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A Review on Tool Life in Coal Measures Rocks

Satya Prakash

Department of Mechanical Engineering, Alliance College of Engineering and Design, Alliance University, Bengaluru – 562106, Karnataka, India; prakash86satya@gmail.com

Abstract

Tungsten carbide inserts in rock drill bits are predominantly used in drilling rocks, particularly in mining industries. The research studies performed on drill bits have been limited to several factors such as collecting failure data of bit components from the field, conducting wear tests considering rock properties, and introducing new coated insert materials. The role of Artificial Intelligence (AI) and Machine Learning (ML) for the betterment of tool wear with real-time data is limited. The present study has offered an evaluative perspective of an essential industrial issue. In this review, a concept map presents a visual organization and representation of knowledge obtained during the study. Utilizing the propositions from the concept map, a brief review of the integrated concepts of researchers relating drill bits, failure data, numerical and statistical models, wear analysis, reliability assessment, and prerequisites in developing new materials have been discussed in the backdrop of the present study.

Keywords: *Coatings, Reliability, Rock Properties, Tool Life, Tool Wear*

1.0 Introduction

During drilling, the main challenge remains to achieve the designed life of the drill bits which depends on geo-mining conditions, bit conditions and operational factors. Bourgoyne *et al.*, listed different geo-mining and bit conditions, such as rock strength, depth of drilling, bit diameter, extent of bit wear, etc., that affect drilling performance[1]. They have developed multiple regression models to realise the optimal performance of drilling operations and bits.

Wijk reported the impact of bit weight, rotary speed, tooth wear and drilling fluid used for flushing the drill holes on the performance of drilling[2]. A numerical model is presented in his study to optimise drilling performance. The penetration rate is the bit performance index, which plays an essential role in drilling operations and predicts the impact of rock formations' strength on drill bits[3]. The Rate of Penetration (ROP) is altered by variables like Weight on Bit (WOB), rotational speed, bit wear, rock formations and flushing media pressure[3-5]. ROP is predicted through models developed by Bourgoyne *et al.*, and Bataee *et al.* The correct prediction of penetration rate in drilling always improves the drilling performance and helps in selecting suitable drill bits. Some studies were performed in the field and laboratories to determine different factors that affect the penetration rate and bit wear together. The reported factors are bit type, WOB, rotary speed, drilling fluid properties, drill fluid hydraulics, formation properties, etc[5,6]. Applicable models of Polycrystalline Diamond Compact (PDC) and tri-cone roller bits are available in the literature, such as the Bourgoyne and Young models, the Bingham model, and the modified Warren model[6] to predict ROP. Praillet and Alber discussed the impact of petrographic (mineralogy, average grain size of minerals, shape of grains, grain cementing) properties and physico-mechanical rock properties (Unconfined Compressive Strength (UCS), Tensile Strength, Young's Modulus, Shear Strength, and fracture toughness of rock) on drill bit wear[7,8]. The studies

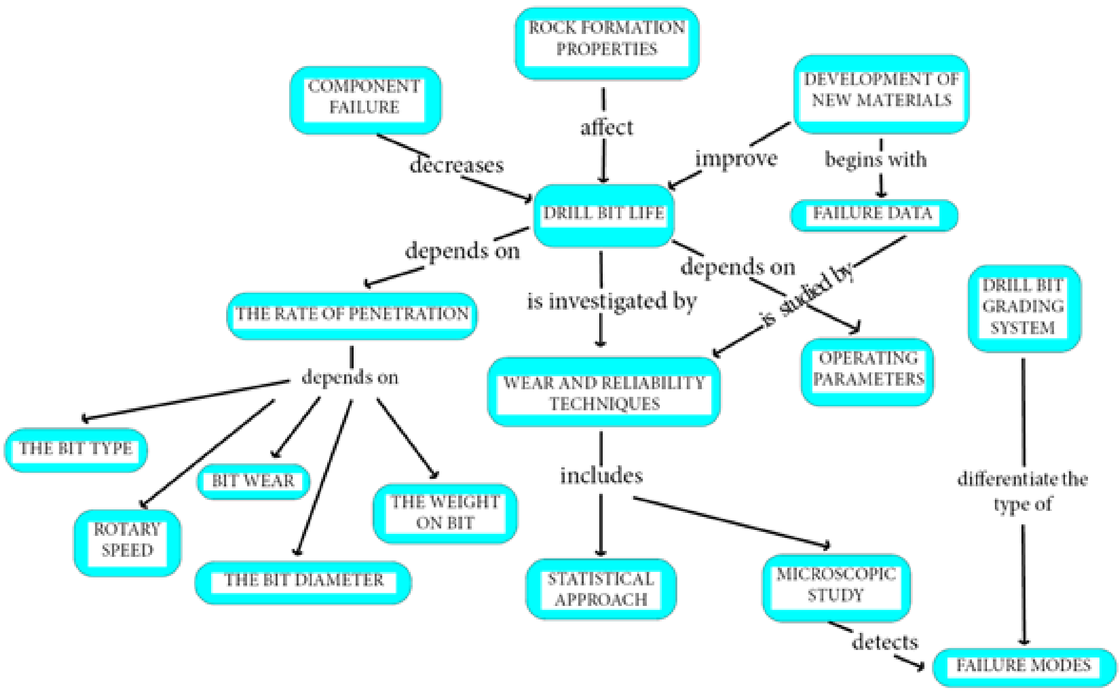

Figure 1. A concept map depicting the interconnection between the keywords.

concluded that the drill bit performance is related to drilling parameters, bit life and ROP.

