cutter material directly with a plowing action, leaving incipient cracks behind; and (2) impact shock, impact fatigue, and (under certain conditions) thermal fatigue, which propagate incipient cracks and form wear particles.

The interaction between abrasive particles and the surface of WC/Co composites depends on the relative hardness and size of the particles and the separate phases of the composite. Abrasive particles that are softer than the WC grains but harder than the Co grains (such as quartz

at room temperature²⁰) tend to preferentially remove the Co binder from the surface layers. Small particles in this category remove Co through a plowing action involving plastic deformation of the Co grains.³⁹ Larger particles that are softer than WC tend to bridge between adjacent WC grains; in this case, Co is preferentially removed by extrusion as WC grains are rocked back and forth by friction with the sliding particles.⁴³ The plastic strain experienced by Co grains during either of these processes causes the formation of voids and cracks in the surface layers,^{24,29,39} as explained above for the bulk material.

Once initiated, surface fractures propagate because of impact shock or impact fatigue. Because most observed fractures tend to travel along WC-grain boundaries and through the Co grains, it has been concluded³⁹ that fracture propagation is usually stable and occurs because of cyclic loading (impact fatigue) rather than impact shock.

The significant role of binder removal in the wear of WC/Co by soft abrasives is illustrated by tests in which specimens were chemically etched to remove Co and then abraded on sandstone.³⁹ Although Co was removed to a depth below the surface of only 0.2 μm (about 5% of the WC-grain diameter), the wear rate was found to be an order of magnitude greater than that of similar unetched specimens. Thus, Co removal is found to be the controlling factor in initiating surface cracking and abrasive wear of WC/Co by soft abrasives. Because Co softens with temperature and, thus, is more easily deformed and removed, wear should accelerate at elevated temperatures.

Abrasives that are harder than WC tend to fracture the WC skeleton and/or individual WC grains on impact. Micromachining of WC grains and surrounding Co grains occurs with small abrasives in this hardness range.³⁹ Larger hard abrasives cut craters or grooves in the surface that are much larger than individual WC grains.⁴³ A significant degree of plastic deformation of WC and Co phases occurs. The inherently brittle behavior of the composite is apparently suppressed by the large hydrostatic compressive forces that develop during grooving and the reduced yield stress at elevated temperatures.²⁶ Void formation and residual tensile stresses again lead to severe fragmentation of the WC grains on the remaining surface.⁴³ Then impact fatigue is able to remove additional material by spallation.

Tests show that preferential removal of Co also accelerates wear by hard abrasives.²⁶ Part of this results from relaxation of residual thermal stresses between the Co and WC phases. Upon cooling from the sintering temperature, the differential thermal contraction of the two phases is such that the Co phase is placed in tension, while the WC phase undergoes compression.^{26,39} The removal of Co from between WC grains allows partial relaxation of the residual compressive stress in the latter, making the development of tensile stresses in WC grains during abrasion more likely.⁴³ Removal of Co also places the remaining Co in even more tension, allowing intergranular crack propagation to occur more readily as well.

The change in wear mechanism from soft to hard abrasion is accompanied by a drastic increase in wear rate, as noted previously. The effects of cutter temperature on this transition illustrate the need to maintain temperatures below 350°C [660°F] to minimize wear.

It seems likely that fractures having their origins in abrasion may be propagated by thermal fatigue occurring on

a macroscopic scale. It is also known that the initiation of thermal stress cracks is sensitive to surface finish (which is severely degraded by abrasion).^{34,37} These observations, coupled with the probable interaction between microcracks initiated by abrasion and macrocracks caused by thermal fatigue, suggest that synergistic wear effects may occur when both mechanisms operate simultaneously. This agrees with the general experience that hard, abrasive rocks can rapidly destroy PDC cutters under certain operating conditions.⁴

One final aspect of abrasion is the finding that, in the presence of rock debris produced during drilling abrasion, WC/Co wear is an order of magnitude greater than that produced during abrasion on a clean rock surface.³⁹ This is caused by extremely small quartz particles (0.1 μm) that are produced during drilling; these are more efficient in removing Co than are large, fixed abrasives. Cutter life may be improved by directing water jets in front of the cutter, as discovered by Hood.⁴⁴ This may be partly because of improved removal of cutting fines as well as reduced cutter loads that result in lower wear/flat temperatures.

PDC's. PDC's wear differently from WC/Co composites because individual diamond grains are harder than all abrasives encountered in drilling, and the metallic binder in PDC's plays no active role in wear behavior, except at very high temperatures. The major wear mechanisms reported in the literature are macroscopic failure (impact shock and fatigue) and microscopic failure (impact shock and fatigue, and thermal shock).

Under high impact forces, or on development of tensile stresses, the PDC fails by gross fracture.²² In contrast with WC/Co behavior, the diamond grain-to-grain bonding is stronger than individual diamond grains. Except with defective bonds, fractures seldom follow grain boundaries but rather propagate directly through diamond grains in a transgranular manner. Fractures change directions locally to accommodate preferred cleavage planes of individual diamond grains but generally run in a straight line in an unstable propagation mode.

As in other brittle materials, fractures can be propagated more slowly at lower stresses during cyclic loading. Tests show that under cyclic (but not impact) loading of a PDC cutter, the force at the cutting edge required to cause cracking or macroscopic chipping is reduced to about one-third its static value after 10^5 cycles.¹⁹ This is attributed to the development of shear- and tensile-stress components and the growth of microcracks near the diamond surface.

On a microscopic level, wear against highly abrasive sandstone occurs by a process of impact shock and fatigue of individual diamond grains, with no apparent contribution caused by preferential removal of the binder phase.²² Two distinct failure modes of diamond grains are possible. On impact with abrasive rock particles, some diamond grains exhibit crushing, in which the edge of the grain is gradually removed in small pieces. Others exhibit cleavage fracture across the entire grain. This dual behavior is attributed to the development of deformation twin bands in some individual diamond grains during the HTHP sintering process. These randomly oriented bands, caused by plastic deformation through angular displacement of one plane of atoms relative to another, interfere

with the development of large-scale cleavage by redirecting advancing cracks.¹¹ Because of bridging effects between grains, some grains undergo little deformation during sintering and do not develop deformation bands. Thus, such grains are susceptible to the type of cleavage fracture prevalent in natural, single-crystal diamonds.

