Competitive Reliability Analysis Of Heavy-Duty Gears In The Shearer's Cutting Part

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To improve the working efficiency of the cutting head of a coal cutter, studying the reliability of the heavy-duty gears in the cutting head under the condition of competitive failure was an effective approach. A reliability model for the gears under natural aging and sudden shock failure is established using stochastic processes. The three forces and three torques acting on the gears were obtained using mechanical system simulation software, and the fatigue damage accumulation value of the gears was obtained using fatigue analysis software. The reliability model for the large gear in the cutting head under the competitive failure condition of natural aging and sudden shock failure is obtained based on the stochastic process solution parameters. The results show that the competitive reliability model proposed in this paper is beneficial for improving the accuracy of gear reliability calculation and thereby improving the working efficiency of the cutting head of the coal cutter.

Keywords: Gear; Stochastic process; Fatigue analysis; Competing reliability

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1. Introduction

The cutting unit of a shearer significantly influences coal mining efficiency. As a critical component of the shearer, the gear transmission system in the cutting unit accounts for approximately 60% of all failure type [1], making its inspection and maintenance particularly important. Scholars and enterprises worldwide have conducted relevant research on the reliability analysis of the gear transmission system in the cutting unit. LI et al. optimized the planetary carrier of the shearer cutting unit through mechanical performance testing and finite element analysis, effectively improving its service life [2]. Zhang et al. used factors such as cutting depth and traction speed as experimental variables to analyze their influence on the vibration of the gearbox in the shearer cutting unit, providing a reference for establishing a theoretical model and reliability analysis of the shearer gearbox [3]. Liu et al. studied the dynamic characteristics of gear meshing transmission under different working conditions using the MG500/1130-WD shearer as the research object, combining theoretical analysis, simulation, and experimentation. Their work offers valuable insights into the mechanical characteristics of transmission components in the gear transmission system [4]. Sheng et al. analyzed the reliability of shearer gears under uncertain loads by establishing load and dynamic models. Their study revealed that the drive gear is more prone to failure, and proposed more rational principles for reliability analysis [5].

In the literature on system reliability modeling, initial studies only considered system failures caused solely by natural degradation or single shocks, i.e., degradation-induced failures (soft failures) and sudden failures (hard failures) [6–8]. However, during the operation of actual systems, the degree of natural degradation also influences the outcome of shocks, indicating a correlation between these two failure modes [9, 10]. References [6, 11] considered two interrelated failure processes and proposed two distinct failure forms: (1) soft failures caused by the combined effects of continuous degradation and sudden degradation damage induced by shock processes; (2) hard failures caused by sudden stress following the same shock process, assuming that shocks result in abrupt degradation. WANG et al. developed competitive reliability models for systems by examining two ways in which shocks affect natural degradation: one where shocks increase the system failure rate and the other where shocks amplify the degradation amount, additionally, they considered changes in the natural degradation under extreme shock conditions [12]. Huang, in addressing the relationship between sudden failure models and natural degradation failure models, first examined whether the two failure processes are independent. If they are independent and the two failure systems are in a series relationship, their reliability can be analyzed by combining their probability density functions using a series model [13]. However, in practice, the exact timing of sudden failures is often difficult to measure accurately, whereas the performance degradation amount at the time of sudden failure is relatively easier to measure. Moreover, the probability of sudden failure increases with higher performance degradation, indicating a certain correlation between the two. Therefore, the relationship between sudden failures and natural degradation failures must be considered.

In existing research, stochastic processes such as the Wiener process [14], Gamma process [15], and inverse Gaussian process [16] are commonly used to describe failure processes due to their practicality in modeling random fluctuations. Reference [17] established a competitive reliability model by combining the joint probability distribution functions of multiple degradation failures and sudden failures, proposing a reliability assessment method for competitive failures involving multiple degradation and sudden failures. When studying reliability models for sudden failures, Couallier et al. used an exponential function to describe the relationship between the amount of degradation and the probability of sudden failure [18].

