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A Review of PDC Cutter Wear Enabled By Computer Vision Damage Classification

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Abstract

This study presents an AI-driven approach to PDC cutter damage classification, analyzing wear patterns across large-scale production datasets. Traditional cutter evaluation methods rely on manual inspections, leading to inconsistencies and subjectivity in damage assessments. By implementing an automated classification system, this study provides a structured and repeatable methodology for identifying cutter wear trends, evaluating drilling performance, and assessing the impact of new drill bit designs. The classification system was applied to a dataset of PDC cutter images from production operations, enabling a per-capita analysis of damage mode distributions over time across multiple drilling configurations.

The analysis revealed significant variations in cutter degradation patterns depending on hole size, basin, and run type. Certain configurations exhibited higher occurrences of localized edge wear, such as Chamfer Damage (CD), while others showed progressive wear leading to Worn Cutter (WC) classifications. Per-capita damage mode tracking over time demonstrated that wear mechanisms evolve gradually, reinforcing the need for long-term performance monitoring rather than isolated failure assessments.

A key focus of this study was the impact of new drill bit designs (new design onboarding) on cutter wear performance. The findings indicate that No Damage (ND) classifications increased significantly following the introduction of new designs, suggesting improvements in cutter durability. However, in some applications, Chamfer Damage (CD) and other localized wear mechanisms also increased post-onboarding, implying that while overall cutter longevity improved, edge degradation remained a challenge. These results emphasize the importance of refining bit designs to balance durability with resistance to localized wear effects.

By analyzing per-application trends, the study identified distinct failure mechanisms within different drilling environments. While some applications experienced a direct improvement in ND and WC classifications after new design onboarding, others exhibited more complex transitions, with fluctuating damage trends influenced by formation conditions and operational factors. The variability in damage mode distributions highlights the need for context-specific bit selection strategies rather than assuming uniform performance across all drilling applications.

The study's findings demonstrate the effectiveness of AI-based cutter damage classification in providing structured, objective insights into wear patterns. The results suggest that integrating classification models with operational data such as weight on bit, torque, and formation characteristics could further enhance predictive capabilities. Future work should focus on real-time monitoring applications, allowing for immediate optimization of drilling parameters based on evolving wear trends.

Through continued refinement of AI-driven classification systems, the industry can move towards more data-driven decision-making, improved bit selection, and increased operational efficiency. This study provides a foundation for long-term cutter wear tracking, predictive maintenance, and data-driven bit design optimization, supporting the ongoing evolution of drilling technology and cutter performance assessment.

Introduction

Polycrystalline Diamond Compact (PDC) cutters are critical components in drill bits used for oil and gas exploration. Their superior hardness and wear resistance allow for high-performance drilling in various formations, reducing operational costs and improving efficiency. However, PDC cutters are subjected to extreme downhole conditions, including abrasion, impact loads, thermal cycling, and chemical degradation, leading to progressive deterioration over multiple drilling runs (Liu, Li, and Gao 2024).

The ability to accurately assess cutter damage is essential for optimizing drilling performance, guiding cutter development, and reducing non-productive time. Traditionally, PDC cutter wear and failure analysis have relied on manual inspection, where experts visually assess cutters post-run and classify damage based on industry standards such as the IADC dull grading system (Liu, Li, and Gao 2024). While widely accepted, this approach presents significant limitations in terms of subjectivity, inconsistency, and inefficiency.

Challenges in Traditional Damage Classification

The manual assessment of cutter damage has long been the industry standard, but its effectiveness is hindered by several key challenges:

- Subjectivity and variability. Human-based inspections are inconsistent, as damage classification can vary depending on the experience and judgment of the evaluator (Liu, Li, and Gao 2024).
- Time-intensive process. Manual inspections require significant effort to analyze cutters from multiple bit runs, making large-scale assessments impractical.
- Limited quantitative data. Traditional visual inspections lack precise numerical metrics for damage progression, limiting the ability to correlate cutter performance with drilling parameters.
- Scalability constraints. As drilling operations generate large datasets of worn cutter images, manual processing becomes a bottleneck, preventing efficient utilization of valuable performance data (Ali et al. 2023).

To overcome these limitations, the industry has increasingly turned to computer vision and artificial intelligence-based solutions for automated damage classification.

Role of Computer Vision in Cutter Damage Assessment

Recent advancements in computer vision, deep learning, and high-resolution imaging have enabled the development of automated cutter damage classification systems (Ali et al. 2023). Computer vision technologies utilize machine learning models trained on extensive image datasets to identify and categorize cutter damage with high accuracy and repeatability (Liu, Li, and Gao 2024).

By leveraging convolutional neural networks and image recognition algorithms, these models can distinguish between various failure modes, historically including:

- Wear - Progressive material loss affecting cutter geometry and efficiency.
- Chipping - Formation of micro-fractures and localized material loss.
- Breakage - Severe cutter failure due to impact loading or structural defects.
- Thermal degradation - Loss of diamond integrity due to high-temperature exposure (Liu, Li, and Gao 2024).

The adoption of AI-driven damage assessment offers multiple advantages over traditional inspection methods. AI-based models reduce human bias, enhance repeatability, and automate large-scale assessments, leading to more efficient and consistent evaluations. These models also integrate seamlessly with digital workflows, enabling real-time data collection and analysis, which improves decision-making for bit selection and cutter design. Additionally, AI facilitates early detection of failure trends, supporting predictive maintenance strategies and reducing operational risk (Liu, Li, and Gao 2024). Given the growing importance of data-driven decision-making in drilling operations, the integration of computer vision into cutter evaluation presents a transformative opportunity for optimizing bit performance and reducing operational uncertainties.

