Research on the Degradation Model of the Clamping Device Based on CAE Simulation and Data-driven

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ABSTRACT

The paper is based on PHM oriented design and modeling of durability testing for clamping devices. The testing scheme is made out through the Computer Aided Engineering (CAE) simulation result and the degradation model is studied by Data-driven according to the test data. Based on the analysis of main failure mode and mechanism, it is concluded that the reason of clamping device cracking is fatigue which caused by the cycle force. The durability test is conducted by CAE simulation analysis, and the strain data of the device have been collected by the NI data acquisition equipment. Based on the collected data, Data-driven method is used to model the high-cycle fatigue degradation caused by the cycle force. And with the comparison among different regression models, we selected the appropriate one which will provide theoretical support for PHM management of similar machines. In applications, by updating this model with actual degradation data of the target device, can monitor the health state and predict the remaining service life of the target device. So that the actively predictive maintenance can be done and the failure can be avoided.

1. INTRODUCTION

Curing machine is used for curing tire. The production process runs automatically, executing the loading, shaping, curing, unloading, inflating, shaping, cooling processes etc. It is one of the core machines in tire manufacturing plant, and determines directly the tire quality and the production capacity.

Clamping device is the key part of curing machine. As the main force bearing components, the clamping device directly influenced the reliability and security of the system. At present, the health monitoring and remaining service life prediction of the clamping device has become the focus of the new generation curing machine. It is expected to make maintenance strategies, reduce the failure risk of machine.

However, there is not enough information of failure mode and mechanism of the clamping device and also no degradation model for reference. So it is difficult to develop PHM of clamping device. So the objective of this paper is to establish the high cycle fatigue degradation model of clamping device, and summarized a set of failure analysis and PHM developing methods of mechanical products through the research process.,

The structure of clamping device and curing machine shown in figure 1, in which the Hydro-cylinder and the lock sleeve are the fixed part, while the lock rod is the active part. In the normal working cycle, the clamping device is used for clamping, pressurization, pressure relief and unlocking. The clamping device bearing the pull force of Hydro-cylinder in the process of pressurizing, pressure time depends on the tire size, for example: tire of 18 inches need 12 minutes' pressure time. The cyclic pressurizing process causes the cumulative damage of the clamping device, which will affect its remaining service life.

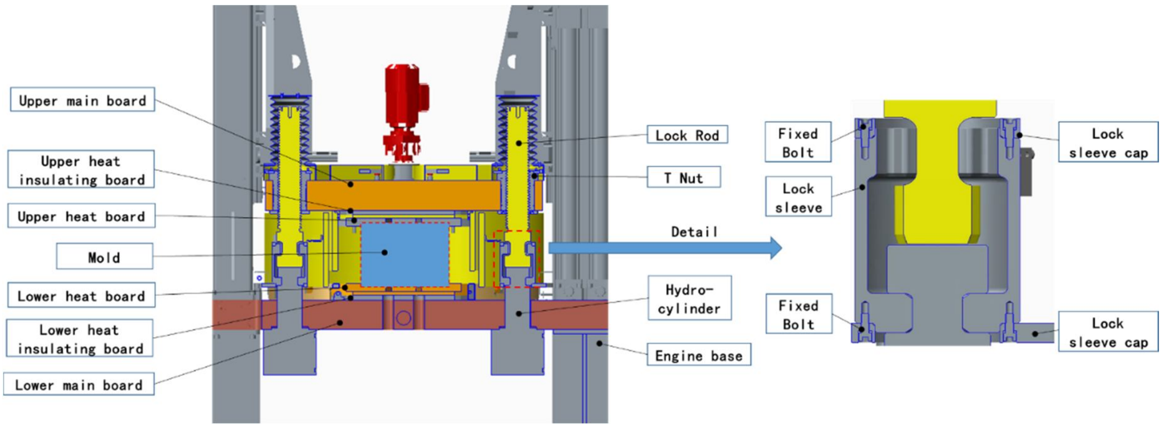


Figure 1. Structure diagram of clamping device and curing machine

2. RESEARCH METHOD

The remaining service life prediction technology of PHM including failure mechanism Model- driven method, Data - driven method and the fusion of the two, etc. . The third one is built on the basis of failure mechanism model, using large datasets to constitute the regression model and renewal it. This is a good practice type in engineering application. In this paper, the fatigue degradation model of the clamping device is established based on test data. The technology roadmap for model establishment based on Data-driven shown in figure 2:

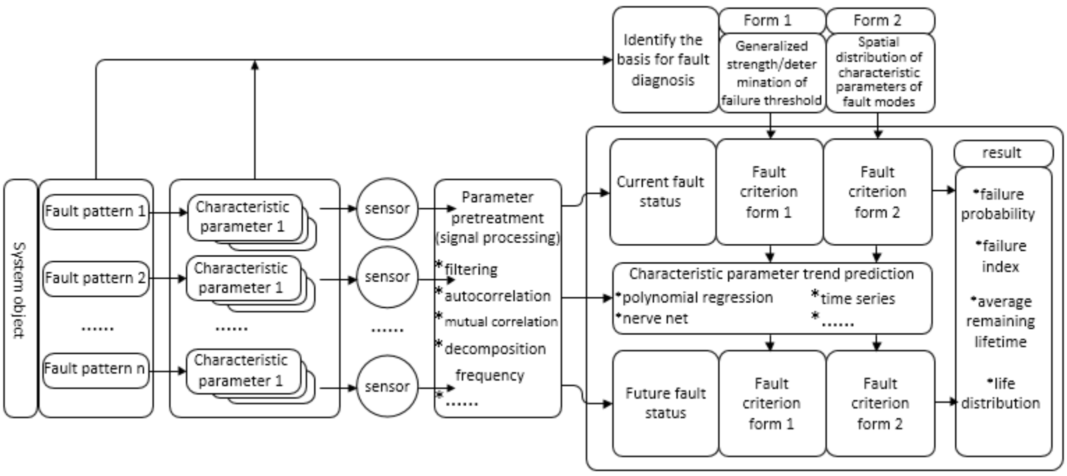


Figure 2. Technology roadmap for model establishment based on Data-driven

In this paper, the technology roadmap is combined with engineering application. The research process is divided into four stages as follow: the failure causes and mechanism analysis stage, the durability testing design and implementation stage, the test analysis stage and the degradation modeling stage. The final degradation model will be used as a reference model for PHM of the clamping device. The research ideas and methods are shown in Figure 3.

In the first stage, based on the historical failure data and the results of Abaqus software simulation analysis report and the physical detection. It is comes to the result that the failure mechanism of the clamping device is the high cycle fatigue which is caused by the cyclic stress of structure. And the eigenvalue is the strain of clamping device.

In the second stage, according to the analysis results of Abaqus software, the durability test of the clamping device can be designed. During the test process the degradation data of the stress weak point of clamping device is collected.

In the third stage, the degradation process data are pretreated and using regression analysis to modeling. Meanwhile, the main failure mechanism of the clamping device is verified by the failure analysis of the test.

In the fourth stage, by analyzing the fitting degree of the regression models and then select the one which proves good effect.

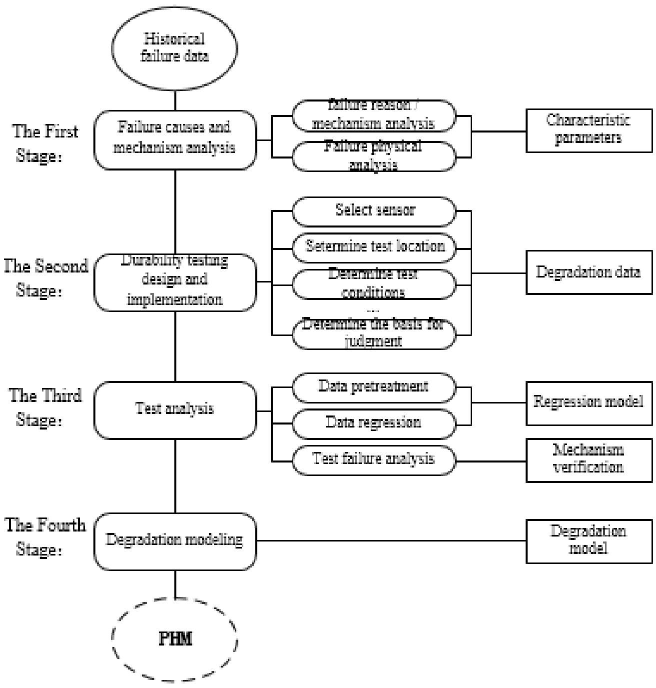


Figure 3. Research ideas and methods for modeling

3. THE RESEARCH PROCESS

3.1. Failure Causes and Mechanism Analysis of Clamping Device

Based on the historical failure data and the FMECA report of curing machine, it is told the main failure mode of clamping device are distortion and fracture. Using Abaqus software to analysis the stress distribution of clamping device in working conditions, shown in Figure 4:

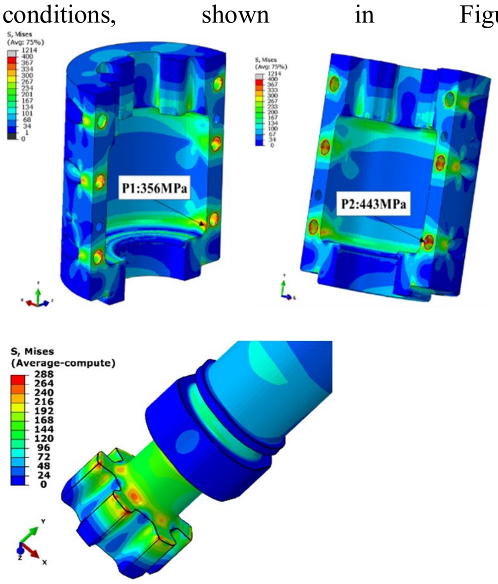


Figure 4. Stress distribution of clamping device

In practical application, through combining the degradation data of the target device with the degradation model, we can update the model and random parameters of the model are estimated posterior, so it can be used to predict the remaining service life and maintenance strategy of the equipment.

The clamping device's static strength and fatigue safety factor under normal working conditions can be obtained by the CAE simulation. Along with the physical analysis, it comes to a conclusion that the failure mechanism is high cycle fatigue. The clamping device endure cyclic stress from Hydro- cylinder, it will cause the initial cracks in stress concentration point, with continuous cycles, crack growth until clamping device failure. Therefore, the strain is selected as the eigenvalue of the high cycle degradation model of the clamping device. Focusing on the stress weak point of clamping device and monitoring the growing trend of the strain during the degradation process.

It is a serious risk of the crack in this device, so we defined the crack generation as the failure criterion of the clamping device.

The high cycle fatigue degradation process is a monotonous and irreversible behavior. When initial crack appears, the strain can lead to significant changes of strain variation surrounds it. Therefore, the crack generation is characterized by the variation of the strain and then the failure of the structures is determined strain variation formula show as follow:

$$\Delta\varepsilon = \varepsilon_{n+1} - \varepsilon_n \quad (1)$$

Where: ε_n represents the strain values of the n test cycle, ε_{n+1} represents the strain values of the n+1 test cycle. We are working on the assumption that the device was cracked if the equation $\Delta\varepsilon<0$ is still tenable over 5 continuous samples, and then determined the clamping device failure has occurred.

3.2. The Durability Testing Design and Implementation

The durability test of the clamping device which is aim to get the strain information was carried out. And through the strain value and the growing trend of the test data, we can study the fatigue degradation of clamping device.

3.2.1. Monitoring Sensor and Monitoring Point Selection

The CAE simulation analysis is used for testing design, using the Abaqus software to simulate the surface deformation, stress concentration of the clamping device under working condition. Based on the result, the factors including stress concentration, strain gradient and structural characteristics must be take into consideration to strain gauge locating. And select the BE120-1AA（11）-G600 type strain gauge as the monitoring sensor. The position of pasting strain gauge in durability test are shown in figure 5, There are four sets of clamping devices in total. The strain gauges are located in their stress concentration zones and its symmetrical part in order to monitoring the growing trend of strain and matching the strain value with the CAE simulation data. The 1# to 24# are the strain monitoring point. The strain data of 24 points will be collected continuously during the test.

