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A Mixed Weibull Method for Reliability Analysis of Tricone Roller Bits in Blasthole Drilling

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Abstract—Practice of rock drilling with tricone roller bits, which are extensively used in surface mines, needs proper modes of descriptive statistics for predicting the failure rates of its different sub-assembled components. The statistical models for drilling with tricone roller bits are investigated in this article and probability of the non-failure operation is calculated. The interdependency of different component failures is examined by 3D contour plot. The failure rate of the components observed is found not significantly different at 95% contour. In such condition, the reliability is best modelled by Mixed Weibull technique.

Keywords: Reliability, 3D contour line plot, scatter plot matrix, tricone roller bits, rock properties.

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INTRODUCTION

Tricone roller bits are commonly used for drilling blast holes in open cast coal mines. A tricone roller bit consists of a bit body made of alloy steel, the cones, and bearings. Cemented carbides (CC) inserts are arranged in a geometric pattern which allows the inserts to cut the rock efficiently [1–3]. In rock drilling operations, rejection of a drill bit before reaching to its specified life is very common due to various factors such as operating parameters of a bit, rock properties, machining parameters, operator's skill and constructional features of the drill bit [4–7]. Abrasion of the binder, formation of cracks, micro-spalling, pullout of inserts, reptile skin and extrusion of binder metal are the common mode of failure mechanisms observed in rock drilling CC bits [7–10].

During rock drilling, the lost of cone due to bearing failure of a bit mainly happens due to bit hitting bottom of the blast hole, dropped drill string, excessive weight on bit (WOB), excessive rotation power and rpm on a bit [3, 11]. The frequent failure occurs mainly in two components of the tricone roller bits and they are bearing of the cone and the inserts. These components come into the category of non-repairable systems. For reliability modelling of non-reparable systems, the Weibull and lognormal probability distributions functions are frequently used [12–14]. The analysis of non-repairable systems generally employs any one of the three techniques, namely the time to failure, condition-based, and stress-strength approach [15, 16].

This article delineates the approach to determine the reliability of critical CC bit components to assist engineers for better maintenance scheduling to improve equipment availability, reduce the maintenance cost and production loss. Considering the factors a few research work are available on life estimation of bit based on operating factors and dimensions of a bit [2, 18, 19]. However, life estimation and prediction of failures of the bit has not been examined by researchers due to excessive insert failure of bits and bearing failures through reliability study.

1. RESEARCH METHODOLOGY

Time-to-failure data of tricone roller bits under study are recorded from a mechanized open cast coal mine for a period of 3 years. The rock properties of the observed open cast coal mine have been determined as per the ISRM standards [20] and investigated using *R* programming framework with *R* studio software [21]. From the failure data, it is observed that the frequent failure occurs mainly in two components of tricone roller bits and they are bearing of the cone and the inserts. The failure of either of the components causes premature failure of the whole bit. The inter-dependency of these components may affect the reliability of the whole drill bit. The inter-dependency of these components is examined by a 3D contour line plot. The reliability analysis of these two components and the drill bit is determined in this study using ReliaSoftWeibull++ version 11.0.1 software. The reliability of the bit is investigated at the same time using mixed Weibull analysis. In case of any doubt, the focus group consisting of maintenance people of the mine was consulted. The source of data is the mine workshop logbook. The collected data are presented in Table 1.

Table 1. Drill bit failure data

Bit no.	Time to failure, h	Mode of failure	Bit no.	Time to failure, h	Mode of failure
1	90	Insert	1	180	Bearing
2	106	Insert	2	191	Bearing
3	115	Insert	3	202	Bearing
4	144	Insert	4	234	Bearing
5	146	Insert	5	235	Bearing
6	154	Insert	6	121	Bearing
7	161	Insert	7	244	Bearing
8	116	Insert	8	140	Bearing
9	124	Insert	9	150	Bearing
10	182	Insert	10	296	Bearing
11	187	Insert	11	310	Bearing
12	132	Insert	12	162	Bearing
13	141	Insert	13	163	Bearing
14	232	Insert	14	338	Bearing
15	245	Insert	15	346	Bearing
16	252	Insert	16	376	Bearing
17	263	Insert	17	175	Bearing
18	189	Insert	18	214	Bearing
19	194	Insert	19	228	Bearing
20	196	Insert	20	249	Bearing
21	211	Insert	21	283	Bearing
22	217	Insert	22	290	Bearing
23	227	Insert	23	293	Bearing
24	285	Insert	24	295	Bearing
25	296	Insert	25	182	Bearing
26	304	Insert	26	313	Bearing
27	335	Insert	27	193	Bearing
28	352	Insert	28	185	Bearing
29	165	Insert	29	314	Bearing
30	201	Insert	30	195	Bearing
31	125	Insert	31	199	Bearing
32	204	Insert	32	317	Bearing
33	311	Insert			
34	319	Insert			
35	129	Insert			