Background & Literature Review

PDC Cutters and Damage Mechanisms

Polycrystalline Diamond Compact (PDC) cutters are essential components of drill bits used in oil and gas drilling due to their exceptional hardness, wear resistance, and thermal stability. They consist of a sintered layer of synthetic diamond bonded to a tungsten carbide substrate, providing high durability under extreme drilling conditions (Ashok et al., 2020). This combination of materials allows for efficient drilling in abrasive formations while maintaining cutter integrity.

Despite their robustness, PDC cutters are susceptible to several failure mechanisms that can significantly impact drilling efficiency and tool life. The severity and distribution of these damage types dictate their impact on drilling performance. Excessive wear leads to a gradual loss of efficiency, while chipping and breakage can cause immediate performance degradation, requiring premature bit replacement and increasing operational costs (Gjertsen et al., 2023).

Traditional Cutter Inspection and Classification Methods

For decades, the oil and gas industry has relied on manual visual inspections to assess PDC cutter damage. The IADC dull grading system remains the most widely used classification method, in which inspectors evaluate cutter wear, breakage, and other damage characteristics using a standardized rating system (Ashok et al., 2020). While this system provides a structured framework for drill bit condition assessment, it has several limitations:

- Subjectivity and inconsistency: The grading process depends on human judgment, leading to potential variability in results.
- Time-intensive process: Manually inspecting each cutter is labor-intensive and inefficient for large-scale operations.
- Limited quantitative accuracy: The dull grading system relies on qualitative assessments rather than precise numerical measurements of wear and damage.

To address these shortcomings, some companies have introduced metrology-based inspection techniques, including laser scanning and profilometry, which provide precise measurements of wear volume and surface roughness (Gjertsen et al., 2023). These methods improve accuracy and repeatability compared to manual inspections, though they remain resource-intensive and require specialized equipment.

Advances in Computer Vision for Cutter Damage Classification

Recent advancements in computer vision and machine learning have introduced scalable and objective alternatives to manual inspection. Studies have demonstrated that convolutional neural networks (CNNs) can classify cutter damage with high accuracy using high-resolution images, reducing human bias and improving scalability (Al-Hameedi et al., 2023).

Key developments in AI-driven cutter damage classification include:

- Automated damage detection and segmentation: Deep learning models can isolate damaged areas from images, reducing the need for human intervention.
- Enhanced classification accuracy: CNNs trained on labeled datasets can differentiate between wear, chipping, and breakage with improved precision.
- Integration with real-time monitoring: Some systems incorporate real-time damage tracking, allowing for predictive maintenance and operational adjustments (Gjertsen et al., 2023).

These innovations significantly improve upon traditional methods, offering faster, more reliable, and scalable cutter condition assessments.

Brief Literature Review on AI-Based Cutter Classification

The integration of artificial intelligence (AI) and computer vision into PDC cutter damage classification has gained significant traction in recent years. Traditional inspection methods, such as manual dull grading and metrology-based assessments, have been widely used in the industry. However, the emergence of AI-driven approaches has improved consistency, accuracy, and scalability in cutter evaluation. Several recent studies have explored the implementation of deep learning techniques, particularly convolutional neural networks (CNNs), in automating cutter damage classification.

One of the key advancements in AI-based classification is the use of deep learning models trained on high-resolution images of worn cutters. These models leverage CNN architectures to extract features from cutter images and classify damage types, such as wear, chipping, breakage, and thermal degradation (Al-Hameedi et al., 2023). Unlike traditional methods that rely on qualitative observations, AI-based classification provides quantitative metrics for assessing damage severity.

The study by Ashok et al. (2020) demonstrated the application of image analysis and deep learning in automating drill bit damage classification. Their approach incorporated a fully connected neural network, which processed cutter images to predict damage categories with high accuracy. The findings highlighted a significant reduction in grading inconsistencies compared to manual inspections.

Gjertsen et al. (2023) introduced an enhanced AI model incorporating photometric classification techniques for cutter damage evaluation. This method allowed for automated dull grading using image-based quantification, reducing human subjectivity and providing a repeatable approach to damage classification. Their work emphasized the integration of AI into existing dull grading systems, improving reliability across different cutter types.

Wei, Liu, and Gao (2022) focused on the effect of cutter shape on impact resistance using AI-driven image analysis. Their research underscored how data-driven modeling enhances the understanding of structural weaknesses in PDC cutters, paving the way for AI-assisted cutter design improvements.

The literature overwhelmingly supports the superiority of AI-based classification over traditional manual inspection techniques. The key advantages of AI-driven approaches include:

- Higher classification accuracy: Deep learning models outperform human evaluators in distinguishing between damage types.
- Reduced variability: Automated classification minimizes inconsistencies introduced by subjective assessments.
- Scalability: AI-based systems can process thousands of cutter images efficiently, making them suitable for large-scale operations.
- Integration with real-time monitoring: AI models enable continuous tracking of cutter conditions, facilitating predictive maintenance strategies (Gjertsen et al., 2023).

Despite these advantages, AI-based cutter classification is not without challenges. The primary concerns include dataset availability, model training complexity, and computational resource requirements (Ashok et al., 2020). Furthermore, AI models require robust validation against field data to ensure reliability across various drilling conditions.