In summary, this paper investigates the reliability of the low-speed heavy-duty gear in the shearer cutting unit's gear transmission system under different failure modes. By utilizing the Wiener process and Gamma process to characterize gear failure mechanisms, reliability analysis models are established. The interrelationships between these developed reliability models are examined, leading to the construction of a competing reliability model for the heavy-duty gear in the shearer cutting unit. The accuracy of this model is subsequently validated through an engineering case study.

2. Failure mechanism analysis of gears

The gear transmission system is a critical component for transmitting and delivering power within the cutting unit's drive system of a shearer. The operational principle involves the motor generating power, which is then conveyed through the gear transmission system to the cutting drum [19]. Failures in the shearer cutting unit's transmission system predominantly occur in the high-speed spur gears, accounting for approximately 60% of all failures. The most common primary failure modes for gears include pitting, tooth breakage, and tooth wear [20], with occurrence probabilities of approximately 24.9%, 52.3%, and 14% respectively. Pitting primarily results from chemical corrosion, phosphating, or electrical erosion. Tooth breakage is mainly caused by variable loading, improper gear installation, or substandard gear materials. Tooth wear typically occurs when foreign matter, such as iron debris or dust, enters the gear meshing zone, leading to wear through relative sliding friction between the meshing tooth surfaces.

When calculating gear fatigue life based on the cumulative damage theory, the gear operates under a certain number of stress cycles. However, due to the complex and variable stresses experienced by mining machinery, damage initiates when the applied stress exceeds the material's fatigue limit. As the operational duration of the mining equipment increases, fatigue damage accumulates. Failure occurs once the cumulative fatigue damage reaches a critical threshold. The rainflow counting method decomposes a load time history into individual load cycles by repeatedly identifying peaks and valleys. Considering both amplitude and mean values, this method effectively captures the inherent characteristics of fatigue loading and is widely used in engineering fatigue analysis [21]. The linear fatigue damage rule was initially proposed by Palmgren and later refined by Miner, resulting in the widely known Miner's Rule. This rule postulates that each stress cycle inflicts a certain amount of damage, and that the fatigue damage from each cycle is independent. Each fatigue cycle contributes an amount of damage, denoted as (i=1,2,...,n). Failure due to fatigue is predicted to occur when the cumulative damage from m cycles meets or exceeds a critical value D. This cumulative damage is expressed by the formula:

$$D = \sum_{i}^{m} \frac{n_i}{N_i} \tag{1}$$

When indicates that the component has undergone fatigue failure.

In ANSYS software, the fatigue analysis damage value is also derived based on the Palmgren-Miner equation and obtained through fatigue analysis using the rainflow counting method. Therefore, it is feasible to use ANSYS software for fatigue analysis of the shearer's low-speed heavy-duty gear. This paper adopts the linear cumulative damage theory, which is most commonly used in engineering, and utilizes the cumulative fatigue damage value caused by one load cycle as the data basis for reliability calculations.

2.1. Natural wear and tear degradation failure model

The primary failure mode of the high-speed spur gear in the shearer cutting unit is wear. During the operation of the shearer, the interaction between the cutting drum and the coal-rock mass generates a significant amount of dust, creating a harsh working environment [22]. The ingress of substantial dust into the gear transmission mechanism greatly increases the probability of wear in the gear transmission system [23]. However, due to the influence of numerous factors such as the coal-rock cutting position, cutting speed, and drum type, and considering the individual variability of the high-speed spur gears during the natural wear process, the cumulative fatigue damage of the gear per unit time is independent and non-negative. This characteristic precisely aligns with the non-negative, strictly increasing nature of the Gamma process. Therefore, the Gamma process can be used to describe the natural wear degradation process of the high-speed spur gear, denoted as $X(t) - Gamma(\alpha, \beta)$. Here, $X(t)$ is a non-negative random variable, α is the shape parameter, and β is the scale parameter. Its probability density function is:

$$
\begin{aligned}
f(X(t);\alpha,\beta) &= G_a(X \mid \alpha,\beta) \\
&= \frac{\beta^{\alpha}}{\Gamma(\alpha)}\chi^{\alpha-1}\exp(-\beta\chi)
\end{aligned} \tag{2}
$$

In the formula: the reliability function of gear degradation failure is:

$$
\begin{aligned}
R_g(t) &= P\left[T_g > t\right] = P\left(X(t) < D_g\right) = 1 - F_g(t) \\
&= 1 - \int_{D_g}^{\infty} f\left(X(t), \alpha(t), \beta\right) dX
\end{aligned} \tag{3}
$$

In the formula: T_g represents the time to degradation failure; $F_g(t)$ denotes the failure probability when considering only the degradation failure mode.

