

Reliability Analysis of Ring Mold Granulator based on Minimum Maintenance Model

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Abstract

Granulation molding equipment is the most critical link in the granule feed production line. The ring mold granulator is one of the main equipment of feed machinery, but its low life, frequent failures, and high maintenance costs seriously restrict the development of granulators in China. Based on the minimum maintenance model, this paper proposes the timing replacement strategy (CIRP) analysis, so as to obtain the Weibull probability diagram of the time between failures and obtain the fault distribution mode, fault frequency, and reliability of the sub-system of the ring mold granulator. By analyzing the failure statistics of the ring mold granulator, it is concluded that the granulator system and transmission system are the main causes of failures. Improvement measures are proposed for the weak links of the ring mold granulator, providing an important reference for improving the life of the ring mold granulator and reducing failures.

Keyword: ring mold granulator; minimum maintenance model; reliability; preventive maintenance

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1. Introduction

The ring mold granulator is the key equipment of feed granulator production. It has some problems such as serious wear and tear, and the subsystem is prone to failure, which not only reduces the product quality but also increases the production cost.

Wang et al. [1] analyzed the development trend of the biomass energy industry in the future based on the comprehensive evaluation of China's biomass energy resources, industrial development, and policy environment. By using the method of economics and sociology regarding the present situation of China's rural energy and analyzing the industrialization of straw briquette fuel in detail, Liu et al. [2] pointed out the industrialization of the foreground and the role of the government's policy in molding fuel development. For the fault data model, Wang et al. [3] used the trend test, update test, goodness of fit test, and other comprehensive tests to judge whether the fault data had a certain trend in the first place, determined whether it was independent and distributed, and finally tested the fitting degree of the model to ensure the accuracy and reliability of the model. Jiang et al. [4] carried out the ring mold wear analysis test for problems such as rapid wear of ring molds of granulators, measured the wear amount and surface hardness of ring molds, observed the microscopic feature morphology of wear surfaces, and analyzed the wear mechanism of materials on different parts of ring molds. Huo et al. [5] established an evaluation model based on the life cycle inventory analysis principle and the BSAS system and quantitatively analyzed the life cycle of biomass solid molding fuel. Stelte et al. [6] studied the strength and integrity of particles and related them to the quality and mechanism of specific adhesives. The grading results showed that temperature and chemical composition, namely the existence of hydrophobic extracts, had a significant influence on the bonding quality between biomass particles in the granulation process, based on theoretical analysis, numerical simulation, and experimental research. Wu et al. [7] established a precise torque model for the process of powder rotary extrusion granulation molding and conducted the ring mold extrusion granulation test of chicken feed on the wireless torque test system and ring mold granulator as the test platform. Louit et al. [8] proposed a model selection framework to represent the failure process of components or systems based on the review of available trend testing, with the purpose of using statistical distribution to represent the difference between the failure time and the process using random points. Liu et al. [9] adopted the Lagrange equation and block mass

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method to establish the torsion dynamics model of ring mold granulators. Based on the random vibration model, the extrusion model was established.

In order to solve the problem of poor reliability and high cost of the ring mold granulator, this paper analyzes the expected failure number, expected cost, failure probability, and reliability of the ring mold granulator and obtains the parameters of the minimum maintenance model. Finally, the optimal time interval of preventive replacement is determined through an example analysis.

2. Assembly Platform Design

Repairing a complex system of many components can be accomplished by replacing, repairing, or correcting the components of the system. The replacement, repair, and correction of these parts usually only restore the function of the whole system, and the failure rate of the system is still the same as before the failure; this type of maintenance is called minimal maintenance. As the failure rate of complex systems increases with time, the cost of maintaining the system through minimal maintenance increases, and the main variable is the best time to replace the entire system rather than the minimum maintenance. In order to solve the possible failure, the minimum maintenance estimate in the maintenance method is designed to analyze the advantages, disadvantages, and service conditions of the possible problems in the maintenance method, as shown in Table 1.