At increased operating temperatures (but still below 750°C [1,380°F]), the microchipping mode of wear increases in intensity.¹¹ This behavior is caused by a decrease in the hardness of individual diamond grains. Tests show that the Vickers hardness of sintered diamond drops almost linearly to a value at 700°C [1,290°F] of about 65% of its room-temperature value. There is evidence that this is a manifestation of reduced fracture toughness at elevated temperatures that may be caused in part by stresses that develop during differential thermal expansion between the diamond and binder material.

Tests with PDC's have failed to show a dependence of cyclic-loading failure on temperatures below 300°C [570°F].¹⁹ The possibility of such a dependence at higher temperatures, however, cannot be ruled out, especially in view of a possible reduction in fracture toughness.

At temperatures above 750°C [1,380°F], the differential thermal stresses in the microstructure cause failure of the diamond-to-diamond bonds, resulting in intergranular fracture. Wear under these conditions occurs by rapid extraction of whole diamond grains from the compact. Thus, PDC's have no practical life under conditions that lead to temperatures above 750°C [1,380°F].

Analysis

The above review identifies several PDC wear mechanisms that become more intense at elevated temperatures. Downhole cutter temperatures can be controlled, to a large extent, by the use of proper WOB and rotary speed.⁷ Therefore, it is of interest to estimate the extent to which typical operating conditions lead to cutter stress fields that promote these wear mechanisms. The analyses described below were conducted for this purpose. There were several specific objectives: (1) to identify regions in the cutter susceptible to plastic deformation and consequent formation of microvoids, development of residual tensile stresses, and initiation of cracks; (2) to determine the susceptibility of the bulk cutter material to fatigue; (3) to identify regions of tensile stress in the cutter; and (4) to determine conditions leading to thermal shock and fatigue.

The PDC-cutter models shown in Fig. 3 were chosen for this study. A single cutter, together with its share of the bit body, was studied during two stages of wear. The mildly worn cutter is essentially sharp, with the wearflat extending only across the diamond layer. The moderately worn cutter shows wear extending across the WC/Co compact, as may occur when hard, brittle rocks are drilled. The wearflat length, L_w , in this case is about three-fourths the length at which current drilling practice in hard-rock drilling considers the cutter worn out.*

Thermal. The method used to compute PDC-cutter temperature distributions is described in detail in our earlier work.^{7,8} The method is based on two-dimensional (2-D)

finite-element modeling of the thermal response of PDC cutters to frictional dissipation of energy at the cutter/rock interface.

The equation previously derived⁸ for the mean temperature across the cutter wearflat during rock cutting is

$$\bar{T}_w = T_f + \frac{KFvf}{A_w \left[1 + \frac{3\sqrt{\pi}}{4} k_{hf} \left(\frac{v}{\eta L_w} \right)^{1/2} \right]} \quad \dots (3)$$

This equation is used here to determine the weight on cutter, F , that produces a given wearflat temperature, \bar{T}_w , under typical downhole conditions. Of particular interest is the critical weight on cutter, F_{cr} , that was previously defined⁷ as the weight required to produce a wearflat temperature of 350°C [660°F], above which wear apparently increases significantly. Thus,

$$F_{cr} = \frac{A_w(350 - T_f) \left[1 + \frac{3\sqrt{\pi}}{4} k_{hf} \left(\frac{v}{\eta L_w} \right)^{1/2} \right]}{Kvf} \quad \dots (4)$$

A parametric study to determine the sensitivity of F_{cr} to downhole drilling conditions was reported earlier.⁷

Cutter-temperature distributions were numerically computed with transient boundary conditions at the wearflat designed to simulate actual drilling conditions. Thermal histories for the process of placing the bit on bottom and applying weight while rotating were computed. The cutter weight required to produce a desired steady-state wearflat temperature was computed from Eq. 3 with the values shown in Table 1 as typical rock-drilling conditions. This cutter weight then was used to compute the magnitude of the transient wearflat heat flux, q , according to the equation⁷

$$(q)_i = \left\{ \frac{KFv}{A_w} - [(\bar{T}_w)_{i-1} - T_f] \frac{3\sqrt{\pi}}{4} k_{hf} \left(\frac{v}{\eta L_w} \right)^{1/2} \right\} \quad \dots (5)$$

where i signifies the i th timestep and $i-1$ the immediately preceding one. The cutter is initially assumed to be in thermal equilibrium at the fluid temperature. The cutter weight is assumed to be applied as a step function at time $t=0$.

Frictional-heat flux into the cutter at the rock interface was assumed for simplicity to be distributed uniformly across the cutter wearflat. Although some distribution to reflect the stress concentration at the sharp diamond face would have been more realistic, we felt that the simplified assumption was appropriate.

Thermal shock caused by a sudden, complete loss of cutter weight was simulated by a sudden change from the wearflat-heating boundary conditions to convective cooling after the cutter temperature had reached its steady-state value. Temperature distributions then were computed until the cutter cooled to the fluid temperature.

*Private communication, L. Matson, Stratabit Corp., Houston, March 1984.

Structural. Stress distributions were computed with a general-purpose finite-element program.⁴⁵ The cutter was modeled with 2D planar finite elements. The cutter physical dimensions are similar in the coordinate directions so that a three-dimensional (3D) model of the cutter was considered. We felt, however, that a plane stress model was more within the scope of our study and could provide the necessary information. This was also the approach taken in our earlier work.⁷

The model boundary conditions were chosen to simulate the kinematic restraint provided by the bit body on the carbide stud. The vertical boundaries of the bit-body segment surrounding the stud were assumed to be fixed in both coordinate directions. Mechanical loads, which are the result of the cutting process, were applied to the model, as shown in Fig. 3. For each set of conditions, F was computed as described in the previous section and distributed over the cutter wearflat as a uniform normal stress, F/A_w . The friction force, F_{cf} , was distributed as a shear stress over the wearflat. The cutting force, F_c , was distributed as a normal stress over the surface element nearest the wearflat on the leading diamond face; this is in accordance with the experimental observation¹⁷ that very little, if any, of the leading face is actually in contact with the rock during drag cutting.

