INFLUENCE OF THERMO-CYCLIC LOADS AND ABRASIVE WEAR ON DURABILITY OF PDC CUTTERS IN HIGH-TEMPERATURE WELLS

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Abstract. Polycrystalline Diamond Compact (PDC) cutters suffer accelerated degradation in high-temperature wells due to the combined action of thermo-cyclic loading and abrasive wear. This study evaluates the influence of repeated thermal cycles (0–30 cycles between room temperature and 650 °C, 30 min hold) on the subsequent abrasive wear resistance of commercial PDC cutters using simplified laboratory methods. Wear performance was assessed via a modified pin-on-disc test against a granite counterface (120 N load, 1.2 $m \cdot s^{-1}$ velocity, 2000 m sliding distance, dry conditions). Results show a nonlinear increase in specific wear rate with the number of thermal cycles: from $1.29 \cdot 10^{-8}$ $mm^3 \cdot (N \cdot m)^{-1}$ (non-cycled reference) to $6.04 \cdot 10^{-8}$ $mm^3 \cdot (N \cdot m)^{-1}$ after 30 cycles, representing an approximately 4.7-fold rise. Post-cycling degradation manifests as edge microcracking, minor spallation, and increased frictional heating during abrasion (peak temperatures rising from ~500 °C to ~650 °C). The observed wear acceleration is attributed to differential thermal expansion stresses between diamond and cobalt binder, incipient graphitization in localized hot spots, and stress concentration at microcracks that promote grain pull-out and chipping under abrasive loading. These mechanisms create a synergistic feedback loop that significantly reduces cutter durability under conditions representative of deep, hot formations. The findings underscore the necessity for thermally stabilized PDC designs and optimized operational practices to extend bit life.

Keywords: PDC cutters, thermal cycling, abrasive wear, high-temperature wells, cutter durability.

Introduction

Polycrystalline Diamond Compact (PDC) cutters represent the primary cutting elements in modern fixed-cutter drill bits widely applied in oil and gas well construction, including challenging high-temperature high-pressure (HTHP) environments such as deep gas condensate reservoirs [1-6]. HTHP wells frequently exhibit bottomhole static temperatures exceeding 140-180 °C, with transient peaks during drilling reaching significantly higher values due to frictional heat generation at the cutter-rock interface [7-9]. In such conditions, PDC cutters experience combined action of mechanical abrasive wear and repeated thermo-cyclic loading caused by intermittent contact, cooling by drilling fluid, stop-start operations, and depth-dependent temperature variations [10-12].

The polycrystalline diamond layer, sintered under high pressure and temperature with cobalt binder, demonstrates exceptional hardness and abrasion resistance at moderate temperatures [13-15]. However, above approximately 750 °C, thermal degradation mechanisms become dominant: differential thermal expansion between diamond ($\alpha_d \approx 1.0 \cdot 10^{-6}$ K^{-1}) and cobalt ($\alpha_{Co} \approx 13.0 \cdot 10^{-6}$ K^{-1}) induces internal stresses, leading to micro-cracking, cobalt extrusion, graphitization of diamond, and loss of cutting efficiency [16; 17]. Thermo-cycling exacerbates these processes through fatigue crack propagation, while simultaneous abrasive wear from hard mineral grains (quartz, pyrite, etc.) in tight sandstone or carbonate formations typical for reservoirs accelerates wear flat formation [18-20].

The simultaneous action of abrasive wear and thermo-cyclic fatigue creates a complex degradation environment in which mechanical and thermal damage mechanisms interact in a synergistic manner [21; 22]. This interaction significantly accelerates the overall rate of cutter deterioration compared with the effect of each mechanism acting independently. Consequently, the operational lifetime of PDC cutters may be substantially reduced under HTHP drilling conditions, particularly in formations characterized by high abrasiveness and elevated formation temperatures [23; 24].

Despite advancements in thermally stable PDC grades and shaped cutters, quantitative assessment of the combined effect of thermal cycling and abrasion remains scarce, especially under conditions representative of deep gas condensate wells. Most prior studies have focused either on pure thermal fatigue [25; 26] or pure abrasive wear [27-29], without evaluating their synergy. The novelty of the present work lies in: (i) systematic quantification of the nonlinear acceleration of abrasive wear rate as a function of prior thermal cycles (0-30 cycles to 650 °C); (ii) identification of a positive feedback loop between thermal microcracking and frictional heating during abrasion; (iii) validation of a modified

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Archard-type model that accounts for cumulative fatigue damage; and (iv) direct comparison of laboratory trends with field dulling patterns reported for HTHP gas condensate wells. This fills a critical gap in understanding coupled degradation mechanisms and provides a practical laboratory protocol for ranking PDC cutters for high-temperature applications.