2.2. Sudden Failure Model

During the coal-rock cutting process of the shearer, the geological conditions of the coal seam are complex and variable, with irregularly distributed hard gangue and faults present within the coal rock. Consequently, the shearer is subject to sudden shocks from alternating loads during operation, which are random, unpredictable, and instantaneous. Furthermore, the probability of fewer impacts occurring per unit time is higher than that of more frequent impacts, a characteristic consistent with the Weibull distribution. The reliability function for sudden shock failure, $R_h(t)$, can be expressed as:

$$
R_h(t) = \exp\left(-\left(\frac{t}{\gamma}\right)^{\beta}\right) \tag{4}
$$

In the formula: γ and β represent the scale parameter and shape parameter, respectively.

2.3. Competitive Failure Model

During the performance degradation process of the shearer's low-speed heavy-duty gear, it is necessary to consider the correlation between natural degradation failure and sudden shock failure. These two failure modes may be independent of each other, allowing them to be treated as a series system. In this case, the system reliability $R_i(t)$ can be expressed as:

$$
R_i(t) = P(T > t) = R_h(t)R_g(t) \tag{5}
$$

In the formula: T represents the time to failure.

If a correlation exists between the two failure modes, a conditional probability of sudden shock failure with respect to the cumulative fatigue damage of the gear can be established. Since the distribution characteristics of the cumulative fatigue damage are a function of time, it is unnecessary to consider the direct relationship between the failure rate and time. Instead, the cumulative fatigue damage can be directly used to characterize the sudden failure. Based on relevant literature, the conditional probability of sudden failure given the cumulative fatigue damage can be derived as follows:

$$
R_h(t \mid X) = R_h\big(X(t)\big) \tag{6}
$$

Simultaneously, for sudden failure, assuming the probability density function of the cumulative gear fatigue damage X at time t is $G_c(X, \partial)$, the reliability function for sudden failure $R_h(t)$ at this point is given by:

$$
\begin{aligned}
R_h(t) &= P(T_h > t) = P(X < D_f) \\
&= \int_0^{D_f} G_C(X, \partial)\, dX
\end{aligned} \tag{7}
$$

Therefore, the reliability function for the gear's competitive failure model $R_C(t)$ can be expressed as:

$$\begin{aligned} R_c(t) &= P(T > t) = P(T_h > t, T_g > t) \\ &= \int_0^{D'_f} \left(G_c(X, \partial)\, dX\right) f\left(X(t); \alpha_m(t), \beta_m\right) dX \\ &= \int_0^{D'_f} R_h\left(X(t)\right) f\left(X(t); \alpha_m(t), \beta_m\right) dX \end{aligned} \tag{8}$$

3. Model parameter estimation

A total of $n = M + N$ samples were selected for the gear performance degradation experiment. Among these, M samples exhibited performance degradation, and N samples experienced sudden failure. The performance degradation amount of the gears, represented by the cumulative fatigue damage X_i at time t_p, was recorded at different time points.

Since the sudden failure model for the high-speed spur gear in the shearer cutting unit follows a Weibull distribution, the least squares method can be used for parameter estimation. The regression equation is as follows:

$$T = aX + b \tag{9}$$

In the formula: X_i and Y_i are:

$$\left.\begin{aligned} X_i &= \ln T_i \\ Y_i &= \ln\ln\left(\frac{1}{1 - F_i(T_i)}\right) \end{aligned}\right\} \tag{10}$$

In the formula: T_i represents the ascending order statistics of the censored times for gear sudden shock failures, where $i = 1, 2, ..., N$, $F_i(T_i)$ is the probability of sudden gear failure, and n is the total number of selected samples.