The magnitudes of F_{cf} and F_c were computed as follows. We found that with single-cutter-force data obtained under dry cutting conditions,* the ratio of the horizontal to vertical cutting forces, $(F_{cf}+F_c)/F$, has a typical value of 0.8. Thus,

$$F_c \approx 0.8F - F_{cf} \quad (6)$$

The friction force is given by

$$F_{cf} = KF, \quad (7)$$

where the value of K is taken to be 0.1 for water and 0.3 for typical air-drilling conditions.⁷ Substituting Eq. 7 into Eq. 6 gives the result for air:

$$F_c \approx F/2. \quad (8)$$

Then we assumed that although the friction force is reduced when water instead of air is used for cooling, the cutting force does not change. Eq. 8 thus should represent typical conditions for both air and water drilling.

Temperature distributions computed at each step in the transient thermal analysis were used as boundary conditions in the structural analysis. Temperature magnitude affects material properties, and gradients produce transient thermal forces that are applied to each element in the structural model.

An important part of the structural analysis was the determination of the temperature-dependent WC/Co and PDC material properties. Elastic modulus, yield stress, coefficient of thermal expansion, and postyield hardening slope are affected by the temperature variation. The mechanical properties reported in the literature for WC/Co vary widely, and in addition, high temperature data are almost nonexistent for this material²³ and PDC's. Typical values are used in this analysis. Table 2 lists these values

TABLE 1—CONDITIONS USED IN ANALYSES

Parameter	Water Drilling	Air Drilling
h , W/cm ² ·°C	1.0	0.01
f (mildly worn), cm ² ·°C/W	0.0643	0.956
f (moderately worn), cm ² ·°C/W	0.325	5.46
T_{fl} , °C	50	50
K , coefficient	0.1	0.3
v , m/s	1.0	1.0
Bit body and stud material	Grade 55B WC/Co	Grade 55B WC/Co
k_{hc} , W/cm·°C	0.8	0.8
ρ , g/cm ³	13.9	13.9
C_c , J/kg·°C	0.23	0.23
WC/Co compact material	Grade 883 WC/Co	Grade 883 WC/Co
k_{hc} , W/cm·°C	1.0	1.0
ρ , g/cm ³	15.0	15.0
C_c , J/kg·°C	0.23	0.23
Diamond layer	PDC	PDC
k_{hc} , W/cm·°C	5.43	5.43
ρ , g/cm ³	3.51	3.51
C_c , J/kg·°C	0.79	0.79
Rock		
k_{ht} , W/cm·°C	0.019	0.019
η , cm ² /s	0.01	0.01

at the stress-free reference temperature (assumed to be equal to the fluid temperature) and at elevated temperatures.

The von Mises stress criterion was used to determine yielding of the WC/Co and diamond materials. This is an effective stress criterion that allows a multiaxial stress state to be compared directly with a uniaxial stress/strain curve for the determination of yielding. In cases where the material yielded, the effective plastic strain was also computed. The maximum principal-stress distribution was computed from the stress components to locate tensile regions in the cutter, to determine the stress amplitudes, and to check fatigue conditions in the bulk material.

Analysis Conditions and Results

Thermal and mechanical boundary conditions were applied that correspond to wearflat temperatures of 350 and 700°C [660 and 1,290°F] produced during both water and air drilling. These temperatures bound the range for which PDC-cutter wear resistance must be improved for PDC bits to drill hard, abrasive rock economically.

The analyses were done assuming a cutter velocity of 1 m/s [3.3 ft/sec]. This is the approximate velocity of a cutter near the gauge of a 22.2-cm [8¾-in.] bit drilling at 100 rev/min. The cutter forces under these conditions were computed as described earlier and are shown in Table 3, which also shows the results in terms of WOB, assuming that 40 cutters on the bit share the load equally.

The WOB required to achieve a given cutter temperature increases with cutter wear, but at a rate less than proportional to the wearflat area. As a result, the normal contact stress between the cutter and the rock is actually lower with the moderately worn cutter. The mildly worn cutter, therefore, should achieve more rapid penetration at a given wearflat temperature. Note that air drilling

*Private communication, J.T. Finger, Sandia Natl. Laboratories, Albuquerque, NM, June 1984.

TABLE 2—PDC-CUTTER STRUCTURAL MATERIAL PROPERTIES

Property	WC/Co (°C)				PDC (°C)			
	50	300	600	800	50	300	500	700
Elastic modulus, GPa	648	579	458	403	890	890	890	890
Compressive yield stress, GPa	1.93	1.43	0.86	0.64	6.9	5.2	4.5	3.8
Postyield hardening slope, GPa	188	136	48	38				
Ultimate tensile strength, GPa	1.1	0.81	0.49	0.36	0.51	0.39	0.33	0.28
Thermal expansion coefficient, $10^{-6}/^{\circ}\text{C}$	4.5	5.3	5.2	6.4	1.3	2.5	3.9	3.9
Poisson's ratio	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22

TABLE 3—COMPUTED WEIGHT ON CUTTER
(COMPUTED WOB*)

Wear Configuration	Cooling	Mean Wearflat Temperature (°C)	
		350	700
Mildly worn	Water	1190 N [10,700 lbf]**	2570 N [23,100 lbf]
	Air	170 N [1,530 lbf]	370 N [3,300 lbf]
Moderately worn	Water	4330 N [38,900 lbf]	9370 N [84,300 lbf]
	Air	860 N [7,730 lbf]	1870 N [16,800 lbf]

*Assuming 8¼-in., 40-cutter bit.

**WOB equals weight on cutter multiplied by 40.

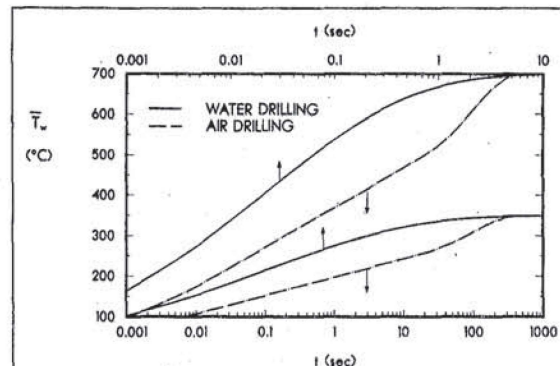


Fig. 4—Computed wearflat-temperature response for a mildly worn PDC cutter in the early stages of drilling (initial temperature = 50°C).

greatly reduces the WOB required to reach a given wearflat temperature. Because air drilling at a given WOB may be faster in some formations than water drilling, no general conclusions can be drawn about the effects of cooling on ROP for a fixed wearflat temperature.