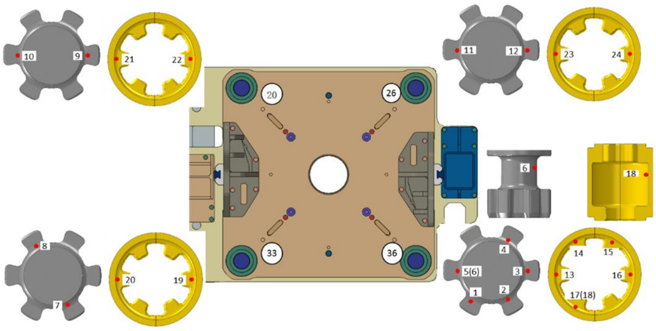


Figure5. Strain monitoring point of champing device

3.2.2.Test Scheme

(1)Test object

The durability test platform is composed of curing machine base, upper right curing chamber (including the claiming device), tooling and hydraulic system. The structure shown in figure 6. Test picture shown in figure 7.

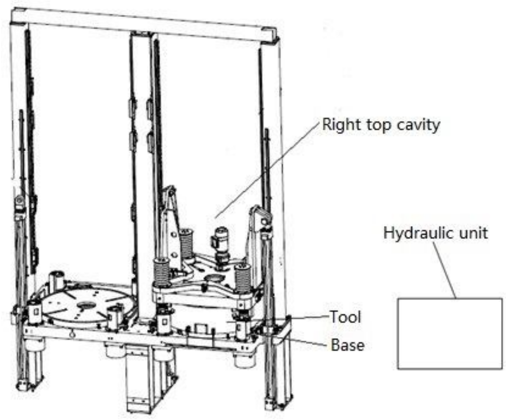


Figure 6. Structure of test platform

Figure 7. Physical test picture

(2)Test scheme

The test was carried out under pressure circularly which is likely to the actually working condition. Time sequence of test shown in table 1 below.

Table 1 Time sequence of the test

Clamping	Pressurization	Pressure relief	Unlocking
1s	3.8s	2s	1s

(3)Test equipment and data collecting method

Using the NI data acquisition equipment to collect strain data of clamping device continuously. In order to minimize the instability factors and the measurement errors, we use the temperature compensated strain gauges and make sure the monitoring point is arranged accurately. The sampling frequency of NI data acquisition equipment is 50 Hz, and record 2 single cycle strain data for every 1000 test cycle. The main testing equipment are shown in table 2 below:

Table 2 List of main test equipment

No.	Name	Product No.	No	Remark
1	Strain gauge +binding post	BE120-1AA （11）-G600	48	24 spare
2	Strain gauge board	NI PXIe4330	3	
3	NI data acquisition equipment	PXI1045/PXI e1082	2	
4	Computer	Lenvov	1	LabView

The 1#-24# strain gauges are connected to the strain acquisition board in the NI data acquisition platform, as shown in Table 3 below:

Table 3 List of the test channel matching

No.	Name of strain gauge board	Channel No.	Strain gauge No
1	PXIe 4330-1	4-0	1#
2		4-1	2#
3		4-2	3#
4		4-3	4#
5		4-4	5#
6		4-5	6#
7		4-6	7#
8		4-7	8#
9	PXIe 4330-2	5-0	9#
10		5-1	10#
11		5-2	11#
12		5-3	12#
13		5-4	13#
14		5-5	14#
15		5-6	15#
16		5-7	16#
17	PXIe 4330-3	6-0	17#
18		6-1	18#
19		6-2	19#
20		6-3	20#
21		6-4	21#
21		6-5	21#
23		6-6	23#
24		6-7	24#

(4) Test failure criterion

These conditions, bolts loose, bolts fracture, mechanical structure parts and components damage are considered as a fault during the test. Then the test need for fault records and exclusion. The test should be terminated when the clamping device fails.

3.3. Analysis of Test Data

According to the fault records, the No.24 clamping device (shown in figure5) fracturing on the 463,064 cycle, the failure images of clamping device shown in figure 8 and figure 9. After fracture analysis, the initial crack zone, crack growth zone and final fracture zone of the fracture of the clamping device are found. Finally the stress cycles cause the high cycle fatigue fracture of the clamping device.

Figure 8. Clamping device failure picture

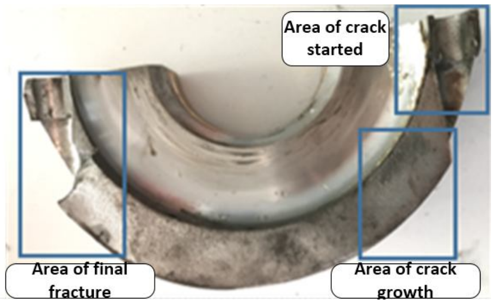


Figure 9. Physical analysis of breaking lock sleeve

Taking the failure of No.24 clamping device as an example, the trend of the strain data collected from 11 # and 12 # strain gauges in the device is analyzed to describe the degradation process of the clamping device. As a matter of convenience, the 11 #, 12 # strain gauge data of the single test cycle as shown in figure 10 A and B curves.

