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Numerical Investigation of PDC Bit Wear under Thermo-Mechanical Conditions in Hot Dry Rock Drilling

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ABSTRACT

The longevity and efficiency of polycrystalline diamond compact (PDC) cutters are key factors to the economic viability of deep drilling in high-temperature geothermal environments. In hot dry rock (HDR) formations, cutter wear is governed by complex thermo-mechanical interactions involving abrasive mechanisms, thermal softening of the matrix, and cyclic loading effects. This study presents a coupled numerical model to simulate the progressive wear of PDC cutters under realistic downhole conditions and the associated temperature rise. The observed combination of lower temperature rise, earlier wear stabilization of PDC are consequences of a brittle rock failure mode. A transition from Friction-Dominated Energy consumption (FDC) to Fracture-Dominated Energy Consumption (FEC) in ductile rock was also observed. The model enables the generation of predictive wear maps and supports the design of thermally resilient drilling tools for future geothermal operations.

1 INTRODUCTION

Geothermal drilling is progressively targeting deeper and hotter reservoirs, commonly hosted in crystalline rocks (granite, gneiss, basalt) where abrasion resistance and mechanical strength are high. PDC bits offer substantial gains in mechanical efficiency and rate of penetration, but severe cutter wear remains a primary limiter of performance, driving frequent trips and high non-productive time. In contrast to many petroleum settings, geothermal drilling adds a strong thermal dimension: rock properties evolve with temperature, and cutter temperatures can rise rapidly due to frictional sliding and limited cooling.

In geothermal settings, temperature tends to promote ductile behavior in crystalline rocks through thermally activated deformation mechanisms (e.g., dislocation glide/climb, microcrack growth, grain-boundary processes). Laboratory studies have shown systematic reductions in strength and elastic modulus and increases in ductility with increasing temperature in many rocks, shifting the brittle–ductile balance toward shear-dominated deformation (Wong, 2005). This domination of ductile behavior can reduce brittle chipping, yet may increase frictional sliding at the cutter–rock interface, raising cutter temperature and potentially accelerating PDC degradation (thermal fatigue, binder softening, and diamond degradation). Therefore, a geothermal-specific wear model should couple failure mode and temperature effects.

Although numerous experimental and numerical investigations have been performed on the cutting behavior of new polycrystalline diamond compact (PDC) teeth, the mechanisms of rock fragmentation and the associated temperature evolution during cutting with worn PDC teeth remain insufficiently understood.

Previous studies have demonstrated that the wear ratio and the temperature increase vary among different rock types under identical cutting conditions. Shankar et al. (2020) documented a maximum temperature rise of 74°C in a fine-grained sandstone characterized by a uniaxial compressive strength (UCS) of 13.70 MPa. In contrast, Han et al. (2025) reported a substantially higher temperature increase, on order of 750°C, in a coal specimen with a UCS of 2.58 MPa under drilling conditions where the applied weight on bit (WOB) on the entire bit assembly was approximately 4 kN.

Rock type refers to distinct rock failure mechanisms that can directly influence the cutting interaction mode, the associated temperature rise, and consequently the PDC wear. Gao et al. (2022) investigated the interface temperature using an infrared thermal imaging device for various rock types and reported a maximum temperature increase of up to 190 °C in granite under drilling conditions of 123 rpm and a rate of penetration (ROP) of 0.9 m/h.

Jahangir et al.

Possible failure modes of PDC cutters are governed by the combined effects of rock failure mode, contact temperature rise, and cyclic thermo-mechanical loading during cutting (Detournay, 1992).

In ductile cutting regimes, typically associated with lower rock brittleness or higher confinement, the cutter is subjected to relatively high and sustained cutting forces, which promote frictional sliding, wear-flat development, and progressive thermal accumulation at the cutter-rock interface (Dai, 2021).