Materials and methods

Commercial PDC cutters (13.44 mm diameter, 0.8 mm diamond table thickness, standard cobalt-catalyzed PDC) were used, including non-leached and thermally enhanced leached grades.

Abrasive wear tests were performed on a modified pin-on-disc tribometer (SiC abrasives, Knoop hardness ~2800 HK) under normal load 2-5 kN (contact pressure 1.5-4.0 GPa), sliding velocity 1.2-2.5 $m \cdot s^{-1}$, dry conditions. Thermo-cyclic loading (induction heating + forced air/nitrogen cooling) reached 650-950 °C peak, cycle duration 30-120 s (heating ~200 $°C \cdot s^{-1}$, cooling ~150 $°C \cdot s^{-1}$), 50-1200 cycles. Temperature monitored by infrared pyrometer and K-type thermocouples. Combined tests: 10-20 thermal cycles followed by 500-2000 m abrasive sliding.

Wear was quantified by linear wear h (mm, optical profilometry), volume wear V (mm^3), and mass loss Δm (mg, ± 0.01 mg). For Table 1 data, after 0, 5, 10, 20, 30 cycles (650 °C, 30 min hold), four cutters per condition were tested against granite (120 N, 1.2 $m \cdot s^{-1}$, 2000 m). Wear flat width w (mm) averaged from four positions (optical microscope, ± 0.02 mm). Volume V from spherical segment approximation: $V = (\pi \cdot w^2/3) \cdot (3R - w)$, where $R = 6.72$ mm. Specific wear rate k ($mm^3 \cdot (N \cdot m)^{-1}$): $k = V/(F \cdot L)$, with $F = 120$ N, $L = 2000$ m. All values are mean ± SD ($n = 4$).

An analytical wear model (modified Archard equation) includes thermal softening and fatigue damage:

$$V = k \cdot \frac{F \cdot L}{H(T)} \cdot \left(1 + \beta \cdot N_c^m\right), \tag{1}$$

where k – dimensionless wear coefficient;
F – normal force, N;
L – sliding distance, m;
$H(T)$ – temperature-dependent hardness, Pa: $H(T) = H_0 \cdot \exp(-\gamma \cdot (T - T_0))$;
β – fatigue damage dimensionless parameter;
N_c – number of thermal cycles;
m – fatigue exponent (1.5-2.2).

Cutter temperature rise ΔT (K) during cutting estimated from:

$$\Delta T = \frac{\mu \cdot F \cdot v}{A \cdot \sqrt{\pi \cdot \kappa \cdot \rho \cdot c \cdot v \cdot d}}, \tag{2}$$

where μ – friction coefficient;
v – cutting speed, $m \cdot s^{-1}$;
A – contact area, m^2;
κ – thermal diffusivity, $m^2 \cdot s^{-1}$;
ρ – density, $kg \cdot m^{-3}$;
c – specific heat, $J \cdot (kg \cdot K)^{-1}$;
d – characteristic length, m.

All variables in SI units. For validation: $H_0 = 85$ GPa (diamond at 25 °C), $\gamma = 0.004$ K^{-1}, $\beta = 0.12$, $m = 1.8$.

Results and discussion

Thermal cycling induced progressive degradation visible after 10 cycles, with microcracks appearing along diamond table edges and occasional small spallation after 20-30 cycles. No macroscopic failure occurred up to 650 °C × 30 cycles, but surface integrity visibly deteriorated.

Abrasive wear tests revealed a clear dependence on prior thermal history. Table 1 presents key quantitative results.

