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# Research on remaining useful life prediction of abrasive belt for the rail grinding

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***Abstract:*** *This study presents an in-depth analysis and prediction of the remaining life of abrasive belts under varying process parameters, based on the identification of their current wear status. A comprehensive approach combining theoretical insights and experimental methodologies was employed to investigate the wear patterns of abrasive belts throughout their entire lifecycle, as well as the influence of process parameters on belt wear. This led to the establishment of a quantitative wear rate model for abrasive belts. Utilizing this model, a abrasive belt wear process model was developed, incorporating Monte Carlo simulation methods to calculate the belts' remaining life. To further enhance the precision in monitoring the wear status and predicting the remaining life of the abrasive belts, this research integrates particle filtering techniques with the wear status monitoring model developed in the preceding chapter. The effectiveness and accuracy of the combined model were assessed and validated through experimental data, providing a significant contribution to the field of predictive maintenance and wear analysis in industrial applications.*

***Keywords:*** *Abrasive Belt Wear Analysis, Remaining Life Prediction, Process Parameters, Wear Rate Model, Monte Carlo Simulation*

## 1. Introduction

In the realm of industrial manufacturing, the efficient and reliable operation of machinery is pivotal to productivity and cost-effectiveness. Among various components, abrasive belts are critical in numerous manufacturing processes, particularly where precision surface finishing is required. However, the inevitable wear of these belts poses challenges in maintenance and operational efficiency. This study addresses the significant need for accurate wear analysis and remaining life prediction of abrasive belts, a key aspect often overlooked in predictive maintenance strategies.

A significant contribution of this research is the development of a quantitative wear rate model, which serves as a foundational tool for predicting the remaining life of these belts. A machine learning approach, involving classifiers like Decision Tree and Neural Networks, has been successfully applied to determine the abrasive belt wear in industrial processes. This approach achieved an accuracy of up to 86.1% in detecting belt wear and could predict machine abrasive parameters with high accuracy, which is essential for operational efficiency [1]. Research on the wear characteristics of abrasive belts during abrasive of medium density fiberboard (MDF) revealed that three distinct phases exist in the lifecycle of an abrasive belt. Fracture and abrasion were identified as predominant wear patterns, influencing material removal and thus affecting the efficiency of abrasive processes [2]. An in-process tool condition monitoring system using support vector machine and genetic algorithm was developed for abrasive belt grinding. This system ensures the effectiveness of the belt and the surface integrity of the material, highlighting the importance of real-time monitoring in maintaining the quality of finished components [3]. These studies collectively underscore the importance of accurate wear analysis and life prediction of abrasive belts in industrial manufacturing. By implementing such advanced methodologies, industries can expect to achieve enhanced operational efficiency and cost savings.

A study on the failure mechanism of abrasive belts during abrasive of MDF found that the mass of the abrasive belt mainly increased during the abrasive process. The study also observed patterns like "grits gathering" and "blocking" as predominant failure mechanisms. This research contributes to improving wood-material-abrasive theories and extending the life of abrasive belts [4]. A novel material removal rate model based on single grain force for robotic belt grinding was developed. This model, which divides the grinding process into stages based on grain wear, could be useful in the industry to predict the wear process of abrasive belts [5]. These additional studies further emphasize the significance of accurate wear analysis and life prediction in enhancing the efficiency and longevity of abrasive belts in industrial manufacturing.

A study on milling tool wear and life prediction established an integrated predictive model based on trajectory similarity and support vector regression. This approach, which focused on tool wear, is relevant for predicting the wear and life of abrasive belts in industrial contexts [6]. In the research by Romek et al. (2021), the wear processes of belt conveyors, an analogous system to abrasive belts, were studied to understand the intensive wear of metal parts, providing insights relevant for the durability and maintenance of abrasive belts [7]. Each of these studies contributes valuable insights into the dynamics of wear and maintenance of abrasive belts and related industrial tools, highlighting the importance of predictive maintenance and operational efficiency.

By addressing both the theoretical and practical aspects of abrasive belt wear and maintenance, this research fills a crucial gap in the field of industrial machinery maintenance. The findings and methodologies proposed in this study are expected to have wide-ranging implications for predictive maintenance, ultimately leading to enhanced operational efficiency and cost savings in various industrial applications.

