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Study on the Failure Mechanism of the Polymorphic Mixture for Remanifactured Machinery Parts

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The polymorphic mixture failure mode for multiple heterogeneity of remanifactured (RM) machinery parts makes it difficult to assess their lifetime. The Weibull distribution failure model of RM parts (substrate, coating layer, bonding surface and sudden failure) is constructed with failure time statistics of the parts in service, the latter is used to characterize the failure patterns of RM parts. In view of the multiple heterogeneity of RM parts, the Kaplan–Meier type decoupling method is used to analyze four sets of failure statistics, and each state of the Weibull failure function of the above parts is solved. It reveals the in-service failure mechanism of polymorphic mixtures for multiple heterogeneity of RM machinery parts. The validity and feasibility of the model are verified by the case study. Research results provide the theoretical basis for the design and preparation of a RM alloy powder and the improvement of RM technology. Moreover, the method for lifetime prediction and failure time evaluation of RM parts is proposed and validated.

Keywords: remanufacturing, Weibull distribution, failure time, uncertainty, alloy powder.

Introduction. Remanufacturing is the process enabling old machines to regain their vital energy [1]. Possessing good quality, high efficiency, low cost and pollution-free, it is resource-saving and environmental-friendly technology [2].

In order to improve the quality and reliability of remanufactured (RM) products, many experts study the RM product design [3], performance evaluation of RM blanks [4], RM process optimization [5], quality control of RM assembly [6], and so on. However, the research on failure analysis and reliability of RM-oriented mechanical equipment is quite scarce [7]. Studies [8–13] indicate that the failure mechanism and reliability design of RM parts is a short board to improve the safety and reliability of service in RM products. Studies [14–18] on the surface coating of RM parts reported high uncertainties in their quality, as compared to the original parts.

The above studies point the urgent problems in this domain. It is topical to further study the failure mechanism and lifetime prediction of RM parts, to provide theoretical and and methodological support for the quality assurance technology system of RM parts. However, it is quite problematic to reveal the in-service failure mechanism of polymorphic mixtures of RM machinery parts with multiple heterogeneity.

This paper is based on the study of the polymorphic mixed failure mode of the RM parts of the multiple heterogeneity. Then, the Weibull distribution failure model of polymorphic mixture for RM parts is constructed. The aim is to reveal the failure mechanism of polymorphic mixtures for multiple heterogeneity of RM machinery parts in the service process, and provide theory and method support for the service lifetime prediction and failure time evaluation of RM components.

1. Failure Model. In the service process, substrate, coating layer and the bonding surface of the multiple heterogeneity for machinery RM parts under the interaction of multifield strength (such as temperature field, force field, etc.) would have a change in performance and shape. Under complicated and changeable conditions, it can aggravate the fatigue damage of matrix, coating layer and bonding surface, and then affect the lifetime of the parts. The wear, fatigue, corrosion and other forms of failure of substrate, coating layer

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and the bonding surface occurred at the same time under the interaction of multi field strength. Then, the failure mechanism of the multiple heterogeneity for machinery RM parts has the characteristics of polymorphic distribution, mixed failure and so on. Therefore, it is necessary to construct the failure distribution function of the matrix, the coating layer and the bonding surface of multiple-heterogeneity RM parts to characterize failure modes.

1.1. Weibull Distribution Failure Model. Because the service lifetime of machinery RM parts depends on the weakest link, which is similar to the failure distribution of the chain structure, it can be used to describe the Weibull distribution [19]. The latter is based on the weakest link model or series of models and reflects the material defects and stress concentration on the lifetime of substrate, coating layer and the bonding surface. Since the increasing failure rate has to be in conformity with the practical application, the Weibull distribution is applicable to the lifetime distribution model of substrate, coating layer and bonding surface. The Weibull probability density distribution function [19] is defined as

$$f(t)=\frac{\beta}{\alpha}\left(\frac{t}{\alpha}\right)^{\beta-1}\exp\left[-\left(\frac{t}{\alpha}\right)^{\beta}\right], \tag{1}$$

where α is failure time (scale parameter) and β is the Weibull slope (shape parameter).

Thus, the solution of the cumulative failure fraction of Weibull distribution is

$$F(t)=\int_0^t f(t)dt. \tag{2}$$

By re-arranging Eq. (2), the function logarithm can be obtained

$$\ln[-\ln[(1-F)]=\beta\left[\ln\left(\frac{t}{\alpha}\right)\right]. \tag{3}$$

According to Eq. (3), at $F = 0.63212$, we get $\ln[-\ln[(1-F)]\to 0.$

This shows that the characteristic time of parts failure is the failure time of the failure rate of 63.212%. Therefore, the Weibull distribution failure time is $\alpha=t_{63}$.

The Weibull slope β can be derived from Eq. (3):

$$\beta=\left[\ln\left(\frac{t}{t_{63}}\right)\right]^{-1}\ln[-\ln(1-F)]. \tag{4}$$

In view of the generally reliable lifetime of RM parts, its reliability is $R = 0.95$, so introducing $F = 0.05$ (t_5) into Eq. (4), we get the Weibull slope β. In fact, any cumulative fraction of F and the corresponding failure time can be substituted into Eq. (4).