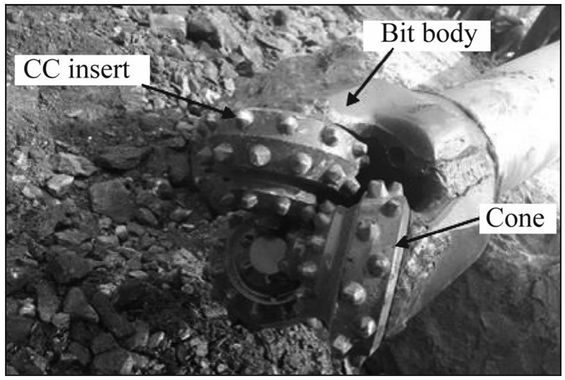

Fig. 1. Tricone roller bit.

A wide variety of rollers is used for drilling. The major components of the bit are bit body, roller cones, bearings and cemented carbide (CC) inserts (Fig. 1).

The drill bit is designed to drill abrasive coal overburden and medium to hard rock formations. Frequent failures of bearings and roller cones are the main reasons for which the bit cannot attain its desire life. The cones rotate independently at the time of drilling and supported on bearings. The axes of cones are off-set to generate additional working force. Two types of roller cone bits were studied; they are milled tooth type and tungsten carbide insert type [2, 4]. The diameter of a bit varied from 152 to 311 mm. The drill bit product specification, which is given in Table 2, is used for the study purpose.

Figure 2 shows two different types of drill bit failure mode observed in coal mines. The new International Association of Drilling Contractors (IADC) Roller Bit Dull Grading system characterizes the below two types of the failure mode in two broad categories: loss of cone due to bearing failure and wear of insert [11].

2. ROCK SAMPLES PREPARATION AND OBSERVATIONS

Rock is heterogeneous in nature; its properties vary from place to place. It is imperative to understand the rock material properties to assess various modes of failure. The failures affect the recommended drill bit life. The rock strata of a large open cast mine mainly consist of sandstone, schist, and shale. In this study, the properties of sandstone are estimated as per the International Society of Rock Mechanics (ISRM) standards [20]. A total of 25 samples for each test run from 5 different location using 20 block samples has been prepared and tested as per suggested by ISRM standard. The samples are shown in Fig. 3. The summary of the dataset which is investigated by a series of laboratory tests on sandstone rock sample is given in Table 3 (*G*—dry density, *P*—porosity, CHI—Cerchar hardness index, BTS—Brazilian tensile strength, UCS—uniaxial compressive strength, V_p—sonic velocity, *E*—Young's modulus)

Table 2. Product specification of tricone roller bits

Bit size	Operating parameters			Design data (IADC 622)			
	Weight on bit	RPM	Rock formations	API Pin connection	Bearing type	No. of rows	Teeth/inserts
6.1/4	3000–6000	65–90	Medium–hard	3.1/2 Regular	Air bearing	Total 11 Inner 8 Gauge 3	Total 101 Inner 64 Gauge 37