The first results discussed are the cutter stresses that develop in the early stages of drilling. The mean-wearflat-temperature response for the mildly worn cutter caused by rotating under an applied WOB is shown in Fig. 4. For both final equilibrium temperatures (350 and 700°C [660 and 1,290°F]), the wearflat heats up much faster for water drilling because of the higher cutter weights required. With water cooling of the cutter, the wearflat approaches its steady-state value within 1 second, whereas with air cooling, it may take more than 1 minute.

Cutter stresses, in general, were found to increase with wearflat temperature. The maximum stresses during drilling thus occur after the cutter has reached thermal equilibrium. Stress distributions with water and air cooling were found to be very dissimilar. This is attributed to the differences in applied mechanical loads as well as differences in temperature distributions. The steady-state temperature distributions for the mildly worn cutter at 700°C [1,290°F] are shown in Figs. 5 and 6. With water drilling, thermal gradients on the order of 600°C/cm [2,740°F/in.] develop near the wearflat, and the bulk of the cutter and bit body remain at moderate temperatures. With air drilling, the entire cutter experiences elevated temperatures. This results in a reduction in the thermal gradients by an order of magnitude.

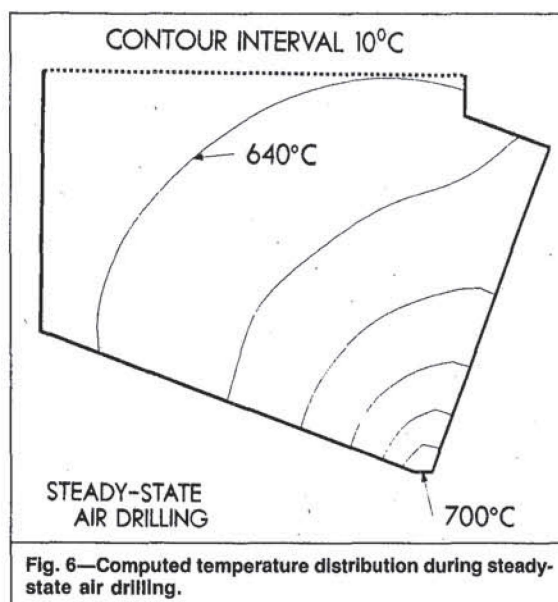
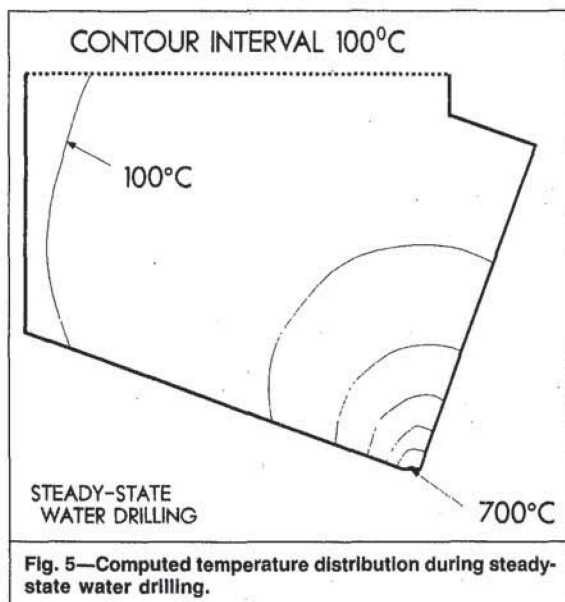
Fig. 7 shows the maximum principal stresses developed in the mildly worn cutter with water cooling. As expected, a compressive stress state exists along and near the

wearflat because of the interaction of the mechanical and thermal loads. As shown in Fig. 8, yielding occurs in the wearflat region from a combination of mechanical and thermal loading, yet neither alone is sufficient. The effective plastic strain is larger in the mildly worn cutter by a factor of 2.5, but the moderately worn cutter has a greater volume of yielded material.

Fig. 7 also shows a tensile stress field in the diamond layer. This stress develops as a result of the differential thermal expansion between the WC/Co and the diamond. The WC/Co expands more because of its higher expansion coefficient, which both bends and stretches the diamond layer. The maximum stress is actually just below the assumed diamond tensile strength at the local temperature in this case. If mechanical loads are suddenly removed without changing the thermal field, the maximum tensile diamond stress increases by 100%. Thus, the maximum stresses caused by thermal loading alone are greater than those caused by the combination loading.

Small tensile stresses also develop along the backside of the cutter stud and along the angled clearance face behind the wearflat. The existence of these tensile stresses is attributed to two mechanisms. First, material in this region is placed in tension by the expansion of the hot wearflat region. Second, bending-induced strain caused by differential thermal expansion between the diamond and the WC/Co substrate near the wearflat places the clearance face in tension. These tensile stresses also increase in magnitude when the cutting forces are removed suddenly without changing the thermal field.

The stress distribution within the moderately worn cutter is similar. The wearflat stresses are slightly reduced because of lower distributed mechanical loads, while the



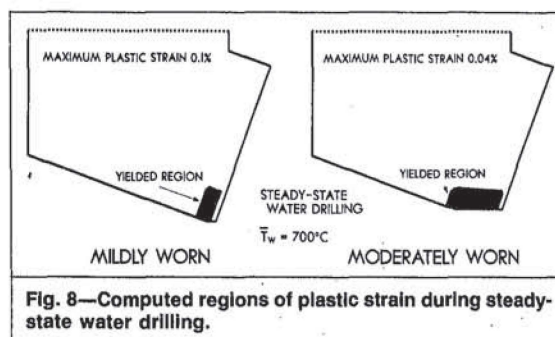
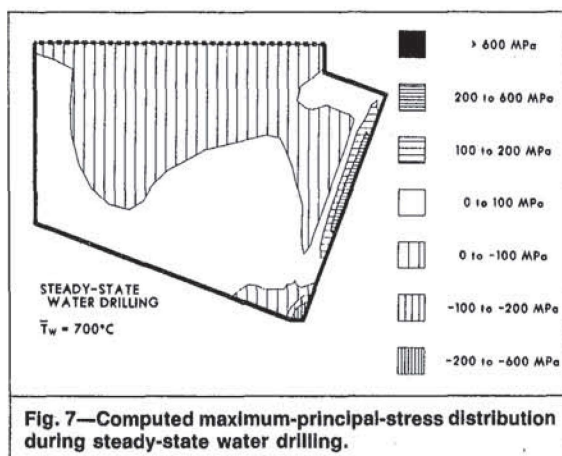
diamond stresses exceed the tensile strength because of the larger thermal field developed by the moderate wearflat.