Kahraman developed an ROP model using regression analysis of Down-The-Hole (DTH) drilling performance in surface mines[9]. The author explored the effects of operational parameters and the geotechnical characteristics of rock mass on drill performance and bit life. Altindag stated that the penetration rate is closely related to the fragile nature of the rock[10]. Bilgin *et al.,* correlated the results of the net penetration rate of rotary drilling with rock properties and discovered that the UCS, point load strength, and Cerchar Hardness exhibit strong correlations with bit wear rate. Saeidi *et al.,* developed a penetration rate model for rotary bits using Principal Component Analysis (PCA) considering WOB, rotational speed, bit diameter and UCS of rocks. The authors observed that the UCS of rock, WOB and bit rotational speeds are the convincing parameters that affect both ROP and bit wear. Alireza *et al.,* succeeded in developing Specific Rock Mass Drillability (SRMD) index model to forecast the penetration rate of rotary drills[13]. The authors established a relation of SRMD with different rock properties and established that UCS and rock hardness values are the compelling factors affecting drilling performance and drill bit wear.

Rock properties, rock joint features, weathering of rock and the presence of water in rock strata have been identified as prime geological factors that affect bit life and drilling performance[14]. Researchers have concluded that geological features cause expensive and severe wear in bits[15,16]. Quartz content in rock was considered by Moradizadeh *et al.,* to investigate the rate of wear on drill bits[17]. Investigations showed that the drill bit lifetime per meter of drill hole drilled by a bit (m/bit) decreases with an increase in equivalent quartz content. Thuro and Plinninger investigated quartz content values of sandstone and granite rock samples of different locations and developed an interrelationship between Equivalent Quartz Content (EQC) values and the bit lifetime of button bits in Down-The-Hole (DTH) drilling[18,19]. The results revealed that the drill bit life significantly rests on EQC values. The wear of inserts due to rock abrasivity in bits reduces the level of performance of the drilling operation[20,21]. The Rock Abrasivity Index (RAI) was derived by Plinniger by multiplying the EQC values with the Unconfined Compressive Strength (UCS) of the rock[38]. RAI showed a good correlation with button bit wear rate drilling in hard rock. A correlation between RAI and CAI was obtained by Plinniger to derive geotechnical wear indices which are now internationally standardised[22].

Sato *et al.,* Agapiou and Pj reported that temperature rise during drilling increases wear on inserts[23-25]. The study concluded that as drilling progresses, the temperature of the drill holes increases. A rise in temperature near the surface of a drill bit during dry drilling could be one of the reasons for the fast wear in drill bit inserts. Suto *et al.,* designed an experimental test set-up to predict the rise of bit surface temperature in a tri-cone roller bit considering WOB and rotary speed on the drill bit[26]. The results revealed rise in wear rate with rise in temperature, increase in rotational speed and WOB. Appl *et al.,* explored the overall effect of rock properties and temperature in Polycrystalline Diamond Compact (PDC) drill bits[27]. During experimental investigations, the applied force on the bit was measured by a dynamometer and the bit temperature by thermocouples fitted on the bit. The authors predicted the abrasive wear rate of PDC drill bit based on test parameters. Shankar *et al.,* discussed the importance of bit-rock interface temperature on Tungsten Carbide (WC) drill bits[28]. During experiments, they measured the inter-relationship between temperatures and wear rate using Computer Numerical Control (CNC) technique and showed that the wear rate of the drill bits increases with a rise in temperature in different types of sandstone rock samples.

The relationships between mechanical properties of the rock, drilling noise, bit specifications, bit wear rate and operating parameters have been determined in some of the studies[29,30]. Piri *et al.,* have reported that the noise level can also be a strong indicator of the drill bit condition[31]. They compared the wear rate of rotary drill bits with Tungsten Carbide (WC), Diamond-DLC, and Titanium-Aluminum-Silicon (TiAlSi) coatings. The results divulged that the TiAlSi coated drill bit produces the lowest noise levels when performing drilling at constant rotational speed and causes less wear. Investigators have developed Drilling Vibration Monitoring & Control System (DVMCS) to minimize the axial, lateral and torsional vibrational behavior of drill bits to control bit wear rate[32]. Gradl *et al.,* documented noise levels from bit-rock interactions during drilling with the help of microphones and related with the drill bit vibration[33]. Tian *et al.,* proposed torsional vibration model to reduce the wear rate in PDC drill bits[34]. This work discusses the state-of-the-art laboratory test on tool wear and provides valuable information for bettering tools in rock drilling conditions. The present work also emphasizes on the role of coatings and their advantages and disadvantages on tool. Further, the application of artificial intelligence and machine learning in tool wear have been discussed for the rectification of tool.

2.0 Laboratory Investigations

Reliability assessment of rock drill bits from bit wear and failure data is practically not pursued by researchers. The available published research work on reliability assessment is very limited specifically on rock drill bits, though not uncommon for mining equipment and their components. Most of the published work addresses the reliability of cutting tools. Bit life is the time a bit is reliably and efficiently used for drilling before it is discarded or re-conditioned. This is essential since considerable time is lost whenever a bit is replaced and reset. Traditionally the method of assessing the condition of bits is based on its physical appearance and experience. The assessment is not done systematically and scientifically. The overall process reliability, insert materials and coated/uncoated inserts affect bit reliability. This application can allow bit life treating operating conditions systematically by considering the experimentally observed results of the bit condition. Figure 2 depicts the different aspects, which affects tool life.