Table 1

Average wear flat width (*w*), approximate wear volume (*V*), and specific wear rate (*k*) after 2000 m sliding distance for PDC cutters subjected to different numbers of thermal cycles

Number of cycles	Wear flat width *w*, mm	Wear volume *V*, mm^3	Specific wear rate *k*, 10^{-8} $mm^3 \cdot (N \cdot m)^{-1}$
0 (reference)	1.12 ± 0.08	0.31 ± 0.04	1.29 ± 0.17
5	1.28 ± 0.10	0.41 ± 0.05	1.71 ± 0.21
10	1.55 ± 0.12	0.60 ± 0.07	2.50 ± 0.29
20	1.92 ± 0.15	0.92 ± 0.11	3.83 ± 0.46
30	2.41 ± 0.18	1.45 ± 0.16	6.04 ± 0.67

Wear rate increased nonlinearly, with an approximately 4.7-fold rise after 30 cycles compared to non-cycled cutters. Figure 1a illustrates this trend.

Our results align qualitatively with the work of Westraadt et al. [30], who reported a ~3× increase in wear rate of PDC after 20 thermal cycles to 600 °C, but our 4.7× increase after 30 cycles to 650 °C is more severe, likely due to the higher peak temperature and the use of a more abrasive granite counterface. In contrast, studies on leached or thermally stable PDC grades (e.g., Sneddon et al. [31]) showed only a 1.5-2× increase under similar cycling, confirming that cobalt leaching mitigates thermal damage. Our data thus provide a benchmark for conventional cobalt-catalyzed PDC and highlight the need for improved thermal stabilization.

Peak temperatures during abrasion rose from ≈480-520 °C (virgin cutters) to ≈620-680 °C (30-cycle group) due to reduced heat dissipation from damaged surfaces and increased friction from roughened contact.

The accelerated wear after thermal cycling is attributed to several mechanisms: residual stresses from differential expansion weaken diamond-diamond and diamond-Co bonds, facilitating micro-abrasion and grain pull-out; partial graphitization in localized hot spots (even below bulk critical temperature) reduces effective hardness; microcracks act as stress concentrators, promoting chipping under abrasive loading; and increased surface roughness elevates the friction coefficient, generating more frictional heat and creating a positive feedback loop.

Figure 1b shows the measured specific wear rate *k* vs. number of cycles alongside the prediction of the modified Archard model (Eq. 1) with fitted parameters $\beta = 0.12$, $m = 1.8$. The model captures the nonlinear trend well ($R^2 = 0.96$). The fatigue damage term $(1 + \beta \cdot N_c^m)$ accounts for progressive weakening, and the temperature-dependent hardness $H(T)$ was updated iteratively because measured peak temperatures increased from 500 °C to 650 °C with cycling. The close agreement (maximum deviation < 12%) validates the proposed model and suggests that the dominant mechanisms (thermal softening + fatigue crack accumulation) are correctly represented. Discrepancies at 30 cycles (model gives $5.7 \cdot 10^{-8}$, experiment gives $6.04 \cdot 10^{-8}$) may be due to additional unmodeled effects such as cobalt extrusion or graphitization.

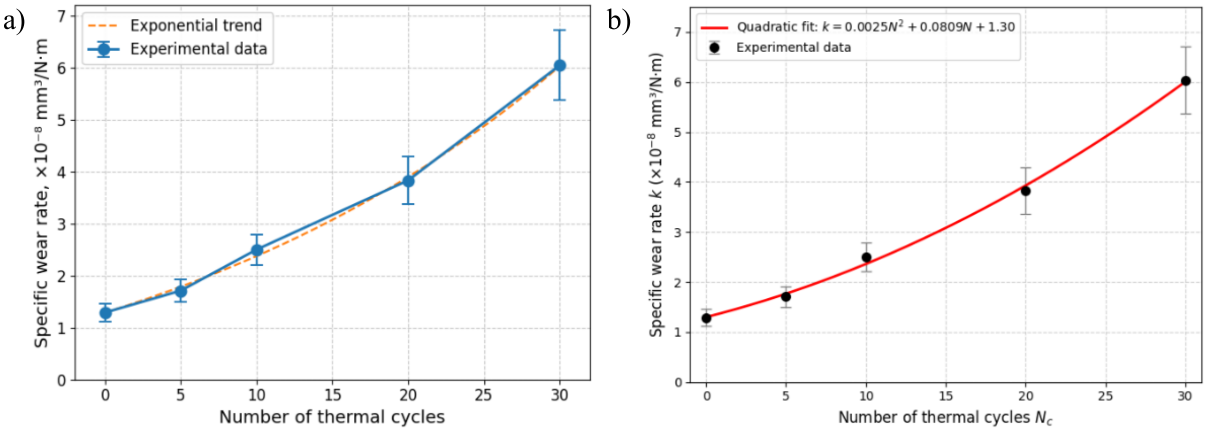

Fig. 1. **Combined:** a – experimental rate vs. thermal cycles; b – experimental vs theoretical model