$$\left.\begin{aligned} \hat{a} &= \frac{\sum_{i=1}^{N} X_i Y_i - N\bar{X}\bar{Y}}{\sum_{i=1}^{N} X_i^2 - N\bar{X}^2} \\ \hat{b} &= \bar{Y} - \hat{a}\bar{X} \\ \bar{X} &= \frac{1}{N}\sum_{i=1}^{N} X_i \\ \bar{Y} &= \frac{1}{N}\sum_{i=1}^{N} Y_i \end{aligned}\right\} \tag{11}$$

In the formula: $\hat{a}$ and $\hat{b}$ are the estimated parameters of the regression equation, and

$$\left.\begin{aligned} \hat{\gamma} &= \exp\left(-\hat{b}/\hat{a}\right) \\ \bar{\beta} &= \hat{a} \end{aligned}\right\} \tag{12}$$

During the gear degradation process, the unknown parameters in the natural wear degradation failure model—namely the shape parameter and the scale parameter—are estimated using the maximum likelihood estimation method.

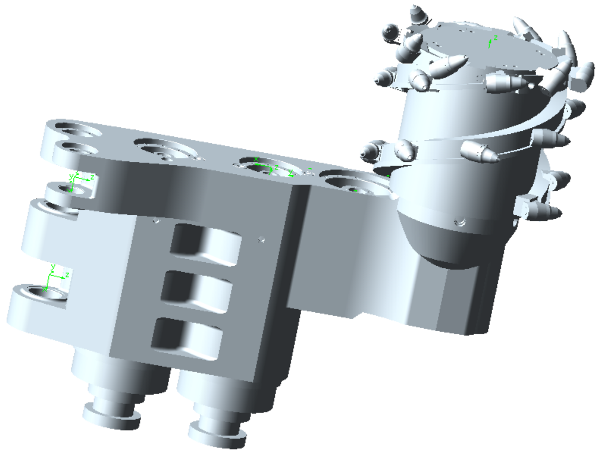


Fig. 1. Overall Model of the Shearer Cutting Unit

Table 1. Key geometric parameters of compound gears

Type	Parameter Name	Value
External gear	Module (mm)	7
	Number of teeth	29
	Pressure angle (°)	20
	Tooth width (mm)	75
Internal width	Module (mm)	3
	Number of teet	25
	Pressure angle (°)	30
	Tooth width (mm)	60

Table 2. Material parameters of the gears

Parameter Name	Numerical value
Density (kg/m^3)	7.91E+03
Elastic modulus (MPa)	1.97E+05
Poisson's ratio	0.286

4. Case analysis

During the operation of the thin coal seam mining machine, the gear transmission system of the cutting unit often fails before reaching its design service life. The low-speed, heavy-duty large gear is most susceptible to fatigue damage under alternating loads. Therefore, this study focuses on analyzing this heavy-duty large gear. This gear has a straight tooth meshing structure on the outside and an internal spline hole connection structure inside. The key geometric parameters of the gear are shown in Table

1; the base material of the gear is 18Cr2Ni4W alloy structural steel, which is a typical material for heavy-duty gears of the mining machine and has mechanical performance parameters as shown in Table 2; the tri-axial forces and tri-axial moments acting on the gear were obtained through simulation using Adams software, as shown in Figures 1-3:

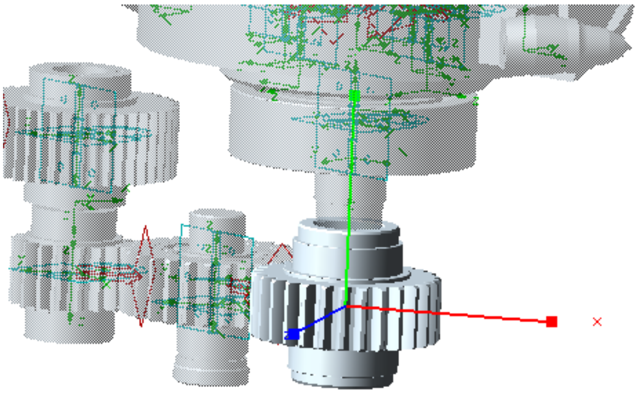
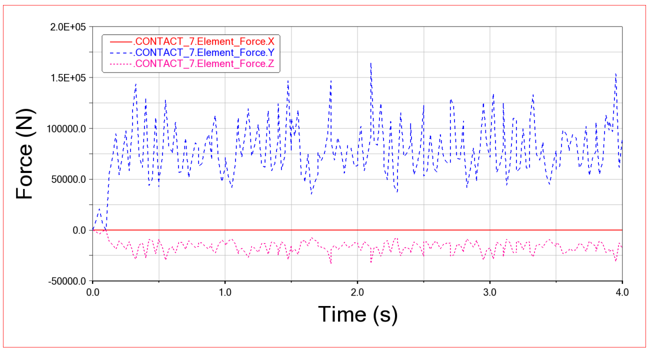
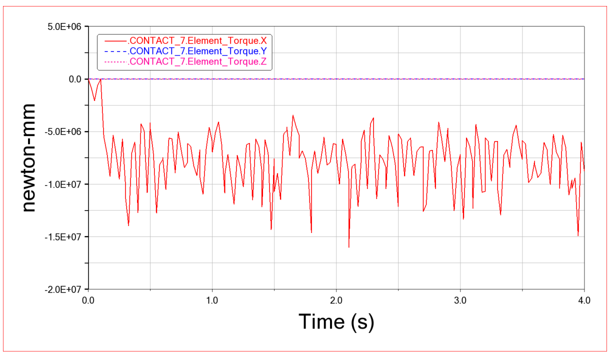


Fig. 2. Model of the low-speed heavy-duty gear in the shearer cutting unit



(a)



(b)

Fig. 3. Tri-axial forces and tri-axial moments

Utilize ANSYS software for the next step in analysis. The generated model was imported and material properties were assigned. A tetrahedral mesh was selected in the meshing options to generate the mesh, as shown in Fig 4. Add constraints to restrict all degrees of freedom except for the axial rotation. Through the comparison of multiple sets of grids, it is verified that the calculation results under the current grid configuration are stable and reliable, and can meet the precision requirements of subsequent analyses. The tri-axial forces and moments were imposed, and the solution was executed. The nCode time-series high-cycle fatigue analysis module was subsequently accessed. The load spectrum from the ANSYS post-processing results was imported, material properties were assigned to the model, and the solution was run; the results are shown in Fig 5. Based on the drum's rotational speed and the load characteristic curve, a duration of 0.5 seconds was defined as one cycle for the simulation experiment. Five sets of data were selected as periodic loads for simulating natural wear failure, repeating the aforementioned simulation steps for each set. Each load dataset contained two sudden impact events occurring at different times. Based on the simulation results, five sets of cumulative fatigue damage data caused by sudden impacts were extracted for each impact instance. The respective averages of the two sets of data were used as input for the sudden impact reliability model.

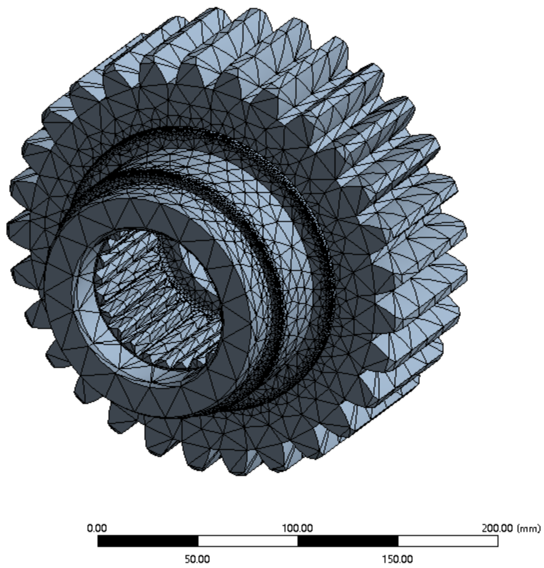


Fig. 4. Mesh generation

The obtained fatigue damage data for the low-speed heavy-duty large gear within one cycle is shown in Table 3. Data obtained from experiments conducted over the full life cycle based on the results in Table 3 is presented in Table