For the Weibull distribution (β, t_{63}), the cumulative fraction F can be assessed as

$$t_F=t_{63}\exp\left\{\frac{1}{\beta}\ln[-\ln(1-F)]\right\}. \tag{5}$$

The above calculation procedure yields the reliability function as follows:

$$R(t)=1-F(t)=\exp\left[-\left(\frac{t}{\alpha}\right)^{\beta}\right]. \tag{6}$$

The Weibull distribution application in the lifetime distribution model is quite effective, so it is used to describe the lifetime distribution of matrix, coating layer, and the bonding surface of RM parts.

1.2. Polymorphic Failure Model. From Eq. (6), the failure model of RM is

$$F(t) = 1 - \exp\left[-\left(\frac{t}{\alpha}\right)^{\beta}\right]. \tag{7}$$

The multiple heterogeneity of machinery RM part mainly includes matrix, coating layer, and the bonding surface, as shown in Fig. 1. The failure mode in the service process of RM parts includes not only the failures of substrate, coating layer, and bonding surface, but also a sudden failure due to the uncertainty of RM parts or other causes. So, we construct the failure model of the matrix, burst, coating layer, and bonding surface failures.

$$F_i(t) = 1 - \exp\left[-\left(\frac{t}{\alpha_i}\right)^{\beta_i}\right], \tag{8}$$

where $i \in \{1, 2, 3, 4\}$, $i = 1$ is matrix failure, $i = 2$ is sudden failure, $i = 3$ is bonding surface failure, and $i = 4$ is coating layer failure.

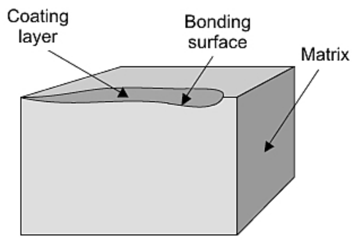

Fig. 1. Structural diagram of RM parts.

The Weibull failure model characterizes all above failures and explicitly describes the failure mode of RM parts.

2. Decoupling Method. Decoupling of polymorphic mixed failure modes is the necessary precondition for the reliability research of RM parts. Due to the multiple heterogeneity of RM parts, it is inevitable that multiple failure mechanisms correspond to the unified data. Given limitations and uncertainty of the data on RM parts in the service process, we use the Kaplan–Meier decoupling method [20], which is applied to the analysis of small or large samples without packet survival rate, to separate different mechanisms.

Assuming that a certain type of RM parts uses the same surface repair technology, there are m sets of failure mechanisms, which are coupled. Admittedly, a cumulative integral of failure F_i is very hard to calculate, due to a coupling of failure mechanisms. Assume that the failure rate p_i is the ith failure mechanism in the total sample, where $\sum_{i=1}^{m} p_i = 1$. Then, the failure rate for the jth time period is

$$F^j = p_1 F_1^j + p_2 F_2^j + \ldots + p_m F_m^j. \tag{9}$$

According to the Kaplan–Meier decoupling method, F_i^j is the failure ratio in the $(j+1)$th time period of the ith failure mechanism:

$$1-F_i^{j+1}=(1-F_i^j)\left[\frac{n-\sum_{i=1}^{m}(v_i^{j+1})}{n-\sum_{i=1}^{i-1}(v_i^{j+1})-\sum_{i=1+1}^{m}(v_i^{j+1})}\right], \tag{10}$$

where v_i^{j+1} is the number of failures in the $(j+1)$th period of the ith failure mechanism.

Using the statistical data of RM product service process and Eq. (10), one can be calculate the number of failures for the matrix, burst, coating layer, and bonding surface of RM parts with the multiple heterogeneity and then assess the failure rate of each failure mechanism, to ensure the realization of the Weibull distribution model.

3. Case Study. As an example, consider a company involved in diesel engine remanufacturing business. Their statistics show more than 70% of RM parts in the remanufacturing engine, but the improvement of quality and service reliability of the engine is quite problematic due to many uncertainties. This increases the cost of after-sales service and customer complaint frequency. The lifetime prediction and failure time evaluation of RM parts becomes a critical problem for the enterprise product maintenance management. In order to solve this problem, the project team takes the WF618 RM connecting rod as the research object. This widely used RM connecting rod is produced from 45 steel coated with nickel-base alloy powder. With a help of the enterprise service sector and local service stations, the effective sample data on the past two years were collected and tabulated in Table 1.