Combined with the time sequence of the test of table 1 and strain data of figure 10, we learn that the value of 11 # and 12 # strain gauges increase gradually in the first 3.8 second during the pressurization period, and then decreases from the peak to the initial value during the pressure relief process. In the period of clamping and unlocking, it keeps an initial value.

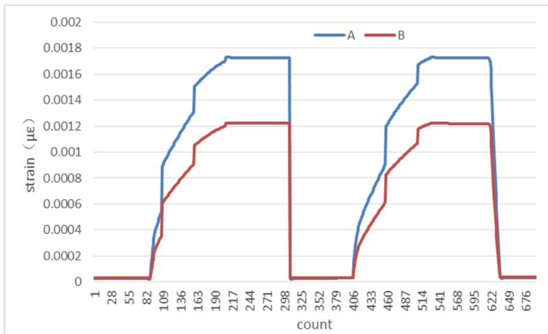


Figure 10. Strain data of single test cycle

Due to the long testing period, we should exclude the factors such as zero drift and creep of the strain gauge when analyzing entire testing process data. So using the peak - peak value of strain data is better for the characteristic description of strain variation. And also applying to data analysis follow-up.

Until the clamping device failure occurs, the trend chart of strain characterization value of the No.26 clamping device is shown in figure 11. Where A and B curves represent the strain trend curves of the 11 # and 12 # monitoring points of the No.26 clamping device. The eigenvalue represents as {x1, x2... x n}, where n stand for the number of test cycles, and it also can characterized the degradation state of the clamping device at the corresponding time.

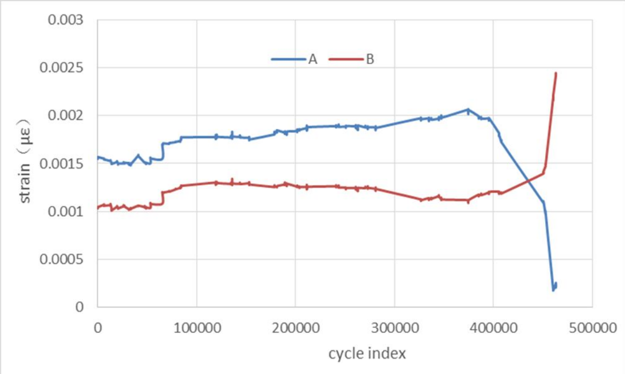


Figure11. Trend chart of strain characterization value of clamping device

3.4. Degradation Process Modeling

During the whole test process, 810 groups (nearly 40 thousand) data were collected. According to the failure, the data of corresponding strain gauge near the failure point (i.e., the A point in Figure 11) is extracted, about 580 valid data in total. Based on the definition of failure criterion, we use 490 data before crack initiation as the data source of the Data-driven model analysis.

In this paper, the Random coefficient regression modeling method is used to model the regression process of clamping device on the basis of test data. This method assumes that the device has a certain degradation path, it can only represent the common degradation characteristics of similar machines, but can't reflect the individual differences.

In order to find an accurate regression model to describe the degradation process, we try to use the quadratic and cubic polynomial fitting method, by comparing these models with software, we selected the better one as the high cycle fatigue degradation model of the clamping device. The regression model was obtained by software, as follows. The fitting curve shown in figure 12.

The quadratic regression model M3.1:

$$y = -2.8351 \times 10^{-15}x^2 + 2.285 \times 10^{-9}x - 4.9726 \times 10^{-5} \quad (2)$$

The cubic regression model M3.2:

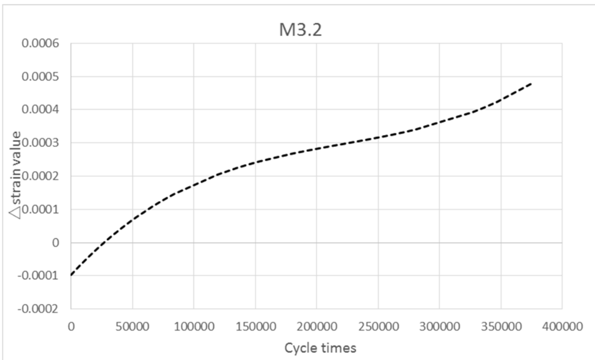
$$y = 2.2528 \times 10^{-20}x^3 - 1.5018 \times 10^{-14}x^2 + 3.9993 \times 10^{-9}x - 9.6143 \times 10^{-5} \quad (3)$$