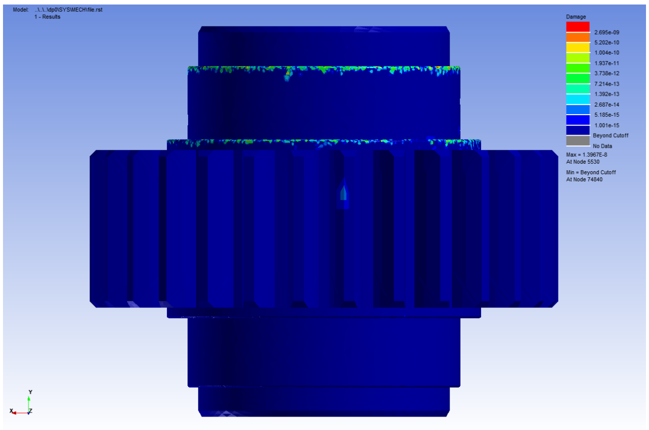


Fig. 5. nCode analysis results

4. According to the simulation experiments, an average of two sudden shocks occur per cycle. The corresponding average cumulative fatigue damage values caused to the gear are listed in Table 5.

Table 3. Cumulative fatigue damage of each group

Group	Cumulative Fatigue Damage
1	1.397E-08
2	1.635E-08
3	2.791E-08
4	1.145E-08
5	1.228E-08

4.1. Sudden Shock Failure Model

From this fatigue damage experiment, five sets of cumulative natural wear fatigue damage values and two sets of cumulative sudden shock fatigue damage values were obtained. These data represent the cumulative fatigue damage occurring at different times under various cyclic load conditions.

Calculations based on Equations (9-12) yield the two parameters for the gear sudden shock failure reliability model as $\hat{\gamma}_t$ and $\bar{\beta}_t$. The resulting reliability curve for gear sudden shock failure is shown in Fig 6.

4.2. Degradation Failure Model

The wear amount on the gear tooth surface during operation increases proportionally and monotonically with time, showing a linear trend. Therefore, the Gamma process can be used to describe this degradation process. Using the maximum likelihood estimation method in MATLAB software with the known data, the unknown parameters in the formula are solved. The estimated parameters for the two-parameter Gamma function are the shape parameter

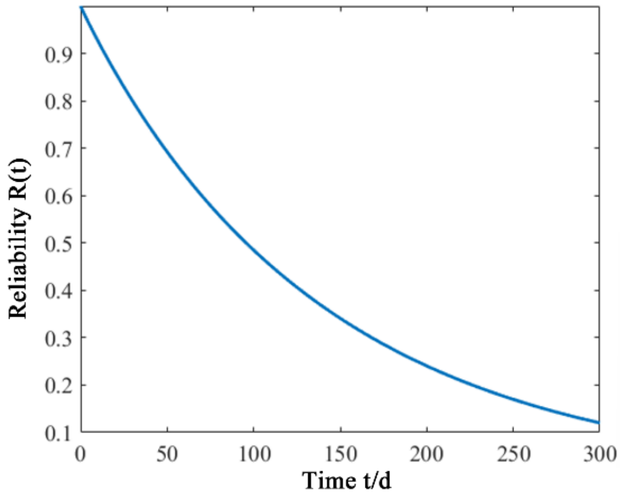


Fig. 6. Reliability curve for sudden failure

$\alpha_m = 4.5646$ and the scale parameter $\beta_m = 0.9054$. The resulting reliability curve for gear natural wear failure is shown in Fig 7.

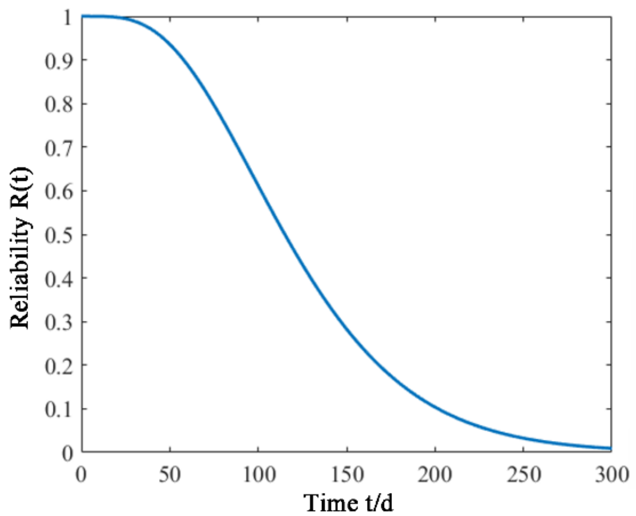


Fig. 7. Reliability curve for wear failure

4.3. Competitive Failure Model

When the natural degradation failure and the sudden shock failure are independent of each other, the competitive reliability model considering their independence can be obtained according to the previous Formula 5:

$$R_i(t) = 1 - \int_1^{\infty} f(X(t); 4.5646, 0.9054)$$
$$\exp\left(-\left(\frac{t}{139.1707}\right)^{0.9775}\right) \tag{13}$$

Table 4. Cumulative fatigue damage under different time conditions

Group	Time (days)				
	20	50	100	150	300
1	4.83E-02	1.21E-01	2.41E-01	3.62E-01	7.24E-01
2	5.65E-02	1.41E-01	2.83E-01	4.24E-01	8.48E-01
3	9.65E-02	2.41E-01	4.82E-01	7.23E-01	1.45E+00
4	3.96E-02	9.89E-02	1.98E-01	2.97E-01	5.94E-01
5	4.24E-02	1.06E-01	2.12E-01	3.18E-01	6.37E-01

Table 5. Cumulative values of sudden impact fatigue damage

Group	Cumulative Fatigue Damage
1	6.74E-06
2	2.64E-06

Based on Equation 13, the competitive reliability model for the low-speed heavy-duty large gear of the shearer, considering independent natural degradation failure and sudden shock failure, is obtained, as shown in Fig 8.

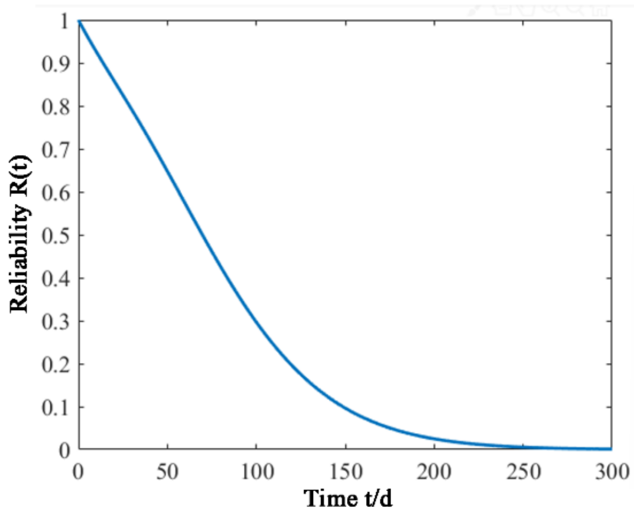


Fig. 8. Competitive reliability curve assuming independence between the two failure modes

Replacing the variable in Equation 10 with the cumulative fatigue damage caused by shocks, and based on Equations (9-12), a new reliability equation for sudden shock failure is derived:

$$R_h(t) = \exp\left(-\left(\frac{t}{17.0524}\right)^{-1.3068}\right) \tag{14}$$

Consequently, when a correlation exists between natural degradation failure and sudden shock failure, the competitive reliability equation for the shearer's low-speed heavy-duty large gear is given by Equation 15, and the corresponding competitive reliability profile is shown in Fig 9.

$$R_c(t) = \int_0^1 \exp\left(-\left(\frac{t}{17.0524}\right)^{-1.3068}\right) \left(1 - \int_1^{\infty} f\left(X(t); 4.5646, 0.9054\right) dX\right) \tag{15}$$