## 2. Experiment and modeling of Abrasive Belt Wear Rate Model

This section investigates the influence of grinding process parameters (grinding pressure, belt speed, and grinding speed) on the wear of abrasive belts. The strength of abrasive grain breakage is related to the severity of internal defects. It is challenging to obtain the distribution parameters of breakage strength, and the location of the cross-section at the time of abrasive grain breakage is difficult to determine. Therefore, establishing an accurate model of abrasive belt wear based on wear mechanisms is quite challenging. Consequently, an experimental-based approach is adopted to analyze its quantitative laws and to interpret the reasons from a mechanistic perspective.

The process of abrasive belt wear refers to the change in the degree of wear of the abrasive belt over time. The wear degree of the abrasive belt is represented by the percentage of wear by mass. The wear process of the abrasive belt can be depicted as a curve $w(t)$ on a coordinate axis, where the horizontal axis represents the grinding time and the vertical axis represents the percentage of wear by mass of the abrasive belt. Since the wear process is influenced by grinding pressure $F_n$ and belt speed $v_b$, the wear process can be represented as

$$w(t) = w(t, F_n, v_b) \tag{1}$$

When the process parameters vary throughout the entire service life of the abrasive belt, the wear process can be represented as

$$w(t) = w(w_0, F_n(1), F_n(2), \dots, F_n(\mathrm{t}), v_b(1), v_b(2), \dots, v_b(\mathrm{t})) \tag{2}$$

In the given context, $w_0$ represents initial wear degree of the abrasive belt. Given the complexity introduced by multiple inputs in the model, the modeling process can be quite intricate. Defining the percentage of wear by mass per unit grinding time as the abrasive belt wear rate, and if the wear rate $r(t)$ is solely related to the current wear degree of the abrasive belt and the current process parameters, and not related to the wear degree at the previous moment, the equation (2) can be represented as

$$w(t) = w(t-1) - r(t) = w(t-1) + r(w(t-1), F_n(\mathrm{t}), v_b(\mathrm{t})) \tag{3}$$

Due to the wear rate being influenced by only three factors, the complexity of the modeling process is reduced. Therefore, by establishing a abrasive belt wear rate model, it is possible to integrate the wear rate based on the known current wear state, thereby obtaining the abrasive belt wear process.

### *2.1. Experiment for Abrasive Belt Wear Rate Model Based on Power-Exponential Function*

In the experiment, the percentage of wear by mass of the abrasive belt, as shown in Figure 1(a), is presented. The dashed lines in the figure represent the end of each cycle (27 grinding sessions). The rate of change of the percentage of wear by mass in Figure 1(a) represents the wear rate of the abrasive belt. From Figure 1(a), it is observed that in Group A experiments, the abrasive belts underwent severe wear. During this period of intense wear, the wear rate of the abrasive belt was significantly influenced by the surface morphology of the belt. Despite an increase in grinding pressure, the wear rate decreased as the degree of wear increased. In contrast, in Groups B to E, the surface morphology of the abrasive belts was relatively stable. In this phase, the wear rate of the abrasive belt was more influenced by process

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parameters. When the grinding pressure was high, the wear rate of the abrasive belt was also higher.

The wear rate of the abrasive belt decreases with the increase in the percentage of wear by mass, and this decreasing trend is not linear; the rate of decrease gradually diminishes. This phenomenon is primarily because, in the early stages of wear, the abrasive grains are sharp. As the abrasive belt loses the same amount of mass, the reduction in height is more pronounced, leading to a greater decrease in the probability of abrasive grain breakage, which in turn results in larger changes in the wear rate. The observed pattern of change in wear rate is consistent with the behavior of an exponential function. Thus, an exponential function is used to fit the relationship between the wear rate and the percentage of wear by mass of the abrasive belt. The specific form of the function is

$$r = ae^{bw} \tag{4}$$

The results, as depicted in Figure 1(b), show that the trend of the fitted curve closely aligns with the experimental value trends. The high degree of dispersion in the experimental values is primarily attributed to not considering the impact of the belt speed and grinding speed.