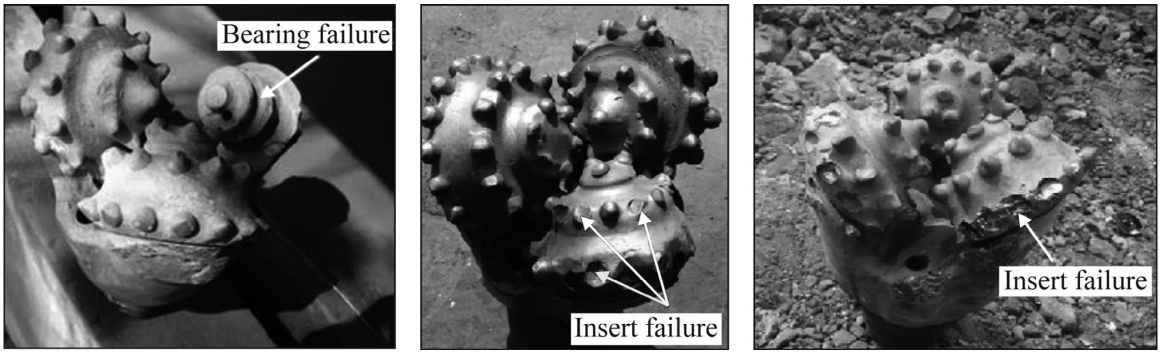

Fig. 2. Drill bit failure types.

In rock drilling operations, the uniaxial compressive strength of rock is an important rock property against which a selection of drill bit is made [22]. Due to change in rock formations, the uniaxial compressive strength value changes from place to place and it leads to different types of failure mode in a drill bit. It is essential to understand the behavior of uniaxial compressive strength of rock with respect to other properties such as dry density, porosity, Cerchar hardness index, Brazilian tensile strength, sonic velocity and Young's modulus. To understand the correlation of rock properties with respect to each other a scatter plot matrix (Fig. 4) has been drawn using *R* programming framework with *R* studio software.

The scatter plot matrix indicates that the specified properties of rock are highly correlated with respect to each other. The upper diagonal of a scatter plot matrix indicates that the correlation coefficient of each variable with respect to the other variables. The correlation coefficient for dry density and uniaxial compressive strength is 0.89. Porosity is found to be negatively correlated with respect to each variable. The lower diagonal of a scatter plot matrix shows that the regression line for each variable with respect to the other variables. The density plot and histogram for each variable are shown in the diagonal of a scatter plot matrix. From the scatter plot matrix it can be seen, that the rock properties for the large open cast coal mine are highly correlated and it affects the drill bit life severely.

3. COMPLETE DATA ANALYSIS OF DRILL BIT FAILURE

3.1. Comparison Analysis of Failure Modes

The time-to-failure data of tricone roller bits are given in Table 1. Reliability analysis of these two major components is investigated using ReliaSoftWeibull++ software version 11.0.1. The failure data of each one of these components have been investigated separately. The distribution with the largest likelihood value is considered to be the best fit distribution for the failure data [22]. 3P Weibull distribution is found as the best fit distribution for both the type of failures as the likelihood value determined for 3P Weibull distribution is largest as compared to other distributions [23].

Fig. 3. Prepared rock samples as per ISRM standards.

Table 3. Summary of sandstone rock samples laboratory tests

Obtained value	G, kN/m^3	P, %	CHI	BTS	V_p, km/s	UCS, N/mm^2	E
Minimum	21.27	1.230	15.70	5.120	3.260	25.63	4.390
1 Qu.	21.64	1.570	25.50	6.200	4.020	49.54	6.620
Median	22.41	2.430	27.30	8.740	4.200	60.92	9.470
Mean	22.39	2.726	28.11	8.417	4.297	57.70	8.833
3 Qu.	22.75	3.350	33.40	10.320	4.780	68.74	10.840
Maximum	23.71	5.230	37.30	11.210	5.020	81.25	11.210
Standard deviation	0.713	1.266	6.293	2.173	0.506	17.328	2.436

The general expression of the 3P Weibull probability distribution is given by:

$$f(t;\beta,\eta,\gamma)=\frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1}e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}},$$

where $t\geq\gamma$ and $f(t;\beta,\eta,\gamma)=0$ at $t<\gamma$; $-\infty<\gamma<\infty$; $\beta>0$ is the shape parameter; $\eta>0$ is the scale parameter; γ is the location parameter.

The shape parameter β (Weibull distribution) describes the rate of the failure. The value of β determines the slope of the line of the probability distribution and identifies rate of failures. $\beta<1$, $\beta=1$ and $\beta>1$ signify decrease in failure rate, constant failure rate and increase in failure rates, respectively [24–26]. The scale parameter η in Weibull distribution describes the spread of the distribution along the age axis. It determines the percentage of population can be expected to have failed. The location parameter γ indicates the earliest time to a failure. The life time from the beginning to the estimated value of γ would be a failure free operating period. Weibull distribution, reliability $R(t)$ and failure rate versus time plot for both types of failure mode has been shown in Fig. 5.