Methodology

The development of an AI-based cutter damage classification system was based on production-level data, ensuring real-world applicability. Data collection was fully integrated into existing repair floor workflows, eliminating the need for modifications to established repair processes. Additionally, the imaging and data collection process does not meaningfully impact total repair time on any given day, allowing for efficient cutter inspection and classification without disrupting operations.

Data Collection & Preprocessing

All cutter images were obtained directly from production environments, capturing post-run cutter conditions as part of routine documentation processes. The imaging process was designed to maintain consistency by capturing each cutter at a fixed 45-degree angle. This standardized approach ensured that key cutter features—including the diamond table, chamfer, barrel, and surrounding cutter pocket—were consistently represented across all samples. Close-range imaging was used to provide high-resolution detail of cutter wear, fractures, and surface characteristics. Each image was linked to relevant metadata, including bit run duration, operational drilling parameters such as weight on bit and rotational speed, and unique cutter identifiers, allowing for enhanced contextualization of observed damage.

To enable supervised learning, a standardized multi-class damage classification system was applied to all images. Given that cutters often exhibit multiple failure modes simultaneously, a multi-label classification approach was adopted. Each image was assigned at least one of the following eleven damage modes, visually showcased in Figure 1:

- **Broken Cutter (BC):** Major damage extending through the diamond table, exposing the carbide substrate.
- **Chipped Cutter (CC):** Angular flaking along the barrel of the cutter, specifically confined to the barrel.
- **Chamfer Damage (CD):** Minor wear, not extending into the face of the cutter, isolated to the chamfer and/or barrel.
- **Complete Spall (CS):** Loss of the entire cutter face, exposing portions of the interface/carbide, but with some PCD remaining on the interface. No virgin (planar) diamond table remaining.
- **Face Crack (FC):** Cracking in the face of the cutter. Often very fine cracks, difficult to identify with the naked eye.
- **Lost Cutter (LC):** Clean pocket with no carbide nor PCD remaining.
- **Indeterminate Damage (LID):** Cutter face / PCD is completely gone, leaving only portions of the carbide remaining in the pocket.
- **No Damage (ND):** Cutters with no visible signs of degradation.
- **Spalled Cutter (SC):** Flaking of the cutter face that does not extend to the carbide, with some of the cutter face remaining intact.
- **Tangential Break (TB):** Damage extending through the diamond table with a fracture plane perpendicular to the cutter face and extending into at least a portion of the carbide, but with some cutter face remaining intact.
- **Worn Cutter (WC):** Smooth wear scar with a well-defined, linear cutting edge extending into the face of the cutter. May occur with or without heat checking and/or spalling.

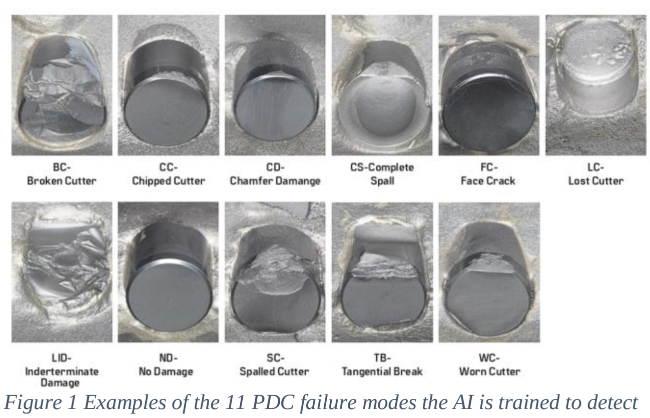

Figure 1 Examples of the 11 PDC failure modes the AI is trained to detect

Because cutters often exhibit multiple damage types simultaneously, a multi-label classification approach was used to train models to detect co-existing failure modes. For example, a cutter displaying **chamfer damage, face cracks, and spalling** was labeled accordingly, ensuring the model learned complex and overlapping damage patterns rather than a single dominant classification. To enhance model robustness across varying imaging conditions, data augmentation techniques were implemented. Rotational transformations and flipping were used to account for cutter orientation differences, while brightness and contrast normalization ensured consistency across different lighting environments. Additionally, noise injection was applied to simulate minor imaging inconsistencies, reinforcing the model's ability to generalize effectively across diverse real-world conditions.

Model Development Infrastructure

The model was developed and deployed using **Azure** for machine learning workflows and **Snowflake** for managing large-scale production data. Azure served as the primary platform for model development, enabling the training, evaluation, and deployment of deep learning-based classification models. The cloud-based infrastructure facilitated scalable computing, allowing for rapid iteration of model improvements while maintaining accessibility across different teams. Model training leveraged GPU-accelerated environments within Azure to process the high-volume image dataset efficiently.

Snowflake acted as the centralized data management system, ensuring structured storage and retrieval of both cutter images and their associated metadata. The integration of Snowflake provided a high-performance solution for managing continuously growing datasets, allowing for real-time querying and retrieval of labeled images for ongoing model refinement. By linking Snowflake's data warehouse capabilities with Azure's machine learning pipeline, a seamless feedback loop was created where new production images could be incorporated into model updates without requiring extensive manual reprocessing.

The combination of Azure and Snowflake not only provided the computational power necessary for model development but also ensured that the classification system remained scalable, adaptable, and integrated with existing production workflows. This infrastructure allowed for continuous refinement of the classification model, ensuring that performance improvements were informed by newly acquired production data without disrupting operational efficiency.