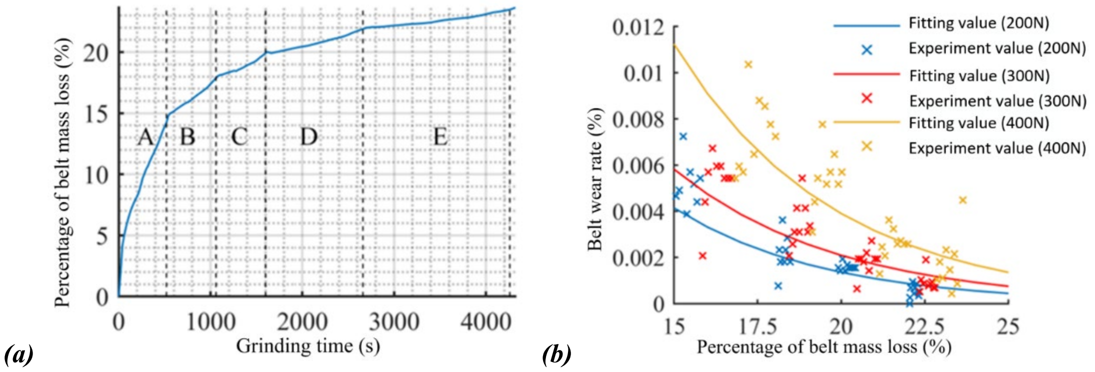


*Figure 1: (a) The change of mass loss percent along grinding time (b) The change of the wear rate along the abrasive belt wear under different pressure.*

### *2.2. Experiment for Abrasive Belt Wear Rate Model during the Accelerated Wear Stage*

The comparison between the fitted values obtained from the abrasive belt wear rate model and the experimental values is shown in Figure 2(a), while the errors in the fitted values are depicted in Figure 1(b). As can be seen from Figure 1(a), the overall trend of the model's fitted values generally aligns with the experimental values, with an average relative error of 32.3%. However, during the intense wear period of the abrasive belt, the fitted values are overall larger than the experimental values, and the error is also greater. Due to the rapid changes in wear during the intense wear period of the abrasive belt, if there is a significant prediction error in the wear rate at this stage, the error will accumulate when calculating the wear degree through integration. Therefore, a segmented approach is adopted, where separate models are established for the periods of intense wear and non-intense wear of the abrasive belt.

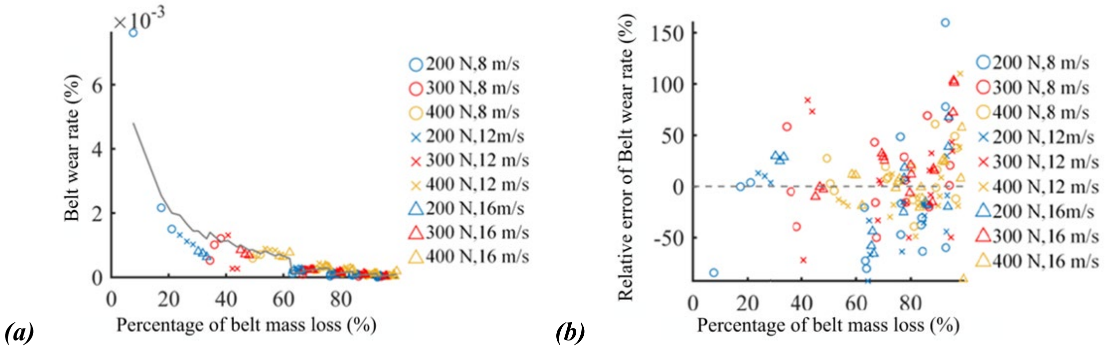


*Figure 2: (a) The experiment and model value of the abrasive belt wear rate (b) The error of the power exponential function of the abrasive belt wear rate.*

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## 3. Research on Remaining Life Prediction Based on the Abrasive Belt Wear Process

This section begins by introducing the method for determining the wear threshold at which the abrasive belt reaches the end of its service life. Subsequently, a method is proposed for calculating the wear process of the abrasive belt based on the abrasive belt wear rate model. Combining these two approaches enables the prediction of the remaining life of the abrasive belt. The remaining life of the abrasive belt is expressed as the mileage of rail grinding operations that the abrasive belt can continue to perform under normal service conditions.