Table 1. Advantages, disadvantages, and applicable conditions of the three maintenance methods

Maintenance manner	Merit	Defect	Application condition
Predictive maintenance (PDM)	Maintenance can be arranged in advance, makes full use of equipment capacity so that the equipment has a high utilization rate, better than preventive maintenance, planned maintenance	High requirements for monitoring and detection technology must be defined in advance of the potential failure state of equipment, higher testing costs	The degradation of equipment function is detectable and there is a definable potential failure state, should take a long time for the equipment to develop from potential failure state to functional failure
Preventive maintenance (PM)	Maintenance plan can be arranged in advance, ensures equipment availability, lowers outage losses, state maintenance	Failure data is difficult to obtain, inadequate utilization of equipment capacity, high maintenance costs	Equipment has a defined period of wear and tear, most can be restored to the specified state, mainly used for the equipment with high requirement of equipment safety and unable to grasp the status in time
Breakdown maintenance (BM)	The ability to make full use of equipment, lowers maintenance costs	Higher stoppage costs, higher cost of spare parts, belongs to aftercare sex to maintain	Generally used for safety and reliability requirements, the preventive cost is greater than the sum of the loss of failure consequences and maintenance costs of equipment

The expected number of failures is calculated through failure coefficients λ , times of failure n , and failure cycles T , so as to get the expected number of failures within t time $M(t)$.

$$M(t) = \lambda^n f(t - nT) \quad (1)$$

The minimum maintenance model usually assumes that the system failure rate function is increasing and the minimum maintenance does not affect the failure rate, and the minimum maintenance cost c_f is less than the cost of replacing the entire system c_r . The estimated cost per unit time at time t of life is:

$$c(t) = \frac{c_f M(t) + c_r}{t} \quad (2)$$

Where $M(t)$ is the minimum number of expected failures for maintenance within $(0, t]$.

In the maintenance process, most maintenance modes assume that the maintenance will make the system function "repair as new". The system is updated after each failure. Although this assumption is true in some cases, in other cases the failed system will continue to work after maintenance and have the same failure rate and effective life as it did at the time of failure. Obviously, when the failure rate of a machine increases with time, its working time after maintenance will become

shorter and shorter, that is, only a limited working time. Similarly, with the aging of the system, the working time after maintenance will become shorter and closer to infinitesimal, and the system will no longer be able to carry out maintenance.

Therefore, reasonable models of these systems should include the following factors:

- (1) The continuous survival time is randomly decreasing.
- (2) The maintenance time is increasing at random.
- (3) The maintenance time is randomly increasing.

Timing replacement strategy (CIRP) is the simplest preventive maintenance and replacement strategy. This strategy is mainly adopted in two ways:

(1) The first is to take preventive replacement at a fixed time. In this case, the life of the parts or components is not considered, but the parts and components are replaced at a predetermined time.

(2) The second replacement method is fault replacement, that is, replacing the failed parts or components. This replacement strategy is shown in Figure 1 and is also known as the batch replacement strategy.

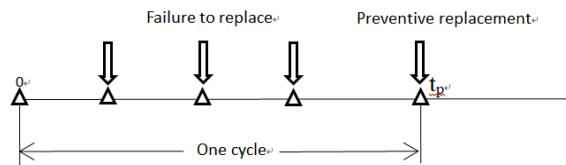


Figure 1. Timing device change

The objective of the optimal preventive maintenance, replacement, and testing (PMRI) model is to determine the preventive maintenance strategy and optimize the parameters of some criteria. The most widely used criterion is the total estimated replacement cost per unit time, which can be achieved by defining the total estimated cost per unit time function, as shown below.

If the total replacement cost per unit time is a function of $c(t_p)$ and t_p , then:

$$c(t_p) = \frac{\text{total estimated cost within } (0, t_p] \text{ time intervals}}{\text{Estimated time length}} \quad (3)$$

The total estimated cost within the time interval of $(0, t_p]$ is the sum of the estimated cost of failure replacement and the estimated cost of preventive replacement. In the time period $(0, t_p]$, the cost of a preventive replacement is c_p , and the cost of a failure replacement is c_f . It is assumed that the expected quantity of replacement (update) in this time period is $M(t_p)$. The estimated length of this time period is t_p , and Equation (4) can be written as:

$$c(t_p) = \frac{c_p + c_f M(t_p)}{t_p} \quad (4)$$

3. Fault Analysis of Ring Mold Granulator

A ring mold granulator is selected as the evaluation object, and the points belong to eight feed production enterprises of 20 granulators after one year of fault data recording and collection. The obtained failure data is used for granulating machine reliability evaluation, as shown in Table 2.

According to the failure statistics table of the ring mold granulator in Table 2 and Equation (6), the failure frequency of each subsystem during the statistical period and its main failure reasons are calculated, as shown in Table 3.