Model Training and Validation

The model was trained using a large dataset of production-level cutter images, all of which were labeled by a cutter specialist with expertise in PDC wear and failure classification. The dataset consisted of 4,000 images, each assigned one or more of the eleven predefined damage modes. To facilitate model development, the dataset was divided into two primary groups: a model training set, which was used to refine and develop the classification model, and a model validation set, which was used to assess performance and generalization. This division allowed for continuous monitoring of classification accuracy and model reliability.

Model validation is an ongoing process, with both datasets being regularly updated to incorporate newly acquired production images. This ensures that the model remains aligned with evolving wear patterns and cutter conditions observed in the field. By continuously integrating new data, the model can improve its generalization across different drilling environments, incorporate emerging damage modes, and refine classification accuracy through iterative updates. By maintaining a dynamic and continuously evolving dataset, the model development process ensures sustained improvements in classification accuracy and operational reliability.

Data Generation from the AI-Based Classification Process

The AI-based cutter damage classification system has enabled automated large-scale analysis of cutter wear and failure modes, generating structured insights from production-level images. By processing over 40,000 classified cutter instances, the system has provided a comprehensive breakdown of damage mode distributions, relationships between cutter degradation and operational parameters, and patterns in model inference scores. The results from this classification process not only streamline manual inspection efforts but also enhance the consistency and efficiency of damage assessments.

Overview of Classified Cutter Data

Analysis of the classified dataset reveals that the most frequently observed failure types were Worn Cutter (WC), Chamfer Damage (CD), and Chipped Cutter (CC), which account for a significant portion of labeled cutters. These damage types represent progressive wear mechanisms, commonly associated with prolonged bit runs and sustained cutter degradation. The dataset also indicates that more severe failure types, such as Lost Cutter (LC) and Complete Spall (CS), occur less frequently but are critical indicators of extreme cutter failure. Their presence in the dataset suggests that these damage types often correlate with high cumulative cutter exposure and aggressive drilling conditions.

The AI classification system's ability to assign multiple damage labels to a single cutter has allowed for further insights into coexisting damage mechanisms. Many cutters classified with spalling (SC) or tangential breaks (TB) also exhibited signs of Face Cracking (FC) or chipping (CC), indicating that these failure types frequently develop in tandem. The model's ability to recognize these patterns across a large dataset provides a clearer picture of how cutter wear progresses under various drilling conditions. The distribution of primary and secondary damage classifications is visualized in Figure 2 and 3.

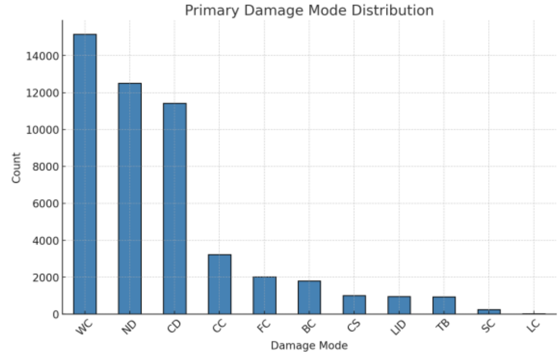

Figure 2 Frequency of different failure types across the dataset

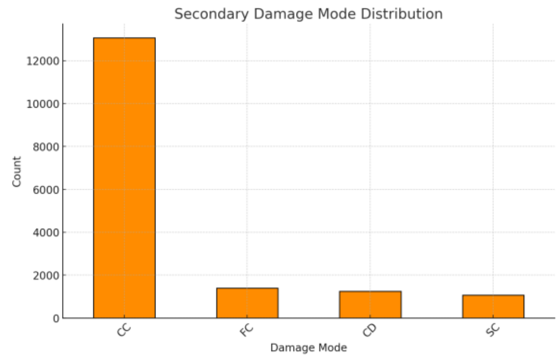

Figure 3 Frequency of secondary failure present in dataset

AI Model Inference Trends

Analysis of the AI model's inference scores provides further insights into classification confidence across different damage modes. High-confidence classifications were observed for No Damage (ND) and Worn Cutter (WC), where the model consistently assigned high inference scores with minimal ambiguity. In contrast, Face Crack (FC) exhibited the lowest inference confidence, suggesting that fine surface cracks are inherently more difficult for the model to distinguish from other minor wear patterns. The distribution of inference scores for each damage mode is shown in Figure 4, where score variability highlights differences in model certainty.

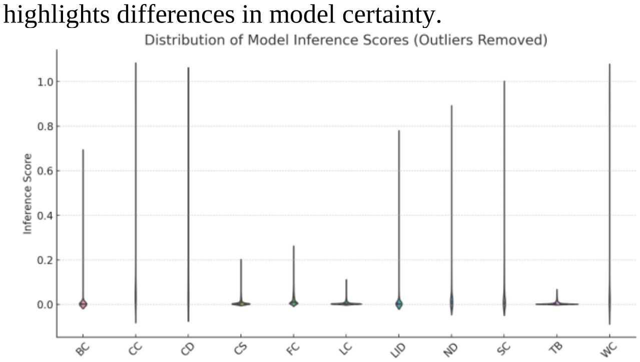

Figure 4 Violin chart showcasing model performance via inference scores

Further refinement of these classification trends can be seen by examining the optimal threshold values at which inference scores achieve maximum F1-scores. Lower threshold values for Face Crack (FC) (~0.035) indicate that the model classifies these instances with low confidence, meaning that predictions for this category often require lower inference scores for acceptance. In contrast, higher threshold values for Chamfer Damage (CD) (~0.53) suggest a higher classification barrier, where the model requires strong confidence before assigning this label. These threshold values, visualized in Figure 5, provide a clearer understanding of the model's classification boundaries and where further refinement is needed.