For conditions where the maximum wearflat temperature reaches only 350°C [660°F], the effective stress is about half that occurring at 700°C [1,290°F], so no yielding of the cutter in the wearflat region is observed. The yield stress decreases by half between 350 and 700°C [660 and 1,290°F] because of thermal effects so that the cutter first yields near 700°C [1,290°F]. Tensile stresses in the diamond layer are also reduced at the lower temperature by a factor of about 40%.

With air as the coolant, the maximum principal stress distribution at 700°C [1,290°F] in the mildly worn cutter changes, as shown in Fig. 9. The entire diamond layer is now in tension, with much of it exceeding its tensile strength at these higher temperatures. Differential thermal expansion at the bimaterial interface is more severe because of the elevated temperature along the interface. Note that the maximum principal stress is tensile even at the wearflat. The mechanical loads required to produce a mean wearflat temperature of 700°C [1,290°F] for air

cooling are necessarily small, so the strain resulting from the thermal expansion dominates the stress response. A computed case where the thermal-expansion coefficient of the diamond was set equal to that of the WC/Co resulted in the maximum principal stress at the wearflat becoming compressive, which implies that the tensile wearflat is primarily a product of differential thermal expansion.

Stresses along the clearance face are also higher for air cooling. The analysis with uniform-expansion coefficient indicated that this increase was caused only partly by the diamond-layer bending stresses. The stress distribution in the upper part of the cutter-assembly model indicates that the fixed vertical boundaries of the bit-body portion of the model induce large compressive forces in the bit body and in the upper portion of the cutter stud. The expansion of the lower portion of the stud is less restrained, and as a result, tensile stress concentrations appear at the upper corners of the exposed stud. It is the interaction of these compressive and tensile strains that is responsible for the rest of the tensile stresses along the wearflat and clearance face. In reality, the bit body may have more freedom to expand than the assumed boundary condition implies. Nevertheless, these effects are likely to be present to some extent and could cause fracturing of the stud at the bit body as well as increased fracture propagation along the wearflat.



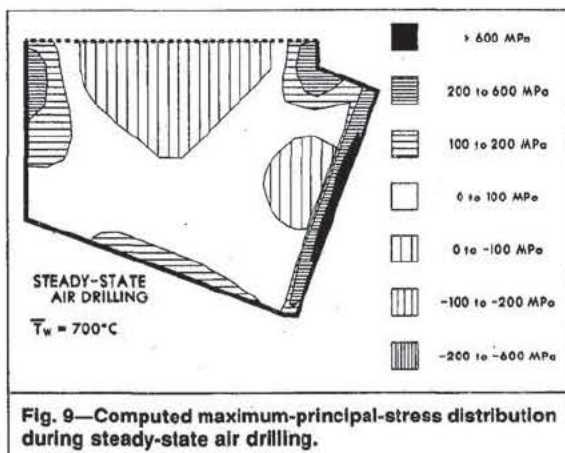


Fig. 9—Computed maximum-principal-stress distribution during steady-state air drilling.

The 350°C [660°F] air-drilling case showed similar trends but reduced stress levels. Nevertheless, the maximum principal stress in the diamond layer with air cooling at 350°C [660°F] is very near that developed with air at 700°C [$1,290^\circ\text{F}$]. Tensile stresses at the wearflat and high diamond stresses, even at the lower operating temperature, could be why air drilling is so detrimental to cutter life.

The previous analyses considered only the heating phases of the cutting cycle. Rapidly cooling a cutter from an elevated operating temperature can cause additional thermal-stress problems. Fig. 10 shows the wearflat-temperature response during rapid quenching with water from 350 and 700°C [660 and $1,290^\circ\text{F}$]. The maximum principal stress distribution in the mildly worn cutter during cooling from 700°C [$1,290^\circ\text{F}$] occurs at $t = 0.24$ seconds and is shown in Fig. 11. The temperature distribution at the same time is shown in Fig. 12. The tensile stresses in the diamond are seen to increase when the mechanical loads are removed. This increase is greater for the moderately worn cutter because of the increased volume of material at elevated temperature. In this case, these tensile stresses exceed the tensile strength in some regions. Tensile stresses also develop along the wearflat and reach their maximum soon after cooling begins. This is because the wearflat is now cooler than the adjacent material, as shown in Fig. 12. Wearflat tensile stresses actually exceed the

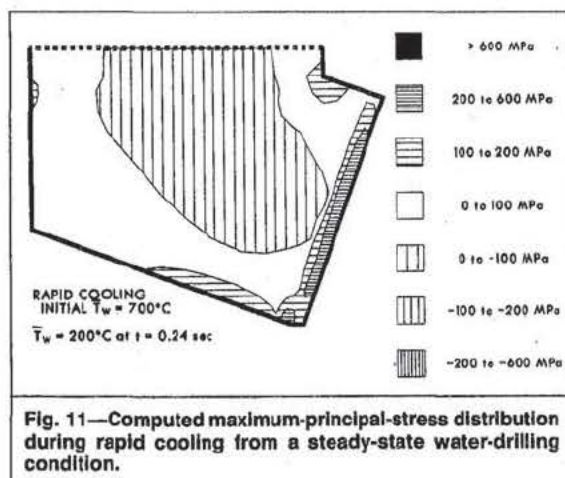


Fig. 11—Computed maximum-principal-stress distribution during rapid cooling from a steady-state water-drilling condition.