In contrast, brittle rock failure is characterized by intermittent chip formation and dynamic fracture events, resulting in pronounced cutting-force fluctuations and high-frequency cyclic loading at the cutter face. These repeated load transients, often amplified by drilling-induced vibrations such as stick--slip or bit bounce, can promote fatigue crack initiation and propagation on the cutter face or along the diamond-carbide interface, ultimately leading to chipping or spalling (Wang et al., 2022).

As wear develops, the enlargement of the wear flat further increases frictional heating and contact stresses, creating positive feedback between temperature rise, cyclic loading, and damage accumulation. Consequently, face cracking and catastrophic PDC failure are best interpreted as the result of coupled thermo-mechanical fatigue rather than purely mechanical overload, with the dominant failure mode strongly influenced by the brittle-ductile response of the rock and the resulting force-temperature history at the cutter scale (Chen et al., 2023).

2 BACKGROUND & METHODOLOGY

With increasing drilling depth, the confining pressure and temperature correspondingly rise, resulting in rock that exhibits greater deformation resilience and an increased resistance to cutting. Research indicates that temperature significantly influences wear mechanisms, with higher temperatures leading to increased wear rates and reduced cutter lifespan (Mazen et al., 2020).

The literature on PDC cutting mechanics differentiates between brittle and ductile failure modes primarily as a function of cutting depth and the resulting chip size. A shallow depth of cut generally promotes ductile chipping, characterized by relatively small variations in cutting forces, which in turn leads to lower stress levels and reduced wear of the PDC cutters. Conversely, a greater depth of engagement tends to favor brittle cutting, associated with pronounced fluctuations in cutting forces and the generation of larger chips, thereby increasing the risk of cutter wear (Wang et al., 2024).

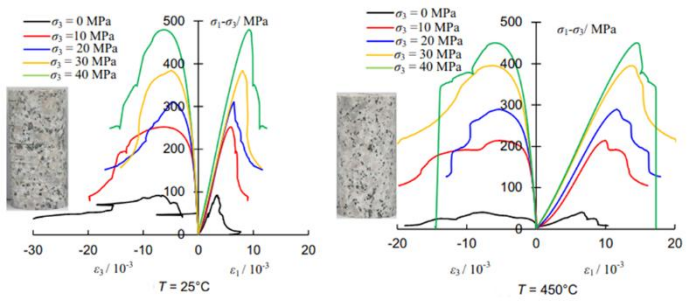


Figure1. Typical triaxial test of a granite under high pressure and high temperature condition Yang et al., (2020).

This study focuses on deep geothermal drilling conditions in which rock, subjected to elevated pressure and temperature, exhibits intrinsically ductile behavior. Figure 1 illustrates the representative mechanical response of granite subjected to elevated confining pressure and temperature. It can be observed that, as the temperature increases from 25°C to 450°C, the rock exhibits an enhanced capacity for deformation in the post-peak regime, implying that a greater amount of energy is required to induce failure and material cutting. This study will investigate a cutting process applied to both brittle and ductile rock, as illustrated in Figure 2. The mechanical response of the rock in each deformation regime is consistent with the experimental results reported by Yang et al. (2020), illustrated in Figure 2 for a confining pressure of 30 MPa, with initial temperatures of 25 °C for the brittle regime and 250 °C for the ductile failure, respectively. Used rock parameters are gathered in table 1.

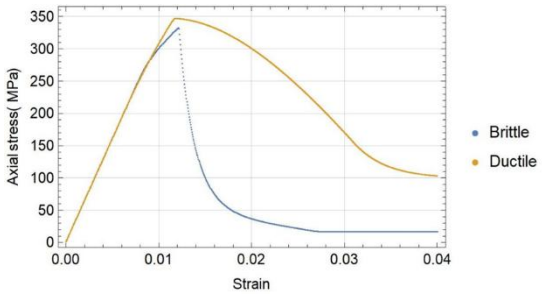


Figure 2. Considered mechanical behavior

3 METHOD AND MATERIAL

Finite element simulations were performed in Abaqus software ((Dassault Systèmes, 2024) to model cutter–rock interaction and wear evolution. The cutter is modeled as either a rigid body (to isolate rock response and wear kinematics) or as an elastic body (to capture cutter compliance). The rock is modeled as an elastic–viscoplastic continuum, with temperature-dependent parameters when applicable. Surface-to-surface contact is defined between the cutter and rock surfaces, with normal contact behavior and Coulomb friction in the tangential direction. The analysis is performed under dynamic conditions with element erosion when its damage threshold is reached.