Researchers have reported several studies on the reliability of cutting tools. Carlson and Strand developed a statistical model using an extended Taylor equation for predicting the tool life as a part of the control strategy[35]. A general way of quantifying the end of a tool life is to put a limit on the maximum acceptable flank wear. Wang *et al.,* presented a reliability-dependent failure rate model of a cutting tool[36]. Klim *et al*., developed a reliability model considering flank and face wear of the cutting tool under variable feed conditions[37]. A study was made by Ding *et al.,* to develop a reliability model using proportional hazards concepts[38]. Rodriguez and Souza investigated optimum cutting tool change time using a reliability model and process planning[39]. Vagnorius *et al.,* developed an age replacement model to characterise wear of cutting tools through Weibull distribution and modelled premature failures using Poisson distribution[40]. A probabilistic approach can resolve the uncertainties of discarding a bit by characterising the variables with a degree of confidence. The probabilistic approach can be addressed to estimate the probability of failure using either First Order Reliability Method (FORM)/Second Order Reliability Method (SORM) or by Monte Carlo Simulation technique. A probabilistic approach using an approximation model, response surface and surrogate technique for assessing tool life with varying cutting speeds and feed rates was explored by Konstantinos *et al*[41].

The drill bits come back from the field after use carry useful technical information on bit conditions for scientific investigations. Keeping a record of the failure data without any loss of information is challenging in mines. Scientifically recorded failure data promote new concepts for improving the performance and reliability of the bits[42]. Industries and researchers took on the use of a dull bit grading system in the mid-1950s for relating typical bit wear patterns on the roller cone bits to judge possible causes and remedies. Their methodology was discovered useful however restricted by the absence of a typical vocabulary for portraying bit wear and archiving the dull condition in reports. Table 1 depicts the method discussed by researchers for estimating tool life in previous studies.

McGehee *et al.,* proposed a new and improved version of the International Association of Drilling Contractors (IADC) on a bit dull grading system[43]. The underlying research carried out by them was appropriated from their published research work between 1986 to 1992. They have listed different wear modes of roller cone drill bits from field investigations. Some of the prime modes of bit failure were broken cones, broken teeth, chipped tooth, cone interference, cracked cone, dragged cones, lost teeth, lost cone, heating effects, worn teeth, etc. Beste *et al.,* have collected the Cemented Carbide (CC) buttons of rotary-percussive drill bits, which were used in the drilling of magnetite rock[44]. They studied different possible wear phenomena on the surface of CC buttons using Scanning Electron Microscopy (SEM), Light Optical Microscopy (LOM), and Energy-Dispersive X-ray Spectroscopy (EDS). Olovsjo *et al.,* performed tests on worn CC drill buttons using high-resolution SEM, EDS, and Auger Electron Spectroscopy (AES) to characterize wear and failure mechanisms[45]. They observed that wear occurred due to fracturing and pull-out of Tungsten Carbide (WC) grains during drilling. Kong *et al.,* gathered and analyzed failure data of PDC drill bits[46]. PDC drill bit was manufactured from PCD (Polycrystalline Diamond)

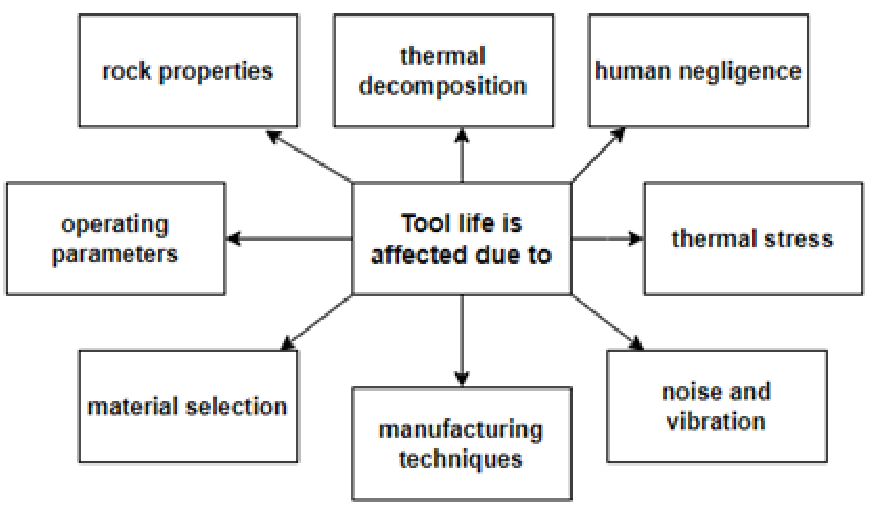

Figure 2. Challenges of tool life in mining conditions.

powder, activator (Cobalt or Silicon) and WC (Wolfram Carbide) material. Studies revealed that the failure modes fall into mechanical wear, fracture and stripping of crystals from the PCD bit. The detailed survey disclosed that the fracture failure to the extent of 41% is in the highest proportion which adversely affected the drilling rate and rock cutting efficiency.

Reliability estimation studies of drill bits have been undertaken lately by researchers. Essential methods such as the stochastic response surface, surrogate modelling, Homogeneous Poisson Process (HPP), Pareto analysis, Renewal Process, etc., were studied in the past to determine the bit wear as a function of distinct parameters. Subsequently, several reliability techniques were considered to assess the reliability of bits. Reliability is mainly accounted for by considering Time Between Failure (TBF) of the components[47]. Hall and Daneshmend discussed the benefits of Pareto analysis of surface mining equipment[48]. Failure Mode Effects and Criticality Analysis (FMECA) techniques are addressed particularly when the availability of failure data found inadequate for analysis[49]. The life-cycle behaviour in terms of Time To Failure (TTF) and repair data can be analysed using Reliability and Maintainability Growth Management (RMGM) techniques[42]. Golbasi and Demirel introduced an elucidating use of the algorithms for mining equipment[50]. They have obtained ideal inspection intervals based on time-dependent failures of components by developing a reliability model. Barabady *et al.,* have studied the reliability and availability analysis through Weibull, Exponential, and Lognormal distribution for the spare part of rock drill bits[42]. They introduced the Non-Homogeneous Poisson Processes (NHPP) models for repairable items, which are highly useful for tracing failure phenomena that possess specific trends, such as reliability growth or deterioration. The fault-tree approach has been adopted for measuring the reliability and operational behaviour of hydraulic excavator failure data in surface mines[51].