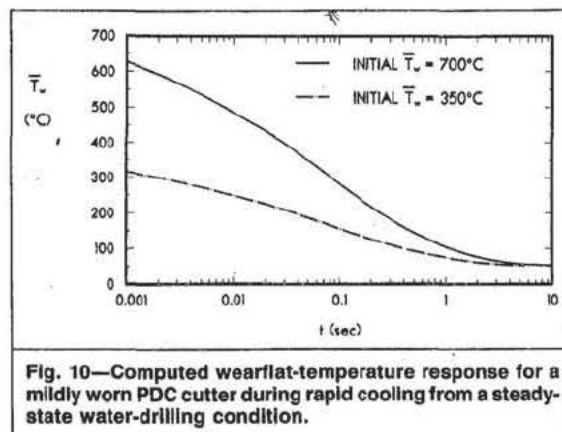


Fig. 10—Computed wearflat-temperature response for a mildly worn PDC cutter during rapid cooling from a steady-state water-drilling condition.

tensile strength of WC/Co for both worn-cutter configurations. As cooling progresses, the wearflat stresses diminish in magnitude, but the size of the tensile zone increases. Finally, the tensile zone shrinks as the cutter nears thermal equilibrium. There are residual tensile stresses on the order of 200 MPa [$29,000$ psi] remaining as a result of the plastic deformation that occurred during heating. Again, these stresses are smaller in magnitude for the moderately worn cutter, but the moderately worn cutter has a larger volume of residual stress.

The stresses developed during rapid cooling from 350°C [660°F] with water are shown in Fig. 13. The tensile stresses caused by thermal shock are still present but are reduced in magnitude from those produced at 700°C [$1,290^\circ\text{F}$], especially along the wearflat and the clearance face. Because there was no yielding during the heating phase at 350°C [660°F], no residual tensile stresses were produced.

Results indicate that thermal-shock effects are more severe for the moderately worn cutter because of the larger volume of material that reaches elevated temperatures during frictional heating and because of the additional cooling surface provided by the moderate wearflat. The

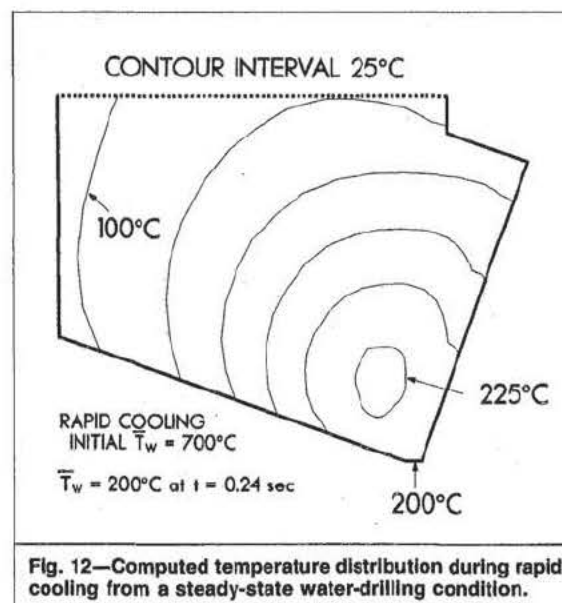


Fig. 12—Computed temperature distribution during rapid cooling from a steady-state water-drilling condition.

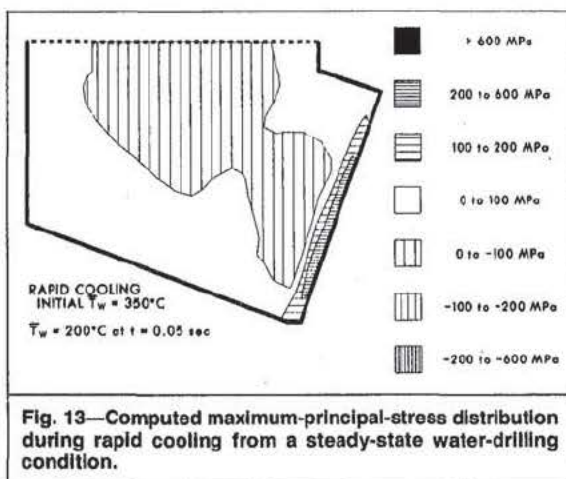


Fig. 13—Computed maximum-principal-stress distribution during rapid cooling from a steady-state water-drilling condition.

thermal loads developed during cooling with air do not produce any additional significant tensile stresses.

The development of destructive tensile stresses along the wearflat during rapid cooling with water prompted an analysis in which WOB was reduced slowly over a period of 30 seconds while allowing the cutter to cool gradually from 700°C [1,290°F]. The thermal response is shown in Fig. 14. Structural results indicate that the wearflat remains in compression throughout the cool-down phase. Fig. 15 shows the maximum-principal-stress distribution at the same wearflat temperature as that which produced the largest thermal stresses in the case where WOB was suddenly removed (Fig. 11). The maximum principal stress at the wearflat in the case with gradual WOB reduction is compressive instead of tensile. This is because some mechanical loading is maintained throughout the cool-down phase. In addition, the temperature distribution shown in Fig. 16 reveals that the gradual weight reduction maintains the necessary thermal gradients in the cutter required to keep the wearflat in compression.

Discussion

The stress distributions predicted by the analyses generally correlate with wear behavior noted in full-scale PDC bit tests. Thermal stress-cracking or heat-checking as pre-

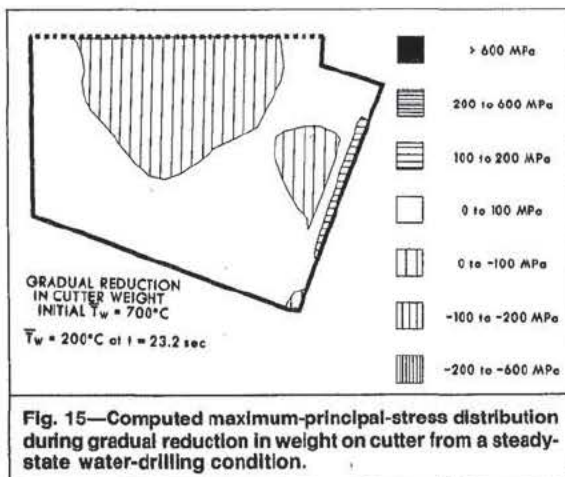


Fig. 15—Computed maximum-principal-stress distribution during gradual reduction in weight on cutter from a steady-state water-drilling condition.