Table 2. Statistical table of failure data for reliability evaluation of granulators [10]

Number	Time between failures/h	Corresponding maintenance time/h	Cumulative number of failures
1	616 387 551 323 397 551 539 471 613	3 7 13 1 9 3 2 11 9	9
2	483 539 615 445 563 539 363 517 436 481 385	4 2 3 8 7 2 3 9 6 5 12	11
3	579 286 397 640 613 588 713 582	8 9 15 3 2 5 13 17	8
4	548 397 590 496 579 634 495 589 496 445 392 588	4 17 6 5 8 11 12 7 9 5 8 11	12
5	634 356 612 580 576 548 14 397 354 568	7 11 13 4 6 10 9 14 5 7	10
6	696 495 617 435 461 473 570 711	17 9 11 2 7 3 4 9	8
7	581 590 551 435 495 514 445 588 595 613	7 11 6 6 3 13 4 7 3 7	10
8	651 411 300 286 634 433 452 461 386 445 588	15 12 3 8 4 7 9 11 13 8 7	11
9	664 410 489 495 471 579 582 517 593	9 2 3 7 11 14 12 5 7	9
10	595 721 628 576 698 581 590	16 8 11 9 7 10 6	7
11	539 435 528 514 426 391 582 495 524 452 613	18 11 9 8 12 3 7 2 11 9 10	11
12	730 411 323 495 485 551 397 582 628	6 6 5 8 12 15 11 10 7	9
13	656 590 559 383 471 489 445 534 445 560	13 7 9 6 11 8 15 9 12 10	10
14	513 574 486 383524 589 519 523 436 584 322 426	9 2 11 19 12 9 11 10 12 8 7 9	12
15	617 539 559 411 548 445 363 436 552 587	15 11 7 3 4 9 10 8 12 11	10
16	585 528 471 496 366 495 514 628 482	9 4 8 12 10 3 11 7 9	9
17	687 426 517 534 481 513 481 559 521 544	14 3 7 9 15 4 8 11 7 13	10
18	615 535 471 386 278 701 525 583	8 4 3 15 11 12 7 9	8
19	646 519 495 548 436 560 552 523 437	17 9 11 5 2 4 6 11 7	9
20	719 559 489 545 498 495 615 613	11 8 9 14 12 13 7 9	8

According to Table 3, available ring die granulator malfunction is one of the most common particle systems (73.56%), followed by transmission systems (13.59%). Other parts of the system frequency are less than 5% of the failure of the granulating system, and the transmission system failure probability is 87.15%. The sum of the two subsystems is the weak link ring die granulator, a key subsystem of the ring die granulator.

Table 3. Failure frequency table of ring mold granulator subsystem

Code	Subsystem name	Number of defects	Failure frequency	Failure cause
E	Electronic control system	3	0.44%	Poor switching and wiring
F	Feeding system	17	2.51%	Bearing wear, clearance is too large
C	Conditioning system	21	3.10%	Poor lubrication and constant overload
P	Granulating system	498	73.56%	Aging wear, insufficient stiffness
T	Drive system	92	13.59%	The belt skidded and burned
L	Lubrication system	28	4.14%	Jam
S	Steam system	18	2.66%	Vibrate

The reliability index of the ring mold granulator is evaluated from the above Table 2:

(1) Mean time to failure (*MTBF*)

The ring mold granulator *MTBF* can be calculated according to Equation (5):

$$MTBF = \frac{\sum_{i=1}^{20} T_i}{\sum_{i=1}^{20} r_i} \quad (5)$$

Where T_i is the cumulative working time of the i granulator in the statistical period and h ; r_i is the cumulative failure times of the i granulator in the statistical period.

By substituting the data of time between failures in statistical Table (2) into Equation (5), the MTBF statistical value of this type of ring mold granulator is obtained as $MTBF = 518.5393h$.

(2) Average maintenance time $MTTR$

The calculation formula is:

$$MTTR = \frac{\sum_{i=1}^{20} t_i}{\sum_{i=1}^{20} r_i} \quad (6)$$

Where t_i is the accumulated maintenance time of the i granulator in the statistical period.

The data of maintenance interval in statistical Table (2) is substituted into Equation (6) to obtain the $MTTR$ statistical value of this type of ring mold granulator: $MTTR = 8.5340h$.