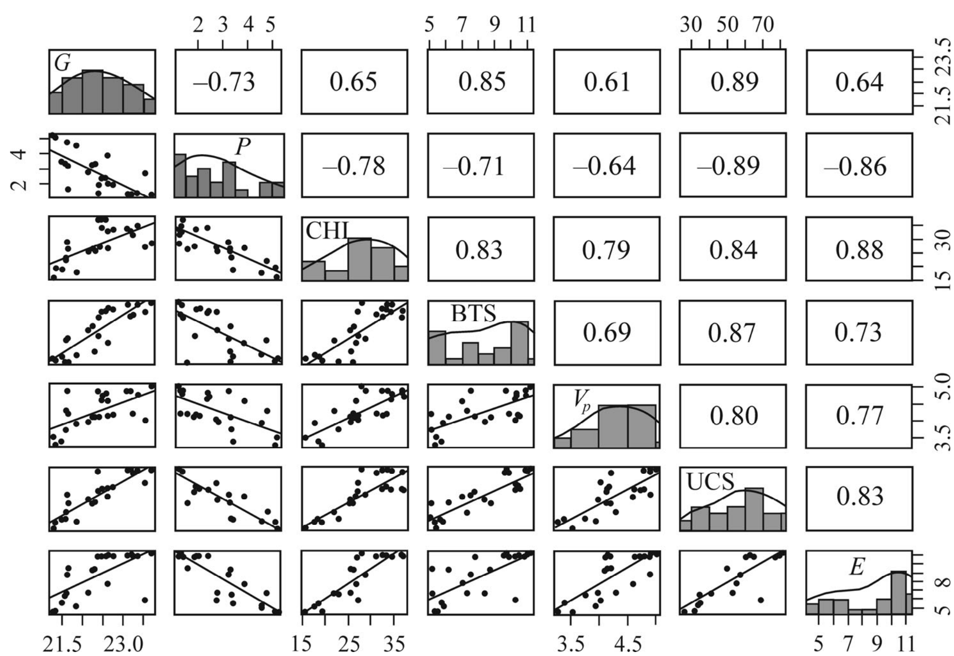

Fig. 4. Scatter plot matrix.