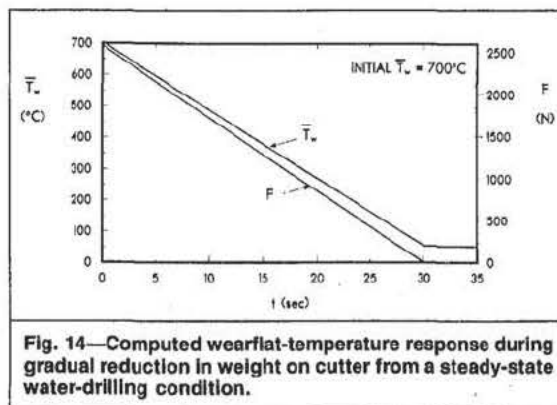


Fig. 14—Computed wearflat-temperature response during gradual reduction in weight on cutter from a steady-state water-drilling condition.

dicted by the analysis has been observed in both laboratory¹⁰ and field^{4,35} tests. Other thermally induced stress patterns predicted by the analysis are qualitatively confirmed by the general observation that high-temperature drilling environments cause accelerated bit wear.⁴ The observed phenomena of diamond spallation and uneven wear across the cutter wearflat^{4,10} correlate with regions of high stress identified by the analyses for high-temperature conditions.

The above results indicate that several measures can be taken during drilling to increase bit life. A general recommendation can be made to prevent excess cutter temperatures with moderate application of WOB. This should reduce abrasive wear, prevent plastic deformation of the cutting structure, and reduce the occurrence of thermal shock and fatigue. With hard rock, it may not be possible to achieve economic ROP's without applying enough WOB to reduce bit life greatly.⁴

An obvious precaution to take whenever possible is to use water or drilling mud instead of air. This will allow

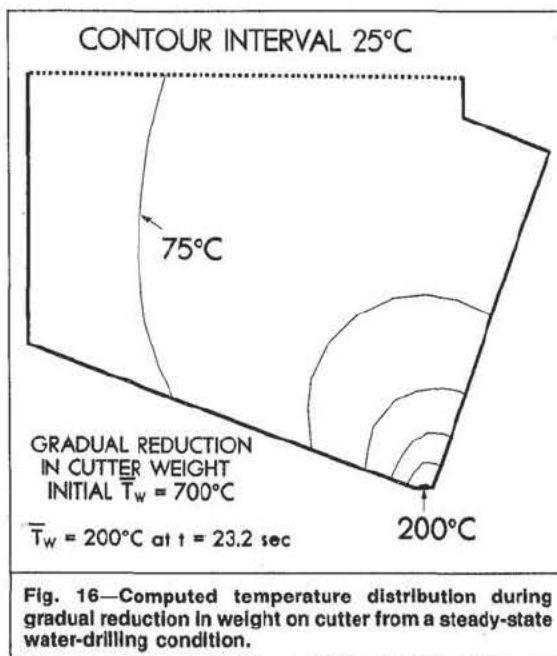


Fig. 16—Computed temperature distribution during gradual reduction in weight on cutter from a steady-state water-drilling condition.

the use of more WOB and will help keep thermal tensile stresses under control. WOB should be maintained at constant levels with shock subs and/or drillstring designs that prevent bit bounce and that reduce impact and fatigue conditions.

A final recommendation for use under conditions leading to elevated wearflat temperatures (such as hard-rock or high-speed drilling) is to reduce WOB slowly, rather than suddenly, when the bit is pulled off bottom for any reason. A linear reduction in WOB from its drilling value to zero over a period of 30 seconds is sufficient to eliminate computed tensile stresses resulting from thermal shock.

In addition to operating precautions, there are several microstructural-design considerations that could increase bit life in a given drilling environment. Plastic straining of the cutter material in the wearflat region under severe operating conditions could be eliminated by improving the high-temperature yield strength and hardness of the cemented carbide. Although WC/Co can be strengthened for static and cyclic compression loading by reducing Co content or WC grain size,²¹ these measures also result in a significant reduction in tensile strength^{21,27,33} and fracture resistance.^{34,46} In cases where impact loading or tensile stresses in the WC/Co are prevalent, the only apparent means for improving high-temperature strength are to develop a substitute binder material with greater high-temperature strength or to improve the existing microstructure by eliminating internal flaws and voids.

The first approach would require extensive research and ultimately may not be possible; practical experience has shown that Co is the best known binder material for fracture resistance of the bulk material.³⁴ The second approach can be accomplished with hot isostatic pressing (HIP). Although HIP does not improve intrinsic strength of the cemented carbides, it does virtually eliminate porosity during sintering, allowing harder WC/Co grades to be used without sacrificing fracture resistance.²³

In the case of the polycrystalline diamond, the ultimate tensile strength and, thus, fracture resistance is improved with a reduction in diamond grain size.⁴⁷

Abrasive wear of WC/Co composites also depends on Co content and grain size. Practical experience has shown that low Co content (6%) and small WC grains (1 μm) are most appropriate for hard, abrasive rocks^{15,46} because of the significance of Co removal in abrasion. A larger Co content for a given WC grain size, or a smaller WC grain size for a given Co content, results in a larger mean free path (diameter) of Co between WC grains.^{14,48} Soft abrasives then are able to remove Co at a higher rate, leading to increased void formation and intergranular fracturing.³⁹ Thus, while increased Co reduces the susceptibility of cemented carbides to bulk fracture, it increases the susceptibility to surface fracture during soft abrasion. It is more important under these conditions to improve Co ductility and bond strength with WC grains than to increase hardness of the composite.⁴³

At elevated temperatures where hard, abrasive wear effects become dominant, the hardness of the composite assumes greater importance.^{14,43} In addition to reducing Co content and WC grain size, a greater hardness can be achieved with WC grains that are more structurally perfect and can better withstand impact forces because of collision with hard abrasives.^{15,34} Fracture-propagation

resistance of surface layers also becomes more critical with hard abrasion. The use of perfect WC grains and the reduction or elimination of residual porosity in the composite by HIP are virtually the only means available to increase surface-layer fracture resistance without increasing Co content.³⁴ The empirical ranking of cemented carbides by abrasion tests with alumina grit has been found to be a valid measure of tool performance during abrasion at elevated temperatures.¹⁶

Because thermal shock and fatigue do not rely on preferential-binder removal to initiate cracks, the primary factor governing resistance to these mechanisms is the fracture-propagation rate.¹⁵ A solution in this case is to improve the ductility of the bulk material. For nonabrasive rocks, experience has shown that composites with high Co content (12%) and large WC grains (3 μm) are more resistant to thermal stresses.^{15,37} Thus, we conclude that the microstructure requirements for improved resistance to thermal shock and fatigue are different from those for improved resistance to abrasive wear. Because both these mechanisms occur simultaneously when drilling hard, abrasive rock, it is apparent that optimization of the microstructure is important if cutters that use WC/Co are to be successful in this application.