### *3.1. Method for Determining the Service Life of Abrasive Belts*

It is found that in most rail grinding operations, the grinding speed is constant, and the belt speed should be maintained at a reasonably high level. By adjusting the grinding pressure, the predetermined material removal rate is achieved. When the pressure is increased to the maximum grinding pressure that the equipment can provide and the abrasive belt can no longer achieve the predetermined material removal rate, it is considered that the life of the abrasive belt has reached its limit. According to this method, the lifespan of the abrasive belt is related to the specific model of the abrasive belt, the maximum grinding pressure of the grinding equipment, and the depth requirements of the grinding operation.

Assume a grinding device uses a specific model of abrasive belt, and the material removal rate over the full life cycle of the belt under different pressures (F_1, F_2, F_3, F_4) varies as shown in Figure 3. When the material removal rate corresponding to the grinding depth required for the grinding operation is Z_1, a horizontal line is drawn through Z_1, representing constant depth grinding. This line intersects the material removal curves under each grinding pressure at points a to e, where each point's horizontal coordinate represents the degree of wear of the abrasive belt. When the abrasive belt is worn to a certain degree, to achieve the material removal rate Z_1, a grinding pressure of F_1, F_2, F_3, or, F_4 needs to be applied. The yellow curve represents the grinding pressure that needs to be applied at different wear levels of the abrasive belt to maintain a constant material removal rate Z_1. Pmax represents the maximum grinding pressure the equipment can provide. Therefore, when the required material removal rate is Z_1, the degree of wear at the end of the abrasive belt's life is represented by the point where the yellow curve intersects with Pmax.

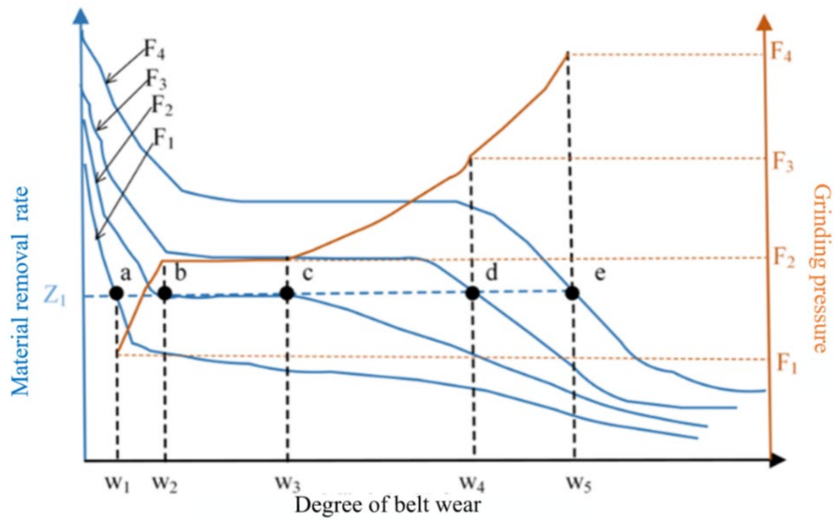


*Figure 3: The diagram of determination of service life of the abrasive belt.*

Therefore, to determine the lifespan of an abrasive belt at a specific grinding depth, one only needs to draw a horizontal line through the predetermined material removal rate. The horizontal coordinate corresponding to the intersection of this line with the material removal rate curve under the maximum grinding pressure indicates the degree of wear at the end of the abrasive belt's life. In the development of actual grinding equipment, it is sufficient to provide the curve of the material removal rate over the full life cycle of the abrasive belt under the maximum grinding pressure, which corresponds to the curve for F_4. Operators or machines can then use this curve in conjunction with the grinding depth requirements to determine the degree of wear of the abrasive belt at the end of its life.