In this section three different parts of whole model will be presented including the PDC contact model, Rock constitutive model and wear model.

3.1 Contact model

Contact between the PDC cutter and the rock is modeled using the general contact algorithm implemented in an element-based framework to robustly handle evolving interfaces associated with progressive damage, wear, and element erosion or deletion. This capability is essential for rock cutting simulations in which the contact topology evolves continuously due to material removal, chip formation, and surface recession.

In an element-based general contact setting, the active contact domain is reconstructed at each increment from the current finite element topology. When elements are eroded or deleted as a result of local damage or wear criteria, their associated faces are removed from the contact candidate set, while newly exposed faces become eligible for contact in subsequent increments. This automatic update of contact boundaries ensures numerical robustness and physical consistency when simulating rock fragmentation and progressive cutter penetration.

3.2 Constitutive Framework for Thermo-Mechanical Damage

To realistically simulate how granite weakens while being cut, we use a well-established model that tracks the rock damage. We adopt a pressure–dependent Drucker–Prager (DP) yield surface for the rock matrix with a scalar damage variable $D \in [0,1]$ that modifies the cohesion and frictional and dilatancy angles (equations 1-3). For the rock undergoing a shearing mechanism, imposed by the cutter, the DP family models are quite relevant (Liu et al., 2019). Equation 1 and 2 show the failure criterion and non-associated plastic potential.

$$f(\sigma, D) = \sqrt{J_2} + \alpha(D) \cdot I_1 - k(D) \leq 0 \quad (1)$$

$$g(\sigma, D) = \sqrt{(J_2)} + \alpha_g(D) \cdot I_1 \quad (2)$$

I_1 and J_2 are the first and second invariants of the stress tensor such as $q = \sqrt{(3J_2)}, p = -I_1/3$. The following equations present the evolution of mechanical parameters where φ is the friction angle, C is the cohesion and ψ is the dilatancy angle.

$$\alpha(D) = \sqrt{(2/9)} \cdot sin(\varphi(D)) \,/\, [3 - sin(\varphi(D))] \quad (3)$$

$$k(D) = 2C \cdot cos(\varphi(D)) \,/\, [3 - sin(\varphi(D))]$$

$$\alpha_g(D) = \sqrt{(2/9)} \cdot sin(\psi(D)) \,/\, [3 - sin(\psi(D))]$$

The following table gather the used rock properties where the only difference between the ductile and brittle rock (Figure 2) is the fracture energy varying from 50 J/m^2 for brittle case to 600 J/m^2 for ductile case.

Table 1. Rock properties.

Description	Values	Units
Elastic modulus	40	MPa
Mass density ρ	2000	kg/m^3
Thermal conductivity k	2.0	W/(m·K)
Heat capacity c_p	690	J/(kg·K)
Thermal expansion α_T	1e-5	1/K
C	5 0	MPa
φ_0,ψ_0	30°, 40°	
UCS	180	MPa
ε_0^P	0.0004	
dilatancy damage (β)	0.2	

3.3 Wear model

Wear is modeled using the Archard formulation available in Abaqus contact wear. In its classical form, the incremental wear depth dw at a contact point is proportional to contact pressure p and incremental sliding distance ds, and inversely proportional to a hardness or reference stress H:

$$dw = k \cdot (p \cdot ds) / H \quad (4)$$

where k is a dimensionless wear coefficient (or a coefficient with appropriate unit conventions depending on implementation). In Abaqus, contact wear is defined through a wear law at the interface and evolves the surface geometry accordingly. In the present framework, k may be treated as a function of temperature T (e.g., k(T) increasing above a thermal threshold).