Laboratory tests like rotary wheel abrasion test, impact test, and micro-tribological test using pin-on-disc wear test apparatus were conducted to investigate

Table 1. Previous methodologies on tool life

Sl No.	Type of approach	Method
1	Statistical	Statistical model using extended Taylor equation
2	Probabilistic	Reliability-dependent failure rate model
3	Probabilistic	Reliability model using proportional hazards concepts
4	Probabilistic	Reliability model and process planning
5	Probabilistic	Weibull distribution and modeled premature failures using Poisson distribution.
6	Semi-probabilistic	First Order Reliability Method (FORM)
7	Uncertainty probabilistic	Second Order Reliability Method (SORM)
8	Probabilistic	Monte Carlo Simulation technique
9	Probabilistic	Probabilistic approach using approximation model
10	Probabilistic	Response surface and surrogate technique
11	Microscopic	SEM, LOM, and EDS
12	Machine Learning and Artificial Intelligence	Regression ANN, CNN, R-CNN, Deep Learning, advanced image processing and forward and reverse-looking AI models

wear characteristics of bits[52,53]. The tests measure the rate of wear in terms of weight loss of the specimen in defiance of sliding distance. Wallin *et al.,* tested inserts of cemented carbide samples of different grades against the surface of granite rock both in dry and wet conditions[54]. It was found that the inserts in dry tests showed less wear than wet tests. The reason cited was that the fine grit powder formed under dry conditions provides a protective layer between the insert and rock surfaces. Different WC–Co test samples with varied Co content were tested by Saito *et al.,* under dry conditions on a Block-on-Cylinder wear-type testing machine sliding against carbon steel (0.45 % C) to appraise the influence of cobalt content on wear rates[55]. It was reported that with an increase in Co content, wear rate increases. Angseryd *et al.,* performed a wear test on CC inserts using a rotating rock cylinder under both dry and wet conditions by applying alumina and silica as abrasive particles[52]. They observed different wear mechanisms on test samples microscopically and concluded that the tests under dry conditions consistently caused less estimated wear than tests under wet conditions. Oskarsson measured the wear rate of cemented carbide bit inserts sliding against granite rock covered with abrasive SiO_2 under different loading conditions[56]. The arrangement was fitted on a lathe. The results showed that no correlation exists between the load and loss in mass. The rubber rimmed with steel wheel as the counter face material was used for wear test by Gant *et al.,* to establish resistance to abrasion property of different WC-Co samples under different loads and rotating speeds[57]. They observed a consistent reduction in wear rate as the hardness of materials increased.

3.0 The Role of Coatings in Drilling Applications

Studies have examined the wear behaviour of drill bits and the abrasion behaviour of rock. Among several methods, covering a drill bit with a layer of resistant coating has been an effective way of increasing the wear resistance of a drill bit. Under different operating conditions, rock drill bits including Steel Tooth Drill Bits (STDB) and Tungsten Carbide Insert (TCI) bits are highly prone to harsh rock that brings about severe wear, erosion and corrosion[58].

Surface modification techniques including Chemical Vapour Deposition (CVD), Physical Vapour Deposition (PVD), boron ion implantation[59-62], pulse-plasma deposition[63], laser surface modification[64], Thermal Spray techniques (TS)[65], etc. have been employed to protect the drill bits against wear, fluid erosion and corrosion. However, CVD, boron ion implantation and pulse-plasma deposition techniques may not be suitable for rock drilling purposes due to the thin thickness of the protective layer and its reduced bonding strength with the substrate.

Several attempts with mixed success have been made in coating CC inserts to enhance life. Some of the coating compounds used are TiN (Titanium Nitride), TiC (Titanium Carbide), Ti(C)N (Titanium Carbo Nitride), TiAlN (Titanium Aluminium Nitride) and AlTiN (Aluminium Titanium Nitride). The coatings help to increase the hardness of the insert and minimize temperature rise during drilling operation[66]. Diamond coatings on cemented carbide substrates developed through PVD or CVD coating techniques in 1982, revealed a new and stimulating field of research in drilling industries[67].

Alahelisten considered cemented carbide (94% WC and 6% Co) in the format of rock drilling bits as substrates for the hot flame-deposited diamond coating techniques[68]. In his study, the test samples were examined in sliding contact with SiC, Al_2O_3, and flint abrasive papers. It was observed that a longer lifetime of the coatings was achieved using coating layers of appropriate thickness. Yahiaoui *et al.,* observed that the coating of Boron Nitride (BN) on the active surface of cemented carbide at a temperature greater than 1280°C using CVD technique lowers the friction coefficient and improves the abrasion resistance of a rock drill bit insert[69]. Keshavan *et al.,* have explored HVOF coatings with cermets (83% WC, 14% Co and 3% carbon), which produced a monolithic carbide coating strongly adhering to the alloy steel surface of a rock drill bit[70]. They concluded that the monolithic carbide coating shows high strain level, shock tolerance properties and higher load-carrying capacity. In addition to this, cemented carbide buttons of WC-Co inserts with complex geometry were coated with a 10 μm continuous titanium nitride layer using the PVD technique. It showed an excellent bonding at the interface between cemented carbide and titanium nitride layer[71].

