Research on Failure Analysis and Maintenance Policy for Machine Tools

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KEYWORDS

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ABSTRACT

Machining tools are the main equipments for metal machining and consist of mechanical parts, electrical parts and hydraulic parts, and so on. In order to reduce the failures and improve the level of machine tools reliability, the paper firstly performs the failure analysis by the statistical method. Then the failure trends for the key parts of machining center are given using the power law process. In contrast with the usual method, which optimizes the maintenance under the repair costs, an optimization approach of maintenance is presented under the reliability constraints for machining center that used in a northeast manufacturing plant of China. The proposed analysis process could be a useful tool to assess the reliability and optimize the machine tools maintenance policy.

Introduction

In the last few decades, machine tools of computerized numerical control have been introduced into the manufacturing works. With the flexibility, high machining accuracy and productivity, CNC machine tools do a lot of interest to the users and enterprise. However, machine tools is a typical electromechanical product mainly composed of mechanical parts, electrical parts, hydraulics and so on, so it is fairly complicated. Especially in most of the cases, it is usually used for single piece machining for a long time, so CNC machine tools fail more often than the other general machine tools as in (Wang, *et al.*, 1999). The failures of CNC machine tools often lead to the breakdown of the production line and even the whole enterprise. Furthermore the repair processes of failures always cause lots of human physical and financial resources. At the same time frequent failures also bring bad effects to the brand of machine tools and machine tool manufacture (Peng, *et al.*, 2013; Wang *et al.*, 2010).

In order to reduce the frequent occurs of failures and improve the strategic and competitive positions of machine tools firms, the manufacturers have to