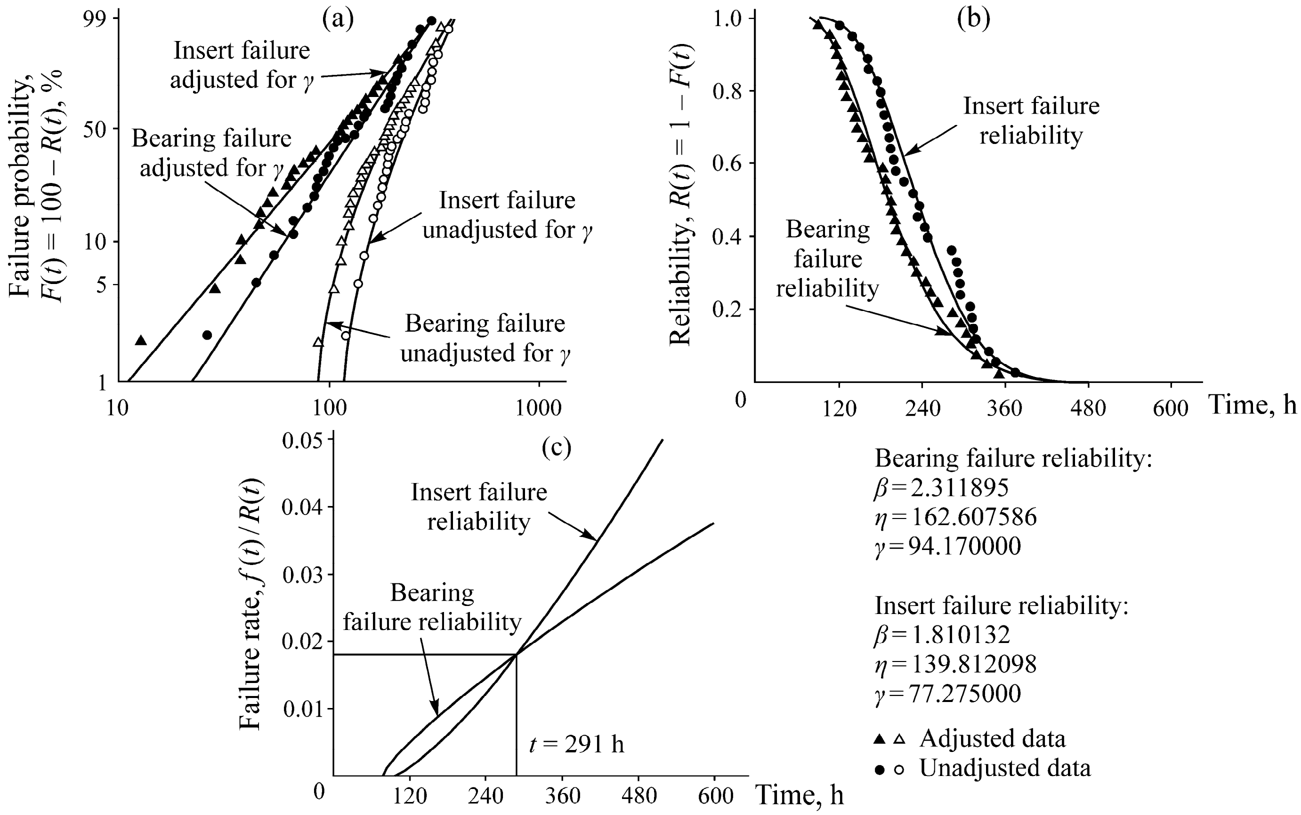

Fig. 5. Probability Weibull plot for (a) bearing and insert failure mode, (b) reliability and (c) failure rate versus time.

In Fig. 5a for both types of failure modes β value is found to be greater than 1 but less than 2.6, which means a positively skewed Weibull Pdf [25, 26]. This implies that the failure rate increases with time for the observed beta values and also known as wear-out failures.

The scale parameter η is also known as the characteristic life of a product. In Fig. 5b, for the observed failure data, the product life has a Weibull distribution of 162 hours and 139 hours for the bearing and insert failure mode, respectively, with scale parameter which implies the time at which unreliability is equal to 63.2% [25, 29]. The value of γ is greater than zero which implies that the distributions start from first failure time in hours to the right of the origin. The earliest time to failure for bearing and insert failure has been calculated as 94 and 77 hours, respectively. It is to be noted, that at 95% confidence bound reliability of bearing failure is more as compared to insert failure mode. At 95% confidence level it is observed, that before time $t = 291$ hrs the failure rate per hour for insert failure is more as compared to bearing failure. From time $t = 291$ hours onwards the bearing failure rate increases with increasing time, therefore, the reliability of bearings is more than the inserts.

3.2. Independency Test of Failure Data

For tricone roller bit life data analysis, the occurrence of bearing failure mode may affect the probability of occurrence of the insert failure mode and vice-versa. A 3D contour line plot is used to compare failure data sets to investigate the independency of one failure mode with respect to the other failure mode and vice-versa [12]. To investigate the independency of bearing failure and insert failure mode with respect to each other a 3D contour line plot has been drawn (Fig. 6). In 3D contour line plot analysis, the best fit with the same type of distribution must be fitted to each type of failure mode [12, 16].

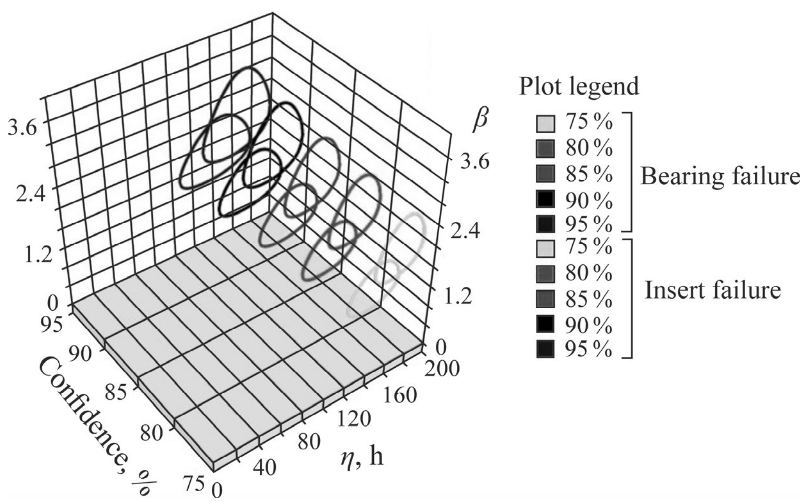

Fig. 6. A 3D contour line plot.