Gunen studied the wear behaviour of thermally sprayed coated steel tooth drill bits by a micro-abrasion wear test and observed that the wear resistance of the coated samples had increased per the increasing coating thickness[58]. The rotary drilling tests done by Bellin *et al.,* demonstrated that the utilization of ultrafine diamond particles increases the wear resistance of the drill bit[72]. Piri *et al.,* examined the effect of hard rocks' mechanical properties on the wear of drill bits[73]. Their study assessed the wear resistance of drill bits with DLC-Diamond coating, Tungsten Carbide (WC) coating and Titanium-Silica-Aluminium (TiAlSi) coating. They observed that with an increase in the rock's mechanical properties (Mohs hardness, Schimazek's abrasivity index uniaxial compressive strength and Young's Modulus), the tested drill bits showed immense differences in wear resistance. Further, they concluded that the TiAlSi coated drill bits showed better performance and achieved the lowest wear rate in comparison to DLC-Diamond coating and Tungsten Carbide (WC) coated drill bits. Interestingly, a new technology of Diamond Enhanced Inserts (DEI) showed improved resistance to bit wear during abrasive drilling conditions[74].

4.0 Importance of AI and ML Study on Tool Wear

Material loss on tools, corrosion, erosion, and cracks can lead to equipment failure and also downtime in the industry. A fast and accurate real-time detection of the tool's condition will save both material loss and time. The current AIML techniques are capable of detecting irregularity for tool wear. Robust sensors are now gathering data from the machine-tool interaction and help AIML techniques to predict models based on the algorithm. Soori *et al.,* observed that the surface quality of the tool after machining can be improved by developing a machine-learning model based on the data generated during machining[75]. The machine learning approach determines patterns from data and makes accurate predictions without the involvement of humans. Deep learning model from AI techniques provides reliable, affordable, and statistical solutions for tool wear in the mining industry. Batruny *et al.,* predicted the tool's performance in rock drilling by considering parameters in the machine learning algorithm, such as weight on bit and rate of penetration[76]. They proposed the methodology for the selection of bits. Cornel *et al.,* developed a study on big data and optimal bit design under tool wear conditions using machine learning[77]. The development of wear on tools due to whole-body vibration has been studied by researchers using sensor data and AI techniques. Gidh *et al.,* utilize the artificial neural network technique for monitoring tool wear with real-time ROP data.

Jeffery and Creegan analyzed the processed drilling data and developed an AIML model to mitigate tool-related issues in detail[79]. Jamshidi and Mostafavi have considered virtual intelligence and Genetic Algorithms to optimize tool conditions with real-time data[80]. Forward and reverse-looking AI models are now popular among researchers for estimating patterns from field data. AIML techniques provide cleaning, partition, scaling, and summary of failure bit data collected from the field and develop a prediction model for optimizing bit behaviour. Forecast periods of service requirement of a tool can also be predicted using artificial intelligence by considering the data generated on tool wear Tool wear data have been analyzed by an advanced image processing method equipped with artificial intelligence, which provides better visualization of tool wear on a nanoscale. Non-linear characteristics of the tool can be best understood with machine learning algorithms. Dunlop *et al.,* proposed that the expected bit wear is the function of the abrasivity of rock and can be best modelled using machine learning[81]. AIML models segregate surface drilling data using algorithms and provide helpful information to the drilling industry to optimize tool design.

5.0 Conclusions

The industry's general need to drill mines more proficiently to decrease the forthright drilling expenses related to coal production has driven the persistent interest in innovative work for better materials and design techniques for the tools, processes, and drilling practices. In this way, the discussions from this manuscript can be summarized as follows:

The review documented different approaches to estimating the reliability of cutting tools based on wear, field data, experimental data, and results obtained from models. The reviewed areas highlight the tool's failure types and operational and wear conditions. The techniques showed potential for assessing tool life in varied conditions.

The need for coated insert material in the rock drilling process has increased since coating enhances the life expectancy of CC inserts through various coating techniques.

The importance of artificial intelligence and machine learning techniques have been discussed for detecting wear-related issues on tools with real-time data. The studies in this section suggest that utilizing AIML techniques will certainly enhance the tool's overall performance.

6.0 Author Contribution

The first and the corresponding author have prepared the manuscript.