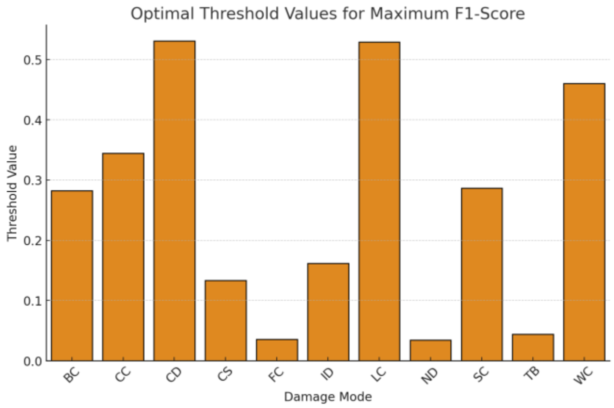

Figure 5 Acceptable values for which a failure mode can be determined to be present

Misclassification Patterns & Model Performance

The confusion matrix analysis provides further insight into how frequently the model misclassifies damage modes and where errors are most prevalent. The results indicate that Face Crack (FC) is the most commonly misclassified category, often being incorrectly predicted as Spalled Cutter (SC) or Worn Cutter (WC). This suggests that the model struggles to distinguish fine cracks from broader wear patterns, potentially due to similarities in visual texture. Similarly, Chamfer Damage (CD) and Worn Cutter (WC) exhibit overlap, leading to occasional confusion in cases where edge degradation transitions into full-face wear. Conversely, severe failure types such as Lost Cutter (LC) and Complete Spall (CS) were classified with high accuracy, as their distinct structural features make them easier for the model to identify. The complete confusion matrix is displayed in Figure 6, which illustrates the frequency of correct and incorrect classifications across damage modes.

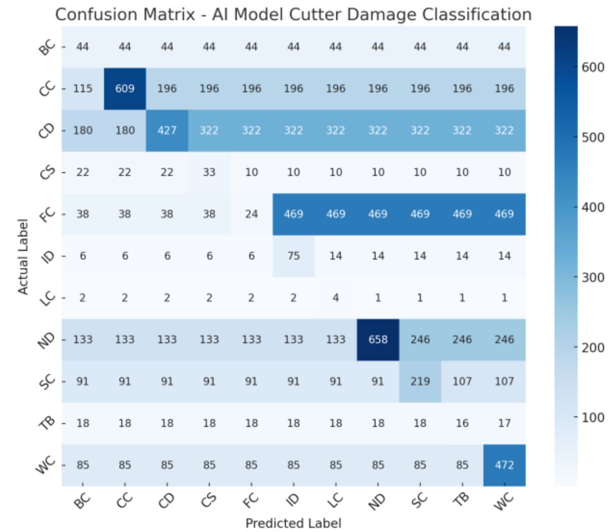

Figure 6 Confusion Matrix detailing the nature of misclassification trends

Performance metrics further support these findings, with Chipped Cutter (CC) and Complete Spall (CS) achieving the highest F1-scores, indicating strong classification reliability. In contrast, Face Crack (FC) has the lowest F1-score, reinforcing its tendency for misclassification. The overall precision and recall values for each damage mode, visualized in Figure 7, demonstrate which categories are well-defined and where classification errors are most common.

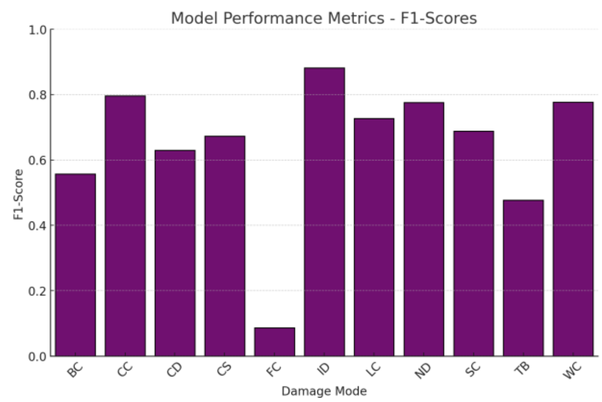

Figure 7 The F1 scores for each failure mode at the optimal threshold

Discussions

This section will focus on applying the learnings and outputs of the AI PDC cutter failure mode detection system. Both large-scale aggregated information and application specific information will be reviewed.

Variability in Cutter Damage Distributions Across Drilling Configurations

The analysis of damage mode distributions across hole size, basin, and run type reveals that cutter degradation is not uniform across all drilling conditions. While the aggregate dataset provides a general overview of how frequently each damage mode occurs, certain drilling configurations exhibit notable deviations from these trends. By focusing on the most variant combinations—excluding any configurations where Run Type = SURF—distinct patterns in cutter failure mechanisms become evident.

The heatmap, Figure 8 of significant deviations highlights configurations where damage classifications differ the most from expected distributions. For example, cutters used in certain CVLT (curve/lateral transition) runs within the DELB (Delaware Basin) show a lower-than-expected occurrence of Chamfer Damage (CD), while exhibiting a higher frequency of Worn Cutter (WC) classifications. This suggests that in these specific runs, cutter edge degradation is less prominent, whereas gradual wear accumulation dominates the failure mechanism. Similarly, LATL (lateral) runs in GRAN (Granite Wash) exhibit lower-than-average occurrences of Chipped Cutter (CC), but higher-than-expected rates of Tangential Breaks (TB), indicating that these runs may involve conditions that promote structural failure over progressive wear.