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### *3.2. Method for Predicting the Remaining Life of Abrasive Belts*

The degree of abrasive belt wear is the integral of the wear rate of the abrasive belt over time, but the mean and variance of its probability distribution cannot be obtained by accumulating the mean and variance of the wear rate at each moment. This is because the mean and variance of the wear rate at the current moment are influenced by the current degree of wear, and the current abrasive belt wear percentage is related to the wear rate at the previous moment, indicating that the wear rates at different moments are not independent. Therefore, the mean and variance of the probability distribution of the degree of abrasive belt wear need to be solved based on conditional probability.

$$\begin{cases} f(x_1) = N(x - x_0|r(x_0), r(x_0)\sigma) = \frac{1}{\sqrt{2\pi r}(x_0)\sigma}\exp(-\frac{(x_1 - x_0 - r(x_0))^2}{2(r(x_0)\sigma)^2}) \\ f(x_2) = \int \frac{1}{\sqrt{2\pi r}(x_1)\sigma}\exp(-\frac{(x_2 - x_1 - r(x_1))^2}{2(r(x_1)\sigma)^2})\frac{1}{\sqrt{2\pi r}(x_0)\sigma}\exp(-\frac{(x_1 - x_0 - r(x_0))^2}{2(r(x_0)\sigma)^2}) \\ \cdots \\ f(x_n) = \int \frac{1}{\sqrt{2\pi r}(x_{n-1})\sigma}\exp(-\frac{(x - x_{n-1} - r(x_{n-1}))^2}{2(r(x_{n-1})\sigma)^2})\frac{1}{\sqrt{2\pi r}(x_{n-2})\sigma}\exp(-\frac{(x - x_{n-2} - r(x_{n-2}))^2}{2(r(x_{n-2})\sigma)^2}) \end{cases}$$

Since the analytical expression involves multiple integration operations, the solution is relatively complex. Therefore, the Monte Carlo simulation method is used to approximate the solution. The basic steps for solving are as follows: First, generate I particles representing the degree of abrasive belt wear, calculate the mean and variance of the wear rate for each particle, and generate J particles {r_oij }(j=1,2,…,"J") for the wear rate based on the Gaussian distribution determined by the mean and variance. The degree of wear particles w_0i combined with the wear rate particles r_0ij represent the particles for the next moment's wear degree (denoted as w_1ij). Calculate the mean and variance of the particle set as the mean and variance of the wear degree. Since the number of particles has reached a certain value, before calculating the probability density function f(x_2) for the next moment, resampling is required to reduce the number of particles and thereby reduce computation time. Repeat the above process until the mean of the abrasive belt wear degree reaches the threshold of its lifespan. Calculate the polishing mileage of the rail grinding vehicle during this process, which represents the remaining lifespan of the abrasive belt.

## 4. Conclusion

This study has focused on the challenging problem of predicting the remaining life of abrasive belts with limited samples under multi-dimensional influencing factors. The main achievements and significant conclusions of our research are outlined below:

1) Through a combination of theoretical analysis and experimental observations, we discovered that the wear rate of abrasive belts decreases exponentially with the percentage of wear by mass. It increases following a power-law function with grinding pressure and belt speed. Consequently, we established a power-exponential model for the abrasive belt wear rate. The model demonstrated a relative prediction error of 31.3%. By integrating the power-exponential model with historical data using Gaussian process regression,

2) The model achieved a heightened level of accuracy in predicting the average wear rate and distribution of abrasive belts, effectively reducing the relative prediction error to 13.0%. This enhancement in predictive accuracy marks a notable advancement in the field of wear analysis.

3) A novel method was proposed for determining the service life of abrasive belts, particularly tailored for rail grinding applications. In tandem with the developed abrasive belt wear rate model, a predictive approach for estimating the remaining life of abrasive belts was introduced. This approach demonstrated exceptional efficacy during the belts' stable and degradation wear phases, achieving predictions with an absolute error within 0.01 and a relative error below 3%. Such precision in prediction underscores the method's practical utility in industrial settings.

4) The model was formulated by a particle filtering-based methodology for monitoring the wear status of abrasive belts and forecasting their remaining lifespan. This method adeptly integrates the wear rate model with continuous wear status monitoring, utilizing comprehensive monitoring data gathered throughout the service life of the belts. This integrated approach resulted in a significantly enhanced accuracy in identifying the current wear status and in predicting the remaining lifespan of the abrasive belts, with a wear status identification error as low as 0.01 and a remaining life prediction error of just

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0.096 km. The success of this method highlights its potential impact on improving maintenance strategies and operational efficiency in industrial applications.

In conclusion, our research provides a comprehensive and effective framework for the prediction and monitoring of abrasive belt wear, offering significant practical value for industrial applications in predictive maintenance and operational efficiency.

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