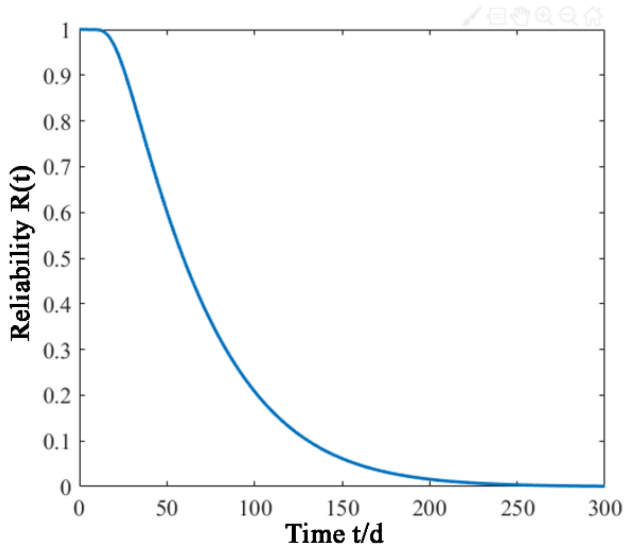


Fig. 9. Competitive reliability curve considering dependence between the two failure modes

By comparing Fig 6 to 9, which illustrate the variation trends of reliability curves for the low-speed heavy-duty gear in the shearer cutting unit under different failure modes, as shown in Fig 10, the following observations can be made: The reliability against sudden shock failure R_h decreases steadily throughout the complete operational cycle of the gear. In contrast, the reliability against natural wear failure R_g remains close to 1 during the first 50 days of operation, then declines rapidly over the subsequent 100 days, and eventually approaches zero after 250 days.

Analysis of the competing reliability curve under the assumption of independence between sudden shock failure

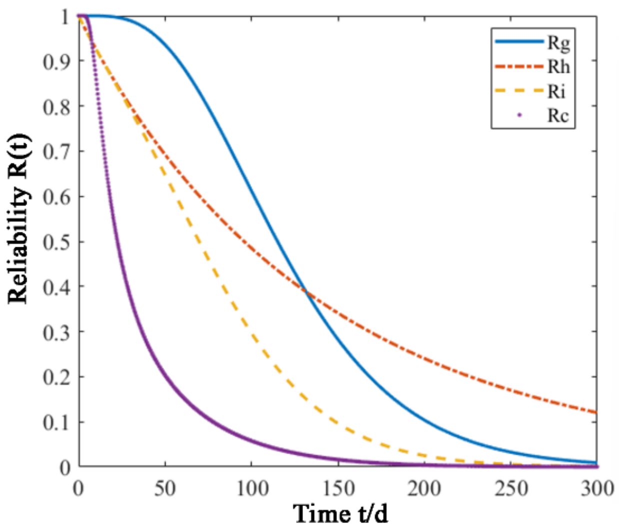


Fig. 10. Comparison of reliability curves

and natural wear failure processes reveals that when the gear's service time is less than 50 days, the curve of sudden shock failure reliability essentially R_h coincides with the independent competing reliability curve R_i. Subsequently, the reliability decreases rapidly over the following 100-150 days and approaches zero after 200 days. In contrast, examination of the competing reliability curve considering the dependence between sudden shock failure R_h and natural wear failure R_g hows that the competing reliability R_c remains close to 1 within the first 30 days, then declines rapidly during the subsequent 100-150 days. Notably, before 50 days of operation, the curve exceeds both R_h and R_i. After 50 days of operation, R_c falls below R_g, R_h and R_i, eventually approaching zero after 170 days.

The above analysis indicates that the gear's reliability typically begins to deteriorate sharply after exceeding 50 days of operation. Furthermore, it can be concluded that a certain correlation exists between the sudden shock failure and natural wear failure processes. This interdependence between the two failure mechanisms accelerates the degradation trend of the gear's reliability.

By comparing with the actual damage patterns observed in low-speed heavy-duty gears of shearer cutting units during field operations, the results show close alignment with the dependent competing reliability model established in this study, which considers the correlation between sudden shock failure and natural wear failure processes, thereby validating the accuracy of the proposed model.

5. Conclusions

(1)The natural wear failure and sudden impact failure processes of the low-speed heavy-duty gear in the shearer are correlated.

(2)The cumulative fatigue damage obtained by nCode fatigue analysis based on the rainflow counting method can serve as the calculation basis for the reliability model.

(3)By comparison with the service life of the low-speed gear in the cutting unit of the coal mining machine under actual working conditions, the accuracy of the competing failure reliability model established in this paper is verified.

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