T a b l e 1

248 WF618 Type RM Connecting Rod Failure Sample Data

Failure time (d)	Cumulative fraction F	Number of failures				F_1	F_2	F_3	F_4
		Matrix	Sudden failure	Bonding surface	Coating layer				
0	0	0	0	0	0	0	0	0	0
100	0.03	1	1	2	3	0.0041	0.0041	0.0082	0.0123
200	0.05	2	4	3	3	0.0125	0.0207	0.0207	0.0247
300	0.07	4	5	5	4	0.0294	0.0416	0.0415	0.0414
400	0.10	5	7	8	6	0.0508	0.0709	0.0749	0.0666
500	0.16	8	9	12	10	0.0858	0.1092	0.1251	0.1092

The characteristic values of each failure mode (Table 2) are obtained according to the model of RM parts and the Kaplan–Meier decoupling, and the characteristic values of each failure mode are obtained. According to the above calculation process, we can get Weibull function of matrix failure for 248 WF618 RM connecting rod as shown in Fig. 2. Through the data statistics and failure mechanism of polymorphic mixtures for RM connecting rod in Fig. 2, one can get the following results. Firstly, the increasing order of reliability of RM parts is: bonding surface failure, sudden failure, coating layer failure and matrix failure. Secondly, nickel-base alloy powder is used in RM coating. The dominating failure of bonding surface shows that RM surface repair technology needs to be improved, and the configuration of sprayed metal powders also needs further development. Therefore, RM processing technology is the most critical technology for the reliability of RM products.

T a b l e 2

Characteristic Values of Each Failure Mode

Characteristic values	RM parts' failure	Matrix failure	Sudden failure	Bonding surface failure	Coating layer failure
t_{63}	2082.54	3493.17	2760.54	2442.95	2892.62
β	1.267133	1.309437	1.318876	1.340691	1.295505

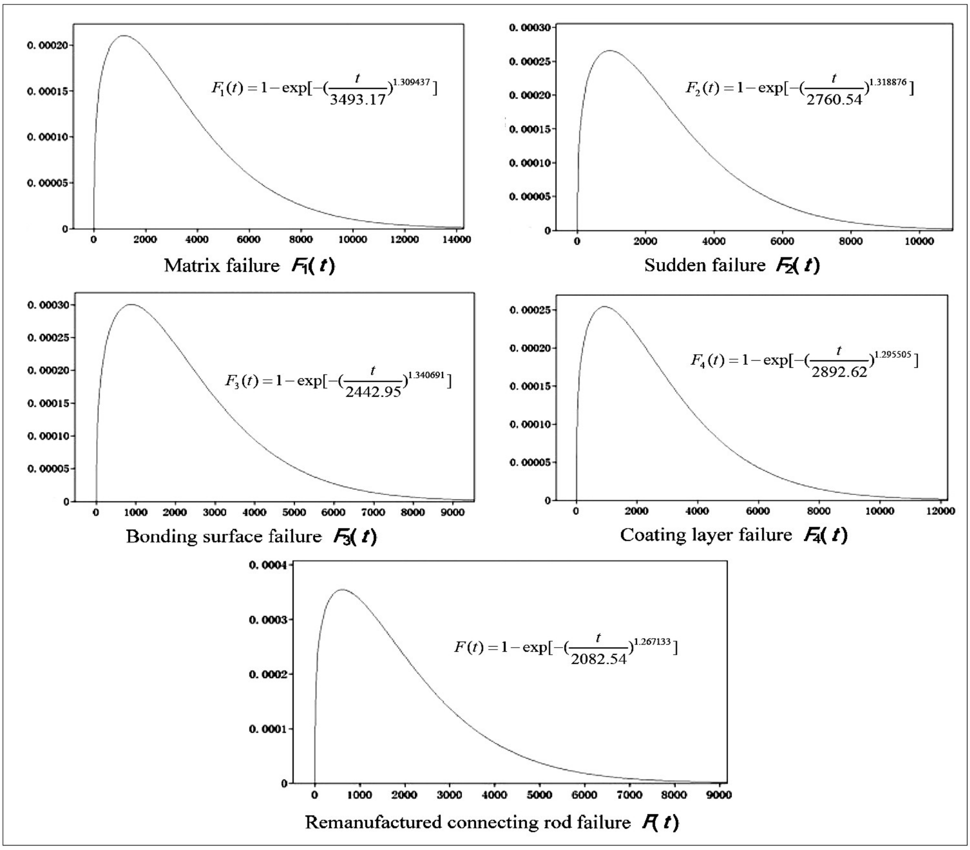

Fig. 2. Failure mechanism of polymorphic mixtures for RM connecting rod.

Thirdly, the maintenance data show that the sudden failure rate is high because of the high uncertainty of RM parts. For a long time, many scholars, experts and engineers believe that the uncertainty of the quality of RM parts is an important factor affecting their safety and reliability. This view is verified from both theory and data by the failure mechanism of the polymorphic mixture of RM parts. Fourth, the polymorphic failure model can quantitatively characterize the failure mechanism of the RM connecting rod in the service process, and provide a scientific basis for the service lifetime prediction and failure assessment of the RM connecting rod to maintain RM engine.

Conclusions. There is a high degree of uncertainty in RM parts; it affects the quality of RM products. Identifying and measuring the uncertainty of RM parts is the primary task in optimizing RM processes to improve the quality of RM products. This paper studies in the failure mechanism of the polymorphic mixture for RM machinery parts, which is the theoretical basis for their safety and reliability. It substantiates the lifetime prediction and failure time evaluation of RM parts. On the other hand, it is instrumental in the design and preparation of RM alloy powder and the improvement of RM technology. It also shows how to improve the quality of RM products. We will further study the modeling and analysis of fatigue, wear, creep and corrosion failures of RM parts.

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