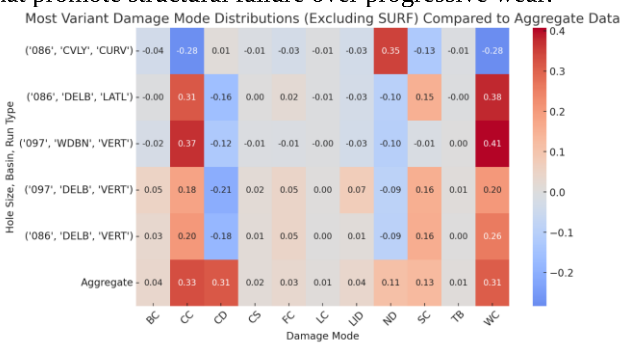

Figure 8 Heatmap showcasing deviation-from-normal monitoring

Further reinforcing these observations, the bar chart in Figure 9 comparing the most variant configurations to the aggregate dataset demonstrates that while Worn Cutter (WC) is the most frequent damage type across all configurations, its relative prevalence shifts depending on drilling conditions. In some cases, such as certain CVLT and LATL runs, Worn Cutter (WC) classifications increase by more than 9% relative to the aggregate dataset, whereas in others, its occurrence declines, with failure modes such as Spalled Cutter (SC) and Face Crack (FC) becoming more prominent.

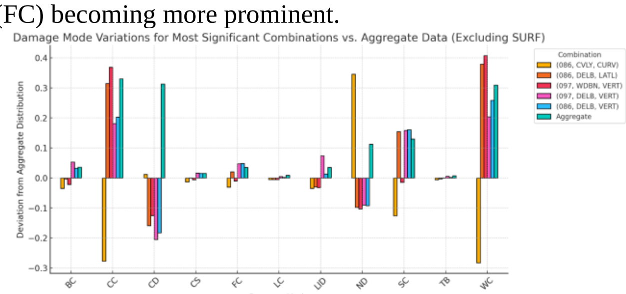

Figure 9 Secondary aggregated deviation monitoring chart

These findings suggest that run type and basin conditions play a significant role in determining how cutters degrade over time. The fact that different drilling configurations experience unique failure modes at different rates implies that damage mode distributions are not purely a function of bit run duration or general cutter exposure, but rather are influenced by localized mechanical and geological factors. This insight highlights the importance of classifying cutter wear using context-specific data, rather than relying solely on aggregate distributions when evaluating bit performance.

Evolution of Damage Mode Distributions Over Time

The 6-week moving average analysis in Figure 10 demonstrates that damage mode distributions are not static but fluctuate in response to changing operational conditions and bit selection. Across multiple applications, distinct cycles of cutter degradation emerge, with some damage modes increasing as others decline. Worn Cutter (WC) and No Damage (ND) generally trend together, with higher ND percentages often preceding higher WC classifications, suggesting that cutters experience a longer wear phase before transitioning to measurable degradation. Chamfer Damage (CD) exhibits significant variability, increasing in some applications while decreasing in others, implying that edge rounding and early cutter degradation are highly dependent on specific drilling conditions. Chipped Cutter (CC) occurrences decline in applications where ND is increasing, reinforcing that higher durability in newer bit designs reduces early-stage cutter degradation.

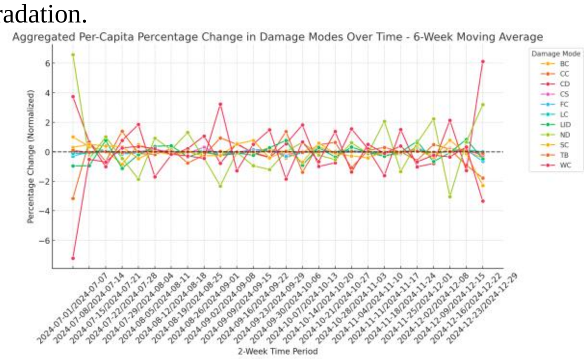

Figure 10 Changes in the relative distribution of different failure modes across the dataset

Application-Specific Damage Mode Insights

The classification trends observed across the top five applications illustrate the complex interactions between cutter wear patterns, drilling conditions, and bit design evolution. While some applications exhibit clear performance improvements following new design onboardings, others show more gradual transitions in wear behaviors, highlighting formation-specific influences. A detailed discussion of each application's damage mode evolution follows, outlining the most significant findings and their implications.

The Delaware Basin, Shallow Intermediate Run (122_DELB_SINT) application exhibits one of the strongest trends in No Damage (ND) increases, particularly following the onboarding of a new design in early July. ND increased by 19.6 percent, while Chamfer Damage (CD) also increased by 6.8 percent. This combination suggests that while cutters were experiencing more controlled wear at the chamfer and barrel level, they were lasting longer before developing significant structural failures. A notable trend in this application is the decline in Worn Cutter (WC) classifications by 12.3 percent immediately after the new design was introduced. This could indicate that cutters were either maintaining sharpness longer or transitioning into different failure modes. The corresponding increase in CD suggests that edge wear may have increased before full-face degradation became significant. Additionally, Chipped Cutter (CC) occurrences declined in mid-July, reinforcing that cutter edge durability improved following the introduction of the new bit design. The absence of any major spikes in extreme failure classifications such as Lost Cutter (LC), Broken Cutter (BC), or Complete Spall (CS) suggests that this new design effectively mitigated catastrophic cutter failures while still allowing for a manageable progression of wear.