This allows the Archard carrier law to incorporate geothermal-specific thermo-mechanical effects while keeping the implementation compatible with standard Abaqus workflows.

4 RESULTS

The following figure shows two typical rock behaviors corresponding to a brittle and ductile cases during the PDC cutting process.

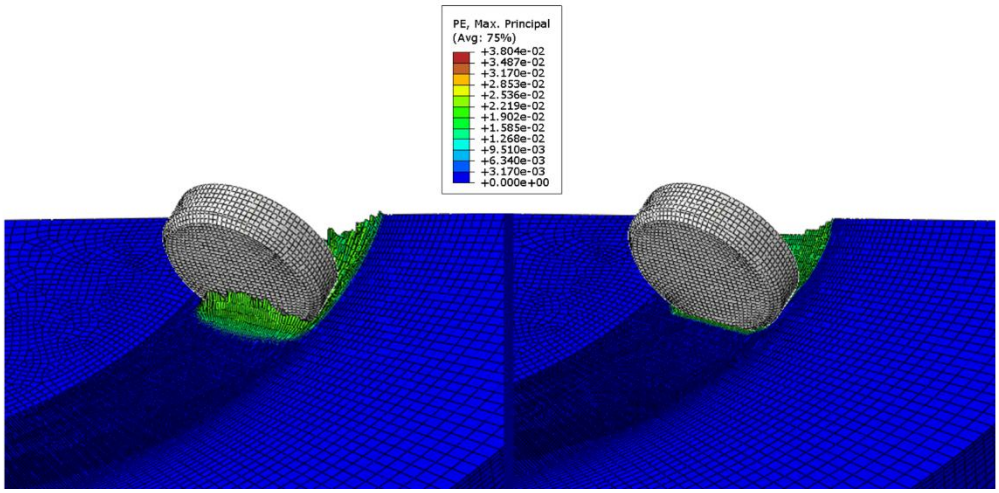


Figure 3. Cutting in Ductile (left) and brittle (right) rock

Figure 4 shows the failure mode effect on flat wear on a ridge PDC cutter with a chamfer. When the cutter cuts the rock in ductile mode, the contact load is more uniformly distributed on the cutter surface. However, in this case, the rock can accommodate a greater amount of strain and impose higher frictional forces on the cutter surface before complete failure occurs.

In the brittle case, the contact is localized over smaller surface regions, thereby generating elevated stress concentrations within the chamfered zone. This results is in agreement with previous works (Liu et al., 2024). The wear flat and temperature rise is shown by figures 4 and 5.