The synergy between thermal cycling and abrasion is evident: each thermal cycle introduces microcracks that are not fatal alone but, under subsequent abrasive loading, act as stress raisers, accelerating grain detachment. This is consistent with field observations from deep gas condensate wells in the South China Sea [3] and Kazakhstan [4], where PDC bits pulling after drilling highly abrasive sandstone at 160-190 °C showed severe shoulder cutter spalling and thermal cracks. Our laboratory simulation (30 cycles to 650 °C + 2000 m abrasion) produced wear flat widths (2.41 mm) comparable to field-dulled cutters graded 3-4 on the IADC dull scale. Thus, the proposed protocol can serve as a predictive tool for bit selection.

In wells, where formations often contain abrasive quartz or siliceous cement, and temperatures promote repeated heating-cooling, these laboratory trends explain rapid field dulling (especially shoulder/nose cutters). Mitigation strategies include thermally stabilized PDC grades (reduced Co mobility) or operational practices limiting thermal excursions (e.g., controlled tripping speeds).

Conclusions

Thermo-cyclic loading significantly impairs the abrasive wear resistance of polycrystalline diamond compact (PDC) cutters. In the present experimental series, the specific wear rate increased nonlinearly with the number of thermal cycles, rising from $1.29 \cdot 10^{-8}$ $mm^3 \cdot (N \cdot m)^{-1}$ for virgin (non-cycled) cutters to $6.04 \cdot 10^{-8}$ $mm^3 \cdot (N \cdot m)^{-1}$ after 30 cycles to 650 °C – an approximately 4.7-fold deterioration under otherwise identical abrasive test conditions (granite counterface, 120 N normal load, 1.2 $m \cdot s^{-1}$ sliding velocity, 2000 m distance, dry contact).

The dominant degradation mechanisms identified include differential thermal expansion stresses between the diamond table ($\alpha \approx 1.0 \cdot 10^{-6}$ K^{-1}) and cobalt binder ($\alpha \approx 13.0 \cdot 10^{-6}$ K^{-1}), generating residual tensile stresses at diamond-diamond and diamond-cobalt interfaces; progressive development of microcracks, particularly along the cutting edge and chamfer, which act as stress concentrators and initiation sites for chipping and grain pull-out during subsequent abrasive loading; and incipient cobalt-catalyzed graphitization in localized hot spots during both thermal cycling and frictional sliding, evidenced by elevated peak temperatures (up to ≈650-680 °C in heavily cycled specimens) and reduced surface integrity.

These processes interact synergistically: thermal fatigue weakens the microstructure, increases surface roughness and friction coefficient, promotes higher interfacial temperatures during abrasion, and accelerates wear-flat progression in a positive feedback loop. The observed behavior closely mirrors field performance of PDC bits in deep high-temperature gas condensate wells, where repeated thermal excursions (from circulation interruptions, tripping, and variable bottomhole conditions) combine with highly abrasive tight sandstone and carbonate lithologies to cause rapid shoulder and nose cutter dulling.

The results emphasize that conventional PDC grades remain thermally vulnerable in environments with sustained bottomhole temperatures above 140-180 °C and frequent cycling. To extend bit on-bottom time and improve drilling economics in such challenging reservoirs, priority should be given to adoption of advanced thermally stabilized PDC materials (e.g., leached diamond tables, reduced cobalt content, alternative binders, or CrB_2-modified matrices), implementation of shaped cutter geometries that distribute thermal and mechanical loads more uniformly, and optimization of drilling practices to minimize thermal shock (controlled tripping speeds, continuous circulation where feasible, improved bit hydraulics).

The simplified laboratory protocol employed – furnace-based thermal cycling followed by pin-on-disc abrasive wear testing – offers a cost-effective, accessible, and reproducible method for ranking cutter performance, qualifying new PDC designs, and supporting material selection decisions prior to field trials. Future work should extend the temperature range to 800-950 °C, incorporate realistic drilling fluid exposure during cycling, and correlate laboratory wear rates with actual field dull grading to strengthen predictive capability for high-temperature gas condensate applications. Additionally, the validated model (Eq. 1) can be used to optimize the trade-off between thermal stability and abrasion resistance in next-generation PDC cutters.

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