In order to compare the fitting degree of the models, importing the residuals, correlation index R2 and AIC (Akaike Information Criterion).Among them,

$$\mathrm{AIC} = -2\log\left(\mathrm{L}(\hat{\theta}|\mathrm{data})\right) + 2\mathrm{K} \quad (4)$$

Where: L represents likelihood function, k represents the number of model parameters. The principle of evaluating the fitness of the model is the smaller the AIC, more effective the model is, and the larger the correlation index R2, the smaller the square sum of the residuals, also proves good effect.

(1)Quadratic regression



(2)Cubic regression

Figure 12. Curve fitting model

The residual, R2 and AIC three parameters are used to characterize the fitting degree of the model M3.1 and M3.2.Compared with the test data, results are shown in table 4:

Table 4 Model fitting parameter

Regression model No.	Residual	Correlation index R2	AIC
M3.1	9.7234E-7	0.910	-9812.6
M3.2	7.1160E-7	0.934	-9963.6

It is shown by the Comparing result in table 3, the fitting degree of the model M3.2 is better. At the same time, compare the test data with the M3.1 and M3.2 model fitting curve, can also be seen on the degradation trend fitting when using the M3.2 model, the prediction accuracy was superior to that of the M3.1, shown in figure 13:

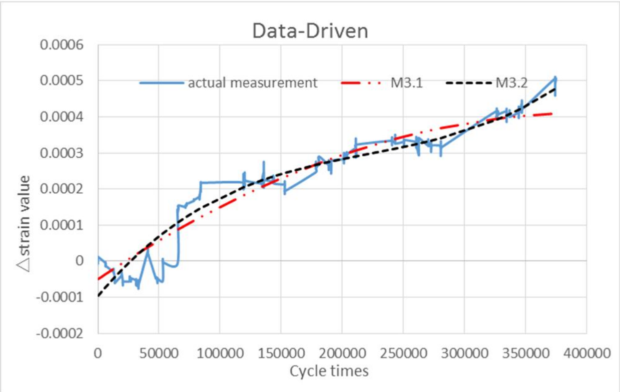


Figure 13 Curve comparison of actual measured data, M3.1 and M3.2

Therefore, the model M3.2 is considered to be the better model for high cycle fatigue degradation of clamping device, and be considered as one of the degradation models to support the PHM management of similar machines. And using to predict remaining service life of it.

4. CONCLUSIONS

This paper take the clamping device of curing machine as the research object to study the degradation process of its high cycle fatigue.

Firstly, the analysis of structural stress concentration of clamping device is confirmed by using Abaqus software. Combined with the analysis of main failure mode and mechanism, the strain is selected to characterize this fatigue degree of clamping device. Then using the CAE analysis results to confirm the location of the strain gauges and guide the design of the durability test. The Abaqus software also support the failure analysis during the test process

Then the strain value of 24 monitoring points are collected and the trend curves during the durability test cycle are analyzed. Based on these data of the strain eigenvalue, we use Data-driven method to carry out the model regression analysis. Meanwhile, the residuals, the correlation index R2 and the AIC indexes are introduced to compare the model fitting effect, then one of the degradation mode of clamping device output.

It support a reference degradation model of the curing machine which can be used in the PHM management and remaining service life prediction of this machine in the future. It also provides an ideal solution of PHM engineering practices based on CAE simulation and Data-driven analysis of the testing data. This method can be extended to other machines PHM research in the future.

The further research on this subject can be studied on these ways:

(1)In this paper, the peak - peak value of strain data is selected as the eigenvalues, and more eigenvalues can be extracted to characterize them in the future research.

(2)We use the regression analysis method in this paper and neural network and other data fitting methods can also be used in future.

(3)This model is just one of reference degradation models. In order to make PHM effectively, we need to do future study on other failure modes and mechanism of the clamping device, and gradually establish a model base to support PHM research of the machine.

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