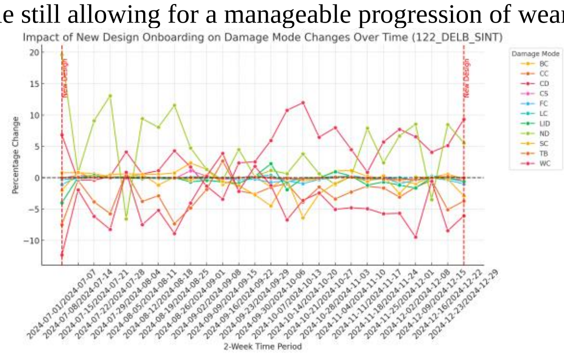

Figure 11 Note that CD seems to trend opposite ND in this application

The Delaware Basin, Lateral Run (061_DELB_LATL) application demonstrates a 9.65 percent increase in No Damage (ND) classifications in mid-July, following the introduction of a new bit design. However, unlike in 122_DELB_SINT, Worn Cutter (WC) decreased by 7.64 percent, suggesting that while the new bit design extended cutter longevity in some cases, it may have resulted in faster wear progression in others. The increase in Chamfer Damage (CD) by 7.84 percent also aligns with this trend, indicating that cutters were maintaining integrity longer but exhibiting more pronounced edge degradation. This may be linked to higher lateral loading in lateral applications, which could be accelerating chamfer wear before face wear becomes measurable. Unlike in 122_DELB_SINT, this application does show some oscillations in Chipped Cutter (CC) classifications, with alternating increases and decreases over the observed time period. This suggests that CC in this application may be more sensitive to formation changes or bit stabilization issues rather than simply responding to new cutter designs.

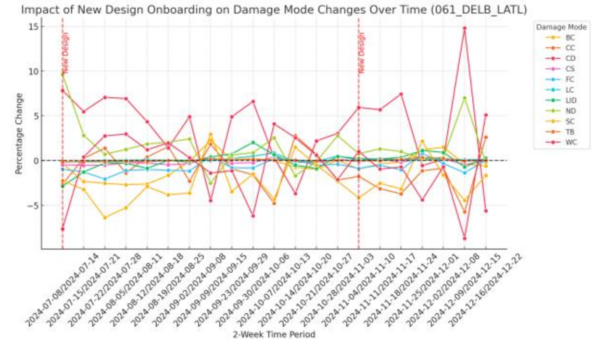

Figure 12 The increasing presence of CD helped make the determination to deploy a new bit design

The Midland Basin, Lateral Run (077_MIDB_LATL) application presents a unique contrast to the two Delaware Basin applications. Unlike in 122_DELB_SINT and 061_DELB_LATL, the onboarding of a new bit design in late July did not result in an immediate increase in ND classifications. Instead, ND decreased by 10.1 percent, while WC increased by 1.4 percent. This suggests that while the new design may have helped stabilize wear behavior, it did not immediately improve overall cutter longevity. One possible explanation is that cutter loading in this application is more aggressive, leading to a higher rate of WC classifications as wear accumulates faster. Interestingly, Chamfer Damage (CD) remained relatively stable, while Chipped Cutter (CC) exhibited a gradual decline. This could indicate that while cutters were lasting longer in terms of structural integrity, they were still accumulating enough wear to enter the WC classification earlier than in other applications.

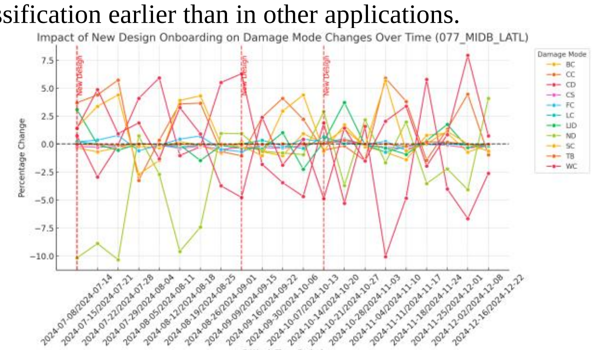

Figure 13 This application presents cyclic challenges of CD and WC

The Delaware Basin, Vertical Run (086_DELB_VERT) application demonstrates one of the most stable cutter wear trends among all applications. No Damage (ND) and Worn Cutter (WC) classifications track closely together, suggesting that bit performance in vertical runs is generally more predictable compared to lateral and intermediate sections. The introduction of a new bit design did not result in major swings in damage mode distributions, but instead maintained a gradual increase in ND and WC classifications over time. This indicates that bit stability improvements resulted in more predictable cutter wear rather than immediate performance jumps. The absence of significant fluctuations in extreme failure modes such as Lost Cutter (LC) and Broken Cutter (BC) further supports the idea that vertical drilling configurations may benefit from a more controlled wear environment.