7.0 References

1. Bourgoyne AT, Young FA. A multiple regression approach to optimal drilling and abnormal pressure detection. SPE Repr Ser. 1999; 49:27–36.
2. Wijk G. Rotary drilling prediction. Int J Rock Mech Min Sci. 1991; 28(1):35–42. https://doi.org/10.1016/0148-9062(91)93231-T
3. Hareland G, Wu A, Rashidi B. A drilling rate model for roller cone bits and its application. 2010. https://doi.org/10.2118/129592-MS
4. Zhao Y, Noorbakhsh A, Koopialipoor M, Azizi A, Tahir MM. A new methodology for optimization and prediction of rate of penetration during drilling operations. Eng Comput. 2020; 36(2):587–95. https://doi.org/10.1007/s00366-019-00715-2
5. Mazen AZ, Rahmanian N, Mujtaba I, Hassanpour A. Prediction of penetration rate for PDC bits using indices of rock drillability, cuttings removal, and bit wear. SPE Drill. Complet. 2021; 36(2):320–37. https://doi.org/10.2118/204231-PA
6. Bataee M, Kamyab M, Ashena R. Investigation of various ROP models and optimization of drilling parameters for PDC and roller-cone bits in Shadegan oil field. 2010. https://doi.org/10.2118/130932-MS
7. Praillet R. Blasthole drilling, rotary drilling and the four kingdoms. World Min Equipments. 1998; 20–23.
8. Alber M. Stress dependency of the Cerchar Abrasivity Index (CAI) and its effects on wear of selected rock cutting tools. Tunn Undergr Sp Technol. 2008; 23(4):351–9. https://doi.org/10.1016/j.tust.2007.05.008
9. Kahraman S. Rotary and percussive drilling prediction using regression analysis. Int J Rock Mech Min Sci. 1999; 36(7):981–9. https://doi.org/10.1016/S0148-9062(99)00050-9
10. Altindag R. The role of rock brittleness on analysis of percussive drilling performance. Proc. of 5th National Rock Mech Symp, Turkey. 2000; 105–12.
11. Bilgin N, Kahraman S. Drillability prediction in rotary blast hole drilling. 18. Imcet. 2003; 1990:177–82.
12. Saeidi O, Torabi SR, Ataei M, Rostami J. A stochastic penetration rate model for rotary drilling in surface mines. Int J Rock Mech Min Sci. 2014; 68:55–65. https://doi.org/10.1016/j.ijrmms.2014.02.007
13. Cheniany A, Hasan KS, Shahriar K, Hamidi JK. An estimation of the penetration rate of rotary drills using the Specific Rock Mass Drillability index. Int J Min Sci Technol. 2012; 22(2):187–93. https://doi.org/10.1016/j.ijmst.2011.09.001
14. Plinninger RJ, Spaun G, Thuro K. Predicting tool wear in drill and blast. Tunnels Tunn Int. 2002; 34(4):38–41.
15. Osburn HJ. Wear of rock-cutting tools. Powder Metall. 1969; 12(24):471–502. https://doi.org/10.1179/pom.1969.12.24.015
16. Plinninger RJ, Spaun G, Thuro K. Prediction and classification of tool wear in drill and blast tunnelling. Proc 9th Congr Int Assoc Eng Geol Environ. 2002; 2226–36.
17. Moradizadeh M, Cheshomi A, Ghafoori M, TrighAzali S. Correlation of equivalent quartz content, Slake durability index and Is50 with Cerchar abrasiveness index for different types of rock. Int J Rock Mech Min Sci. 2016; 86:42–47. https://doi.org/10.1016/j.ijrmms.2016.04.003
18. Spaun G, Thuro K. Introducing the 'destruction work' as a new rock property of toughness referring to drillability in conventional drill-and blast tunnelling. Paper presented at: The ISRM International Symposium – EUROCK 96; 1996 September; Turin, Italy.
19. Plinninger RJ. Abrasiveness assessment for hard rock drilling. Geomech. und Tunnelbau. 2008; 1(1):38–46. https://doi.org/10.1002/geot.200800004
20. Yarali O, Yaşar E, Bacak G, Ranjith PG. A study of rock abrasivity and tool wear in coal measures rocks. Int J Coal Geol. 2008; 74(1):53–66. https://doi.org/10.1016/j.coal.2007.09.007