(3) Availability of A

Availability, also known as validity, refers to "the probability of the normal operation of the repairable equipment at a certain time under specified service conditions and maintenance conditions". The calculation formula is:

$$A = \frac{MTBF}{MTBF + MTTR} \quad (7)$$

The availability of the ring mold granulator test machine is calculated as $A = 0.9838$.

3.1. Fault Distribution Mode

Based on the analysis of system fault data, the fault frequency table of the ring mold granulator subsystem can be obtained. By comparing it with the corresponding curves of several common fault distribution models and combining it with the common fault distribution, the applicable scope is shown in Table 4, and the fault distribution model of the system can be preliminarily determined.

Table 4. Common component fault distribution patterns and their application scope

Fault distribution mode	Range of application
Exponential distribution	Components with a constant probability of failure, no complex system, parts for damage maintenance before the loss of failure, failure in the service life of the components for the weak loss type.
Weibull distribution	Main motor, transmission belt, overload protection device, gear, etc.
Lognormal distribution	Ring mold granulator structure, metal fatigue, etc.
Gaussian distribution	Wear of ring molds, modifiers, rotor assemblies and some mechanical parts.

3.2. Failure Criteria

Failure refers to the event or state in which the equipment or part of the equipment fails to perform the specified function. According to the fault nature, the faults can be divided into associated faults and non-associated faults. Non-associated faults refer to faults caused by failure to use in accordance with specified conditions; otherwise, they are associated faults.

Associated failures include:

(1) Design defects or manufacturing, assembly process defects caused by the fault, such as ring mold specification problems and bearing assembly problems caused by the fault;

(2) Under normal conditions of use, the parts in the granulator production unit promised life of the failure, such as a period after the use of seal damage caused by the oil leakage phenomenon;

(3) The cause of the fault is unknown, but it can be eliminated that the fault is caused by human factors.

Non-associated failures include:

(1) Faults caused by improper installation by users, such as excessive vibration of the granulator or premature fracture of the ring mold due to inconsistent gaps between two pressing rollers and ring molds;

(2) Failure caused by accident, misoperation, or misuse, such as shutdown caused by power failure; workers will replace the safety pin with other parts, resulting in failure of overload protection device of granulator;

(3) Faults caused during maintenance;

(4) Faults caused by overload work, such as motors burning down and ring molds breaking due to continuous overload;

(5) Failures that occur during normal or extended service life.

4. Maintenance Reliability Analyses

Assuming that the failure interval time of the ring mold granulator obeys a Weibull distribution, the `wblplot` function of MATLAB software is used to obtain the maximum likelihood estimation of two parameters of Weibull distribution $W(m, \eta)$:

Shape parameter $m = 6.3346$

Scale parameter $\eta = 556.8605$

The `wblplot` function is used to represent the time between failures on the Weibull probability diagram (as shown in Figure 4). It can be seen that the "+" representing the time between failures mostly falls on the reference line, indicating that the probability that the sample obeys the Weibull distribution is greater. To further test the correctness of the hypothesis, the function $[h, p, ksstat, CV] = kstest(x, CDF, \alpha, type)$ is used to test the goodness of fit of the sample. The Kolmogorov-smirnov (k-s) test is performed on the sample. If $h = 0$, the null hypothesis is accepted at significance level α .

Set the confidence level as 95% (that is, significance level $\alpha = 0.05$), and the return values of the `kstest` function are $h = 0$, $p = 0.6550$, $ksstat = 0.0522$, and $CV = 0.0974$.

$h = 0$ means that the null hypothesis is accepted and the failure interval time follows the Weibull distribution $W(6.3346, 556.8605)$, which means that the density function can be written as:

$$f(t) = \frac{6.3346}{556.8605} \left(\frac{t}{556.8605} \right)^{5.3346} \exp \left[- \left(\frac{t}{556.8605} \right)^{6.3346} \right], t \geq 0$$

The failure probability of the ring mold granulator can be obtained by determining the Weibull probability diagram of the failure interval time as shown in Figure 2, where $F(t)$ is the curve graph changing with time.

$$F(t) = \int_0^t f(t) dt = 1 - \exp \left[- \left(\frac{t}{556.8605} \right)^{6.3346} \right], t \geq 0$$

It can be seen from Figure 3 that with an increase in time, the probability of failure increases continuously, eventually leading to a failure rate of 100%. The maintenance time and reliability curve can be obtained by combining with the expected number of failures (Figure 4).