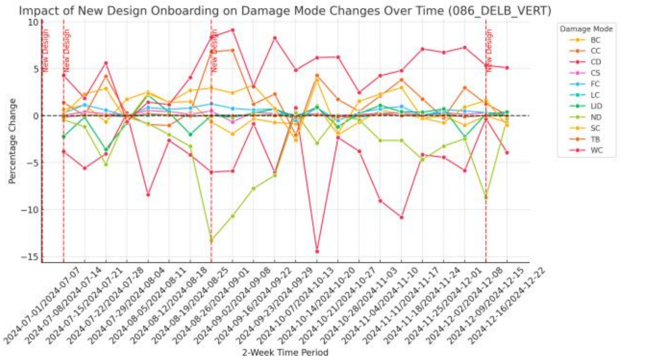

Figure 14 The onboarding of a new design was able to help combat the presences of CC

The Midland Basin, Directional Intermediate (122_MIDB_DINT) application exhibits the highest variability in Chamfer Damage (CD) classifications, which suggests that lateral forces and drilling angle adjustments play a major role in cutter degradation patterns. Unlike in other applications, CD fluctuations in this configuration were not necessarily tied to ND changes, implying that edge wear dynamics in intermediate sections may be more complex. Additionally, Chipped Cutter (CC) classifications showed greater variability, reinforcing that bit stability in intermediate runs is less predictable than in vertical or lateral sections. The unpredictability of CD and CC trends suggests that intermediate runs may be more sensitive to formation changes or drilling parameter fluctuations than other configurations.

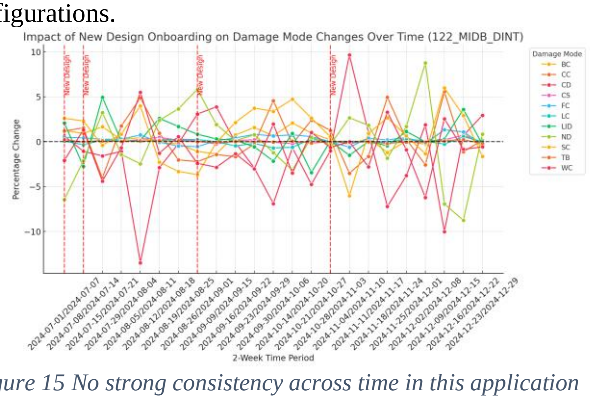

Figure 15 No strong consistency across time in this application

Each of these application-specific discussions illustrates how cutter wear behaviors vary significantly based on drilling environment, bit design updates, and formation influences. While new design onboardings often lead to improvements in No Damage (ND) and Worn Cutter (WC) classifications, they do not always translate into immediate benefits across all applications. The variability in Chamfer Damage (CD) and Chipped Cutter (CC) classifications suggests that formation interactions and operational factors continue to play a crucial role in cutter longevity and performance. These observations further emphasize the importance of continuously monitoring cutter wear trends and refining classification methodologies to improve bit performance tracking and optimize cutter selection for different drilling conditions.

Conclusions

This study has presented a comprehensive analysis of PDC cutter damage classification using AI-driven methodologies, focusing on the automated identification of damage modes, the variability of cutter degradation across different drilling conditions, and the influence of new drill bit designs on cutter performance. A machine-learning-based classification system was applied to a large dataset of production-level cutter images, generating structured damage mode distributions over time. The results were analyzed using per-capita normalized damage mode trends, drilling configuration variability, and the onboarding of new bit designs, referred to as new design onboarding. These analyses have provided critical insights into cutter wear evolution, the impact of design changes, and opportunities for improving bit performance tracking.

A key outcome of this study is the observation that cutter degradation patterns vary significantly across hole sizes, basins, and run types, with certain configurations experiencing higher occurrences of specific damage modes. Some runs exhibited higher rates of Chamfer Damage (CD), whereas others experienced more gradual transitions into Worn Cutter (WC) classifications. The per-capita analysis of damage mode distributions over time demonstrated that wear transitions occur gradually rather than as isolated events, reinforcing the importance of tracking damage evolution rather than focusing solely on final failure classifications.

The study also highlighted the strong correlation between new design onboardings and positive trends in cutter performance. Across multiple applications, the introduction of a new bit design often coincided with increases in No Damage (ND) classifications and reductions in Chipped Cutter (CC) occurrences, suggesting that bit selection plays a direct role in cutter longevity. However, in some cases, Chamfer Damage (CD) increased following the introduction of a new design, indicating that while overall cutter durability improved, edge degradation remained an area of concern. These findings suggest that while new bit designs contribute to longer-lasting cutters, they may also introduce different wear characteristics that require further refinement.

The key takeaways from this study include:

- AI-driven cutter classification provides an effective, scalable method for identifying and tracking cutter degradation over time.
- Damage mode distributions vary significantly across drilling configurations, reinforcing the need for context-specific wear analysis.
- The per-capita tracking of damage trends over time highlights gradual transitions in wear progression

rather than abrupt shifts in failure modes.

- New design onboardings generally lead to improved cutter performance, but the effects are not uniform across all applications.
- Chamfer Damage (CD) increases post-new design onboarding suggest a tradeoff between extended cutter life and localized edge degradation.

Moving forward, future work should focus on incorporating additional drilling parameters such as weight on bit, torque, and formation characteristics into damage mode analysis. By integrating drilling conditions directly into the classification models, it may be possible to improve the predictability of cutter degradation trends. Additionally, expanding AI-based classification to real-time monitoring applications could enable immediate adjustments in drilling strategies to optimize bit life and performance. Further refinements in bit design tracking methodologies would also be beneficial, allowing for more precise correlations between cutter material improvements and field performance outcomes.

Through continued advancements in AI-driven damage classification and deeper integration of drilling data, the industry can move towards more data-driven decision-making, improved bit selection, and ultimately, greater efficiency in cutter utilization.

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