21. West G. Rock abrasiveness testing for tunnelling. Int J Rock Mech Min Sci. 1989; 26(2):151–60. https://doi.org/10.1016/0148-9062(89)90003-X
22. Plinninger RJ. Hardrock abrasivity investigation using the Rock Abrasivity Index (RAI). 11th IAEG Congr. 2010; 341.
23. Sato M, Aoki T, Tanaka H, Takeda S. Variation of temperature at the bottom surface of a hole during drilling and its effect on tool wear. Int J Mach Tools Manuf. 2013; 68:40–47. https://doi.org/10.1016/j.ijmachtools.2013.01.007
24. Agapiou JS, Stephenson DA. Analytical and experimental studies of drill temperatures. J Manuf Sci Eng Trans ASME. 1994; 116(1):54–60. https://doi.org/10.1115/1.2901809
25. Loui PJ, Rao KUM. Experimental investigations of pick-rock interface temperature in drag-pick cutting. Indian J Eng Mater Sci. 1997; 4:63–6
26. Suto Y, Takahashi H. Effect of the load condition on frictional heat generation and temperature increase within a tri-cone bit during high-temperature formation drilling. Geothermics. 2011; 40(4):267–74. https://doi.org/10.1016/j.geothermics.2011.08.004
27. Appl FC, Wilson CC, Lakshman I. Measurement of forces, temperatures and wear of PDC cutters in rock cutting. Wear. 1993; 169(1):9-24. https://doi.org/10.1016/0043-1648(93)90386-Z
28. Shankar VK, Kunar BM, Murthy CS, Ramesh MR. Measurement of bit-rock interface temperature and wear rate of the tungsten carbide drill bit during rotary drilling. Friction. 2020; 8(6):1073-82. https://doi.org/10.1007/s40544-019-0330-2
29. Karakus M, Perez S. Acoustic emission analysis for rock-bit interactions in impregnated diamond core drilling. Int J Rock Mech Min Sci. 2014; 68:36-43. https://doi.org/10.1016/j.ijrmms.2014.02.009
30. Khoshouei M, Bagherpour R. Predicting the geomechanical properties of hard rocks using analysis of the acoustic and vibration signals during the drilling operation. Geotech Geol Eng. 2021; 39(3):2087-99. https://doi.org/10.1007/s10706-020-01611-z
31. Piri M, Mikaeil R, Hashemolhosseini H, Baghbanan A, Ataei M. Study of the effect of drill bits hardness, drilling machine operating parameters and rock mechanical parameters on noise level in hard rock drilling process. Meas J Int Meas Confed. 2021; 167. https://doi.org/10.1016/j.measurement.2020.108447
32. Márquez MBS, Boussaada I, Mounier H, Niculescu SI. Analysis and control of oilwell drilling vibrations; 2015. p. 9–24. https://doi.org/10.1007/978-3-319-15747-4_2
33. Gradl S, Kugler P, Lohmuller C, Eskofier B. Real-time ECG monitoring and arrhythmia detection using Android-based mobile devices. Proc Annu Int Conf IEEE Eng Med Biol Soc EMBS. 2012; 2452-55. https://doi.org/10.1109/EMBC.2012.6346460 PMid:23366421
34. Tian J, Li G, Dai L, Yang L, He H, Hu S. Torsional vibrations and nonlinear dynamic characteristics of drill strings and stick-slip reduction mechanism. J Comput Nonlinear Dyn. 2019; 14(8). https://doi.org/10.1115/1.4043564
35. Carlsson TE, Strand F, Lindstrom B. A statistical model for prediction of tool life as a basis for economical optimization of the cutting process. CIRP Ann - Manuf Technol 1992; 41(1):79-82. https://doi.org/10.1016/S0007-8506(07)61157-3
36. Wang KS, Lin WS, Hsu FS. A new approach for determining the reliability of a cutting tool. Int J Adv Manuf Technol. 2001; 17(10):705-9. https://doi.org/10.1007/s001700170114
37. Klim Z, Ennajimi E, Balazinski M, Fortin C. Cutting tool reliability analysis for variable feed milling of 17-4PH stainless steel. Wear. 1996; 195(1-2):206-13. https://doi.org/10.1016/0043-1648(95)06863-5
38. Ding F, He Z. Cutting tool wear monitoring for reliability analysis using proportional hazards model. Int J Adv Manuf Technol. 2011; 57(5-8):565-74. https://doi.org/10.1007/s00170-011-3316-4
39. Patiño CE, Souza GFM. Reliability concepts applied to cutting tool change time. Reliab Eng Syst Saf. 2010; 95(8):866-73. https://doi.org/10.1016/j.ress.2010.03.005
40. Vagnorius Z, Rausand M, Sørby K. Determining optimal replacement time for metal cutting tools. Eur J Oper Res. 2010; 206(2):407-16. https://doi.org/10.1016/j.ejor.2010.03.023
41. Salonitis K, Kolios A. Reliability assessment of cutting tool life based on surrogate approximation methods. Int J Adv Manuf Technol. 2014; 71(5-8):1197-208. https://doi.org/10.1007/s00170-013-5560-2
42. Barabadi A, Barabady J, Markeset T. Application of reliability models with covariates in spare part prediction and optimization - A case study. 2014; 123:1-7. https://doi.org/10.1016/j.ress.2013.09.012

43. McGehee DY, *et al*. The IADC roller bit dull grading system. 1992. https://doi.org/10.2523/23938-MS PMCid:PMC442840
44. Beste U, Hartzell T, Engqvist H, Axén N. Surface damage on cemented carbide rock-drill buttons. Wear. 2001; 249(3-4):324-9. https://doi.org/10.1016/S0043-1648(01)00553-1
45. Olovsjö S, Johanson R, Falsafi F, Bexell U, Olsson M. Surface failure and wear of cemented carbide rock drill buttons – The importance of sample preparation and optimized microscopy settings. Wear. 2013; 302(1-2):1546-54. https://doi.org/10.1016/j.wear.2013.01.078
46. Kong C, Liang Z, Zhang D. Failure analysis and optimum structure design of PDC cutter. Mechanika. 2017; 23(4):567-73. https://doi.org/10.5755/j01.mech.23.4.14932
47. Kumar U, Klefsjö B. Reliability analysis of hydraulic systems of LHD machines using the power law process model. Reliab Eng Syst Saf. 1992; 35(3):217-24. https://doi.org/10.1016/0951-8320(92)90080-5
48. Hall RA, Daneshmend LK. Reliability modelling of surface mining equipment: Data gathering and analysis methodologies. Int J Surf Mining, Reclam Environ. 2003; 17(3):139-55. https://doi.org/10.1076/ijsm.17.3.139.14773
49. Signoret JP, Leroy A. Failure mode, effects (and criticality) analysis, FME(C)A. Springer Ser Reliab Eng. 2021; 165-72. https://doi.org/10.1007/978-3-030-64708-7_10
50. Demirel N, Gölbası O. Preventive replacement decisions for dragline components using reliability analysis. Minerals. 2016; 6(2). https://doi.org/10.3390/min6020051
51. Badri A, Nadeau S, Gbodossou A. A new practical approach to risk management for underground mining project in Quebec. J Loss Prev Process Ind. 2013; 36(6):1145-58. https://doi.org/10.1016/j.jlp.2013.04.014
52. Angseryd J, From A, Wallin J, Jacobson S, Norgren S. On a wear test for rock drill inserts. Wear. 2013; 301(1-2):109-15. https://doi.org/10.1016/j.wear.2012.10.023
53. Konyashin I, Ries B. Wear damage of cemented carbides with different combinations of WC mean grain size and Co content. Part II: Laboratory performance tests on rock cutting and drilling. Int J Refract Met Hard Mater. 2014; 45:230-7. https://doi.org/10.1016/j.ijrmhm.2014.04.017
54. Wallin J. Tribological testing of rotary drill bit inserts. Uppsala Universitet; 2012.
55. Saito H, Iwabuchi A, Shimizu T. Effects of Co content and WC grain size on wear of WC cemented carbide. Wear. 2006; 261(2):126-32. https://doi.org/10.1016/j.wear.2005.09.034
56. Oskarsson J. Tribological testing of rotary drill bit inserts. Uppsala Universitet; 2012.
57. Gant AJ, Gee MG, Roebuck B. Rotating wheel abrasion of WC/Co hardmetals. Wear. 2005; 258(1-4):178-88. https://doi.org/10.1016/j.wear.2004.09.028
58. Günen A. Micro-abrasion wear behavior of thermal-spray-coated steel tooth drill bits. Acta Phys Pol A. 2016; 130(1):217-22. https://doi.org/10.12693/APhysPolA.130.217
59. Teii K, Hori T, Matsumoto S. Enhanced deposition of cubic boron nitride films on roughened silicon and tungsten carbide-cobalt surfaces. Thin Solid Films. 2011; 519(6):1817-20. https://doi.org/10.1016/j.tsf.2010.10.017
60. Mrochek I, Günzel R, Matz W, Möller W, Anishchik V. Implantation of boron ions into hard metals. Nukleonika. 1999; 44(2):217-24.
61. Yu LD, Shuy GW, Vilaithong T. Friction modification of WC-Co by ion implantation. Surf Coatings Technol. 2000; 128-129:404-9. https://doi.org/10.1016/S0257-8972(00)00642-3
62. Kolitsch A, Richter E. Change of microhardness on ion implanted tungsten carbide. Cryst Res Technol. 1983; 18(1):K5-7. https://doi.org/10.1002/crat.2170180122
63. Kupczyk MJ, Michalski A, Siwak P, Rosinsk M. Evaluation of cutting edges made of nanocrystalline cemented carbides sintered by the pulse plasma method. ASTM Spec Tech Publ. 2012; 1532:313-26. https://doi.org/10.1520/STP153220120022
64. Da Silva WM, Suarez MP, Machado AR, Costa HL. Effect of laser surface modification on the micro-abrasive wear resistance of coated cemented carbide tools. Wear. 2013; 30(1-2):1230-40. https://doi.org/10.1016/j.wear.2013.01.035
65. Berger LM. Application of hardmetals as thermal spray coatings. Int J Refract Met Hard Mater. 2015; 49(1):350-64. https://doi.org/10.1016/j.ijrmhm.2014.09.029
66. PalDey S, Deevi SC. Single layer and multilayer wear resistant coatings of (Ti,Al)N: A review. Mater Sci Eng A. 2003; 342(1-2):58-79. https://doi.org/10.1016/S0921-5093(02)00259-9
67. Bryant W, Santhanam A. Coated cutting tool having an outer layer of TiC. US Pat. 2008; 5:750.