In Fig. 6, it is observed that the failure data of bearings and insert are overlapped at 95% contour. This implies that the two failure modes are not significantly different at 95% confidence level. This confirms that the probability of occurrence of bearing failure mode will affect the probability of occurrence of insert failure mode and vice-versa. Mixed Weibull analysis is used when the probability of occurrences of one mode of failure affects the probability of occurrences of other mode of failure and vice-versa [12, 16, 22, 28]. The other technique is Competing Failure Mode analysis (CFM) and it is applicable where the occurrences of one mode of failure are statistically independent to the other mode of failure [12].

4. MIXED WEIBULL DISTRIBUTION

The failure behavior of the complete data sets can be best modelled by mixed Weibull distribution (Table 1). Mixed Weibull analysis is needed to identify different types of failures and to analyze the failure through failure distributions. In mixed Weibull analysis, the effect of each failure is considered to determine the reliability of the individual bit component under study. This is obtained from the sum of the proportional reliability contributions of each subpopulation [26, 29]. For life test of identical components, the components are tested till the complete failure has occurred and their time-to-failure is recorded. In a life test of a component different types of a failure mode are observed over each region of life.

By applying Bayes theorem [22] the following expression is derived. If there are n subpopulations of N_1, N_2, N_3,… N_n failed components, then for mixed populations, the reliability at any mission time is determined as

$$R_{1,2\ldots n}(t) = \frac{N_1}{N} R_1(t) + \frac{N_2}{N} R_2(t) + \frac{N_3}{N} R_3(t) + \ldots + \frac{N_n}{N} R_n(t), \quad \sum_{i=1}^{n} \frac{N_i}{N} = 1 .$$

The probabilities, reliability versus time and failure rate versus time plot are shown in Fig. 7.

It is observed that at 95% confidence level, the data do not fall into a straight line on the probability Weibull plot (Fig. 7a). The failure data take a shape like S on the probability plot, this indicates occurrence of more than one failure.