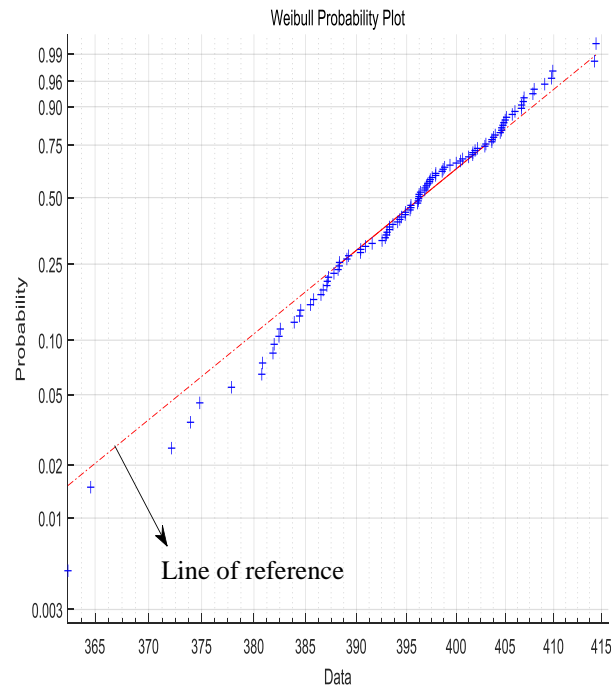


Figure 2. Weibull probability diagram of time between failures

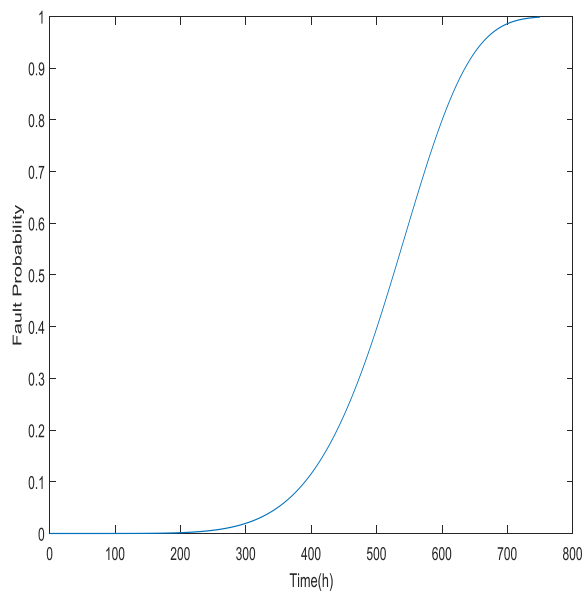


Figure 3. Variation curve of $F(t)$ failure probability of ring mold granulator

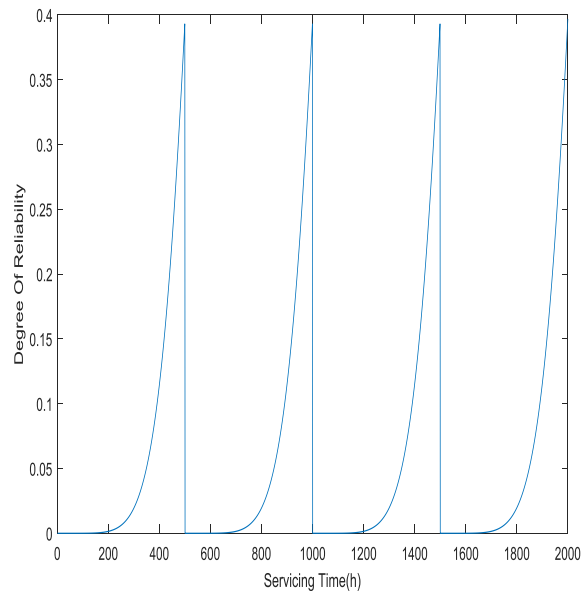


Figure 4. Variation curve of ring mold granulator reliability $R(t)$

5. Conclusions

In this paper, a display dynamics simulation study was conducted for the integral ring key assembly of a certain type of small solid rocket motor, the integrated ring key introduction process was simulated, and a reliability study was conducted. The following conclusions were drawn:

- (1) Through theoretical feasibility analysis, simulation analysis, and experimental research, the reliability of integral ring key installation was ensured, providing a guarantee for the installation quality of integral ring keys.
- (2) A new connection method was developed for the solid rocket motor combustion chamber and nozzle (head).

(3) Reliable data was provided for material selection and the structural optimization design of integral ring keys.

Acknowledgements

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