Improving the thermal conductivity and reducing the thermal-expansion coefficient and elastic modulus of the cemented carbide would reduce the level of thermal stress that develops in any given environment. Matching the thermal-expansion coefficient of the PDC and WC/Co to reduce tensile stresses on the diamond face could greatly improve the diamond's wear resistance. Finally, because of the large tensile stresses that may develop in the cutter because of the constraint provided by the bit body during air drilling, it would be desirable to reduce the thermal-expansion coefficient of the bit body as much as practical. Under such conditions, bit bodies cast in cemented carbide may be preferable to steel bodies because of the substantially lower coefficient of the first material.

Conclusions

1. Thermal effects on the wear of PDC cutters in hard, abrasive rock become significant at wearflat temperatures above 350°C [660°F]. This behavior is similar to that of cemented carbides in metal- and rock-cutting operations.

2. PDC-cutter materials during rock cutting are susceptible to wear by structural fatigue, impact shock and fatigue, thermal shock and fatigue, and abrasion. All of these mechanisms are intensified at elevated temperatures because of reduced mechanical strength and increased thermal stresses.

3. During steady drilling with water cooling, compressive stresses develop in the cutter wearflat region while tensile stresses develop and increase with temperature in the center of the diamond face and along the clearance face and back of the cutter. With wearflat temperatures near 700°C [1,290°F], compressive yielding at the wearflat occurs, leading to greatly increased abrasive wear. Computed tensile stresses are lower than reported material tensile strengths, but the cyclic nature of drag cutting could cause failure by fatigue.

4. During steady drilling with air cooling, tensile stresses throughout the cutter become more severe than those that develop with water cooling at the same wearflat temperature. This is primarily because the lower WOB re-

quired to achieve a given wearflat temperature with air cooling is not sufficient to suppress tensile stresses caused by thermal effects. As a result, the diamond tensile strength is exceeded with air cooling in the center of the diamond face with wearflat temperatures of 350 to 700°C [660 to 1,290°F]. In addition, the wearflat-region stress state changes from compressive to tensile, which could increase abrasive wear significantly.

5. PDC cutters used with water cooling are subjected to large tensile stresses if the wearflat is rapidly cooled from 700°C [1,290°F]. Under these conditions, stresses in the diamond layer approach the material tensile strength. Tensile stresses also develop at the wearflat and, although these are below the reported material tensile strength, they are probably sufficient to cause increased crack propagation and accelerated abrasive wear. Tensile stresses are reduced by approximately 50% if the pre-quench wearflat temperature is only 350°C [660°F].

6. When a PDC bit is lifted off bottom under elevated-temperature conditions, cutter life may be improved by gradually reducing WOB over a period of 30 seconds, instead of lifting the bit suddenly. This procedure is computed to reduce tensile stresses in the diamond face and to maintain the cutter wearflat in compression throughout the cool-down phase.

7. The microstructural design requirements for the cemented carbide supporting the PDC layer are different for resistance to abrasive wear from those for resistance to thermal shock and fatigue. Therefore, downhole conditions must be considered when optimizing microstructural design.

Nomenclature

- A_w = cutter wearflat area, cm^2 [in.²]
 c = constant
 C_c = cutter-material specific heat, $\text{J/kg} \cdot ^\circ\text{C}$ [Btu/lbm $\cdot^\circ\text{F}$]
 C_f = rock specific heat, $\text{kJ/kg} \cdot ^\circ\text{C}$ [Btu/lbm $\cdot^\circ\text{F}$]
 f = thermal response function, $\text{cm}^2 \cdot ^\circ\text{C/W}$ [$\text{ft}^2 \cdot \text{hr} \cdot ^\circ\text{F/Btu}$]
 F = weight on cutter, N [lbf]
 F_c = horizontal cutter force, N [lbf]
 F_{cf} = cutter/rock friction force, N [lbf]
 F_{cr} = critical weight on cutter, N [lbf]
 h = convective heat transfer coefficient, $\text{W/cm}^2 \cdot ^\circ\text{C}$ [Btu/hr $\cdot\text{ft}^2 \cdot ^\circ\text{F}$]
 H_a = hardness of abrasive, GPa [psi]
 H_m = hardness of metal, GPa [psi]
 i = i th timestep
 k_{hc} = cutter-material thermal conductivity, $\text{W/cm} \cdot ^\circ\text{C}$ [Btu/hr $\cdot\text{ft} \cdot ^\circ\text{F}$]
 k_{hf} = rock thermal conductivity, $\text{W/cm} \cdot ^\circ\text{C}$ [Btu/hr $\cdot\text{ft} \cdot ^\circ\text{F}$]
 K = friction coefficient between cutter and rock
 L_s = cutter sliding distance, cm [ft]
 L_w = cutter wearflat length, cm [in]
 q = frictional heat flux into cutter, W/cm^2 [Btu/ $\text{ft}^2 \cdot \text{hr}$]
 t = time, seconds
 T_f = fluid temperature, $^\circ\text{C}$ [$^\circ\text{F}$]
 T_w = mean cutter wearflat temperature, $^\circ\text{C}$ [$^\circ\text{F}$]

- v = cutting speed, m/s [ft/sec]
 V_w = cutter-wear volume, cm^3 [in.³]
 η = rock thermal diffusivity = $k_{hf}/\rho_f C_f$, cm^2/s [ft^2/hr]
 ρ = cutter-material density, g/cm^3 [lbm/ ft^3]
 ρ_f = rock density, g/cm^3 [lbm/ ft^3]

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Metric Conversion Factors

Btu/hr	× 2.928 751	E-01 = W
Btu/lbm	× 2.324 444	E+03 = J/kg
ft	× 3.048*	E-01 = m
ft ²	× 9.290 304*	E-02 = m ²
°F	(°F-32)/1.8	= °C
in.	× 2.54*	E+00 = cm
in. ²	× 6.451 6*	E+00 = cm ²
in. ³	× 1.638 706	E+01 = cm ³
lbf	× 4.448 222	E+00 = N
psi	× 6.894 757	E+00 = kPa

*Conversion factor is exact.

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