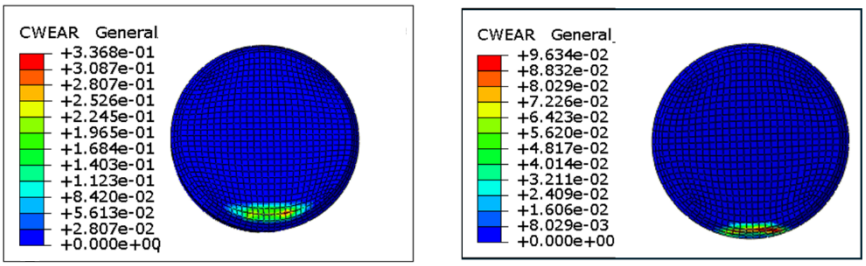


Figure 4. Wear evolution rise in ductile (left) and brittle (right) cases

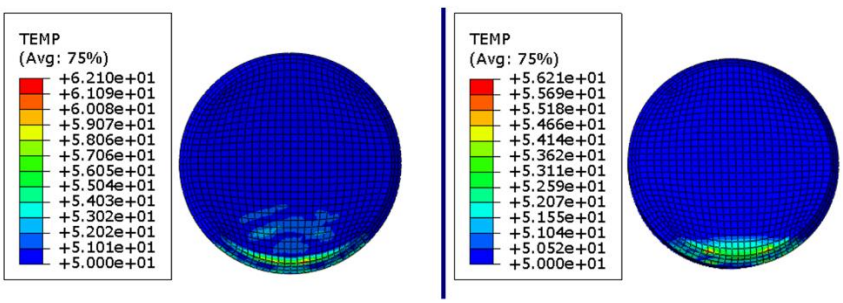


Figure 5. Temperature rise in ductile (left) and brittle (right) cases

The wear flat location for the both ductile and brittle cases are presented in Figure 4. As expected, the magnitude of the wear is higher for the ductile case.

Generally ductile cutting regime (left) exhibits a broader and more stable damaged/shear zone beneath the cutter, leading to sustained contact and higher cumulative frictional work. Consequently, the predicted interface temperature rise is higher (Tmax 62°C vs 56°C) and the Archard wear depth is amplified (0.337 vs 0.096). In the brittle regime (right), chip formation is dominated by localized fracture and intermittent contact, resulting in reduced cumulative sliding/pressure integral and lower predicted wear.

Under deep geothermal drilling conditions, rock cutting occurs under elevated confining pressure and high in-situ temperature, further augmented by the frictional heating generated at the PDC–rock interface. Under these thermomechanical conditions, the prevailing rock failure mechanism tends to transition toward ductile behavior, in which the dominant effect on the PDC cutters is an acceleration of wear processes rather than fatigue failure due to the cutting force fluctuations.

5 DISCUSSION

At fixed operating conditions (RPM = 100, DOC = 1 mm), the simulations reveal two distinct cutting regimes. Ductile cutting is associated with a distributed and persistent contact state, whereas brittle cutting exhibits localized and intermittent contact concentrated near the cutter edge or chamfer. This behavior is consistent with established PDC cutter–rock interaction mechanisms.

Within the Archard wear framework, the local wear evolution is governed by contact pressure and sliding distance:

$$dw \propto (K/H) \cdot p \cdot ds \quad \Leftrightarrow \quad \dot{w} \propto (K/H) \cdot p \cdot v \tag{5}$$

and v the slip velocity. A broader and sustained contact in the ductile regime increases the cumulative integral of p·ds, resulting in a larger and more spatially extended wear response compared to the brittle regime.

The thermal response follows the same dissipation mechanism. The frictional heat generation rate may be expressed using a Moore-type formulation:

$$\dot{q}_f \approx \tau \cdot v \quad \Rightarrow \quad Q_f = \int \tau \cdot v \, dt \tag{6}$$

where τ is the interfacial shear traction

For the present simulations, the ductile regime reaches $Q_f \approx 54.1$ kJ at t = 0.01 s, while the brittle regime reaches $Q_f \approx 24.1$ kJ, corresponding to a ratio of approximately 2.2. This higher cumulative frictional work in the ductile regime consistently explains both the stronger temperature rise beneath the cutter and the amplified Archard wear response under identical RPM and DOC (Figure 6).

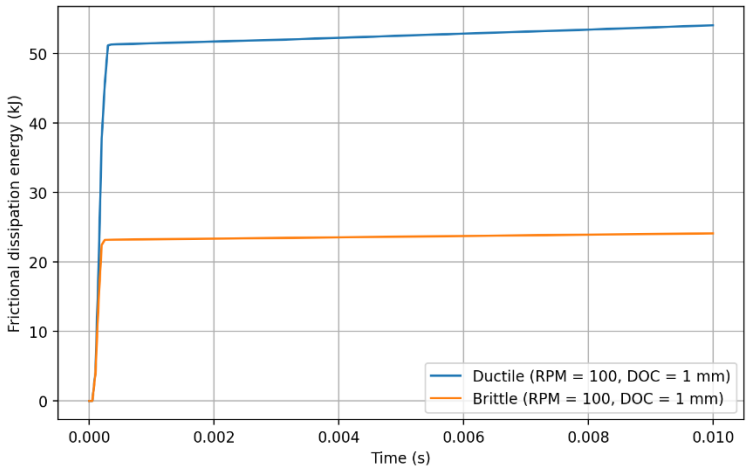


Figure 6. Frictional dissipation for studied cases

For the same cutting time duration, figure 7 shows the wear evolution and the associated temperature rise for both brittle and ductile cases. These magnitudes tend to stabilize when they reach a plateau in the brittle case where for the ductile mode, they increase yet.