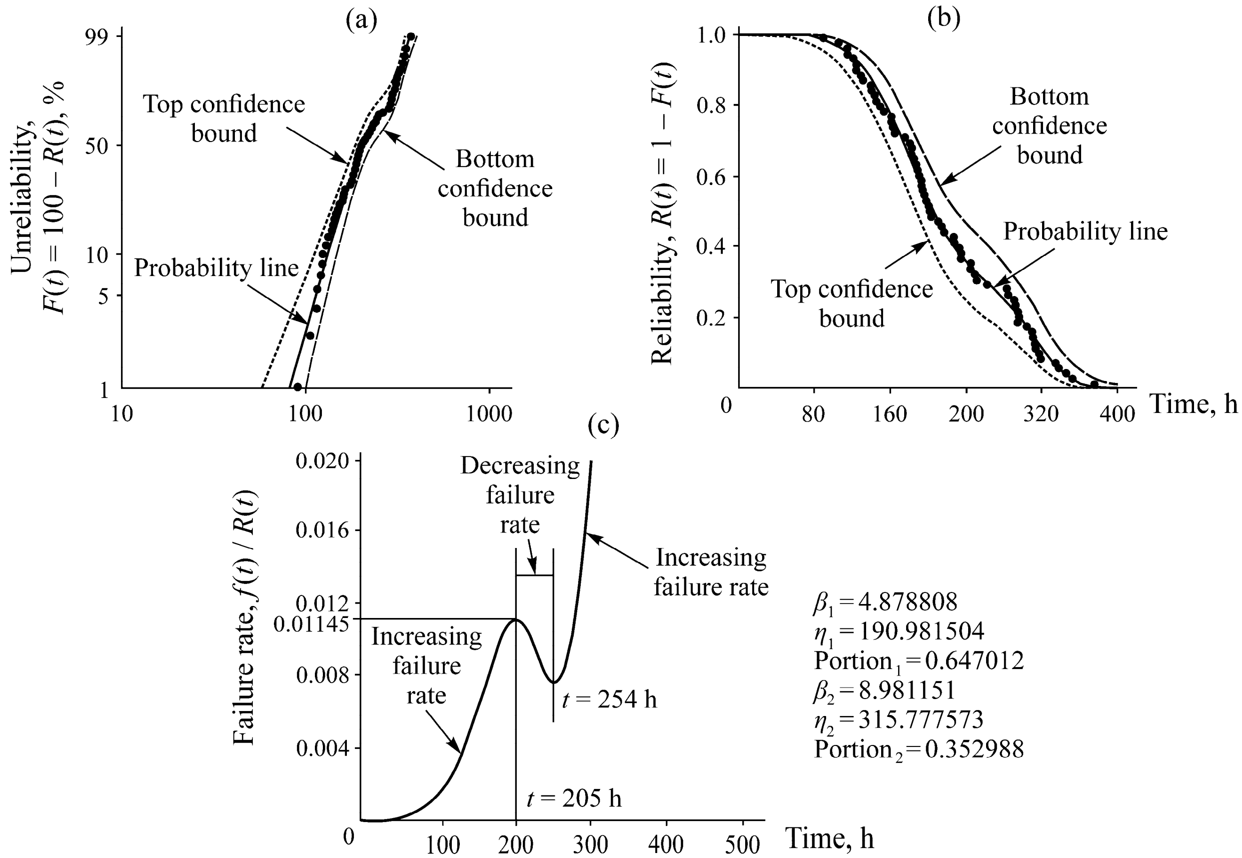

Fig. 7. (a) Probability Weibull plot, (b) reliability and (c) failure rate versus time using mixed Weibull at 95% confidence bound.

In Weibull++ the subpopulation data set automatically fits with Weibull parameters and portion values [29]. However, the presence of data points in a particular subpopulation is not indicated in Mixed Weibull analysis. Let us assume that β_1 and β_2 are the shape parameters for the subpopulation 1 and 2, respectively; η_1 and η_2 are the scale parameters for the subpopulation 1 and 2, respectively. In the results shown in Fig. 7, $\beta_1 = 4.878808$ and $\eta_1 = 190.981504$ were calculated for the first subpopulation; $\beta_2 = 8.981151$ and $\eta_2 = 315.777573$ are the Weibull parameters that were calculated for the second population. In Fig. 7c, the result showing Portion 1 = 0.647012 means that subpopulation 1 comprises 64.70% of the data points, whereas the Portion 2 comprises 35.29% of the data points.

The reliability and failure rate of the bit due to both types of failures have been evaluated together at 95% confidence level using 2 Subpop Mixed Weibull analysis. The reliability of the bit decreases with increasing time (Fig. 7b). The failure rate of a drill bit is increasing before time $t = 205$ hours. The failure rate decreases with increasing the time for the time interval $t = 205 - t = 254$ hours and from time $t = 254$ hours onwards, the failure rate of the bit increases with time (Fig. 7c).

CONCLUSIONS

The time-to-failure life data of tricone roller bit with tungsten carbide insert for the two non-repairable components bearing and inserts have been discussed. The rock properties for the observed open cast coal mine are the factors which lead to bearing and insert failure in a tricone roller bit. Distribution parameters of the two type failures have been studied for 3P Weibull distribution and at 95% confidence bound. The finding of this study states that the insert failure is more frequent compared to bearing failure and that at 95% confidence bound, the bearing and insert failures are dependent on each other. The results of mixed Weibull analysis technique suggest that the reliability of tricone roller bits decreases with increasing time at 95% confidence level. The failure rate of tricone roller bits increases before 205 hours. The failure rate decreases with increasing time during the time interval 205–254 hours. Thereafter, the failure rate of the bit increases with time again.

Since the bearing and inserts more frequently fail, the performance of the bit and drilling as a whole is affected. Modifications into design features are needed to improve the reliability of the components. The study revealed that Mixed Weibull technique for the downtime distribution can be a good choice for the analysis.

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