68. Alahelisten A. Abrasion of hot flame-deposited diamond coatings. Wear. 1995; 185(1-2):213-24. https://doi.org/10.1016/0043-1648(95)06618-7
69. Yahiaoui M, Paris JY, Denape J, Colin C, Ther O, Dourfaye A. Wear mechanisms of WC-Co drill bit inserts against alumina counterface under dry friction: Part 2 - Graded WC-Co inserts. Int J Refract Met Hard Mater. 2015; 48:65-73. https://doi.org/10.1016/j.ijrmhm.2014.07.024
70. Janssen MKKZSG. Polycrystalline diamond materials having improved abrasion resistance, thermal stability and impact resistance. US 7493,973 B2; 2009.
71. Ederyd SSO. Cemented carbide body, for rock drilling mineral cutting and highway engineering. U.S. Patent No. 5,718,948; 1998.
72. Bellin F, Dourfaye A, King W, Thigpen M. The current state of PDC bit technology. World Oil. 2010; 231(11):67-71.
73. Piri M, Hashemolhosseini H, Mikaeil R, Ataei M, Baghbanan A. Investigation of wear resistance of drill bits with WC, Diamond-DLC, and TiAlSi coatings with respect to mechanical properties of rock. Int J Refract Met Hard Mater. 2020; 87. https://doi.org/10.1016/j.ijrmhm.2019.105113
74. Cobb T, Scott D, Nelms D. Superior quality diamond heel inserts improve cutting structure and seal life in abrasive and directional applications. Soc Pet Eng - Can Unconv Resour Conf. 2011, CURC 2011. 2011; 1:123-7. https://doi.org/10.2118/146058-MS
75. Mohsen S, Arezoo B, Dastres R. Machine learning and artificial intelligence in CNC machine tools: A review. Sustainable Manufacturing and Service Economics. 2023; 100009. https://doi.org/10.1016/j.smse.2023.100009
76. Peter B, *et al*. Drilling in the digital age: Machine learning assisted bit selection and optimization. International Petroleum Technology Conference. IPTC; 2021.
77. Simon C, Vazquez G. Use of big data and machine learning to optimise operational performance and drill bit design. SPE Asia Pacific Oil and Gas Conference and Exhibition. SPE; 2020.
78. Yashodhan G, Purwanto A, Bits S. Artificial neural network drilling parameter optimization system improves ROP by predicting/managing bit wear. SPE Intelligent Energy International Conference and Exhibition. SPE; 2012.
79. Christopher J, Creegan A. Adaptive drilling application uses AI to enhance on-bottom drilling performance. Journal of Petroleum Technology 72.08. 2020:45-7. https://doi.org/10.2118/0820-0045-JPT
80. Emad J, Mostafavi H. Soft computation application to optimize drilling bit selection utilizing virtual inteligence and genetic algorithms. IPTC 2013: International Petroleum Technology Conference. European Association of Geoscientists and Engineers; 2013.
81. Jonathan D, *et al*. Increased rate of penetration through automation. SPE/IADC Drilling Conference and Exhibition. OnePetro; 2011.