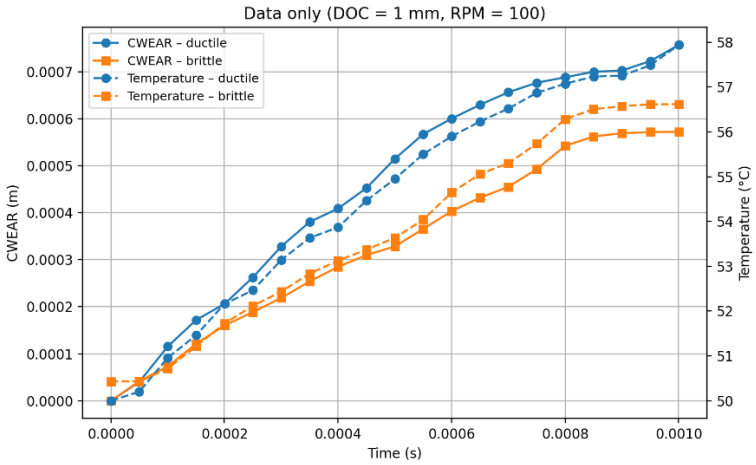


Figure 7. Wear and temperature rise for the studied cases

6 CONCLUSION

Two dominant patterns of PDC cutter damage emerge from the present analysis, governed by the prevailing rock failure mechanism: (i) friction-driven abrasive wear and (ii) cyclic fatigue-controlled damage. Ductile and brittle cutting regimes lead to fundamentally different thermo-mechanical loading conditions at the cutter–rock interface, which in turn control both the magnitude and the spatial distribution of wear.

In ductile formations, continuous cutter–rock contact promotes sustained sliding, elevated frictional dissipation, and significant heat generation at the interface. This results in higher contact temperatures and enhanced abrasive wear, primarily concentrated over an extended wear flat. Such conditions are particularly critical in deep geothermal drilling, where high in-situ temperatures, limited cooling efficiency, and long exposure times amplify thermo-mechanical degradation mechanisms. Under these conditions, accelerated wear may dominate cutter life, directly impacting rate of penetration, bit dull condition, and overall drilling efficiency.

Conversely, in brittle formations, rock removal is governed by intermittent contact and chipping mechanisms, which tend to limit the cumulative frictional work and associated temperature rise. However, the highly cyclic nature of the cutter loading—characterized by repeated stress fluctuations induced by crack initiation and fragmentation—promotes fatigue damage within the cutter material. Even under moderate thermal conditions, this cyclic loading increases the susceptibility of the cutter to microcracking, edge chipping, and catastrophic fracture, ultimately reducing its effective service life. This mechanism is particularly relevant for hard, crystalline rocks commonly encountered in “mean depth” geothermal reservoirs, such as granites and gneisses.

From a deep geothermal drilling perspective, these results highlight the necessity of distinguishing between wear-dominated and fatigue-dominated cutter degradation regimes when designing PDC bits and selecting operational parameters. In ductile formations, strategies aimed at reducing frictional heating—such as improved cooling, optimized cutter exposure, and controlled depth of cut—are essential to mitigate excessive wear. In brittle formations, minimizing cyclic stress amplitudes through optimized cutter geometry, reduced impact loading, and tailored rotational speeds may be more effective in preventing fatigue-induced failure. Overall, a physics-based understanding of the coupled thermo-mechanical processes governing PDC cutter degradation is crucial for extending bit life, improving drilling performance, and reducing operational risks in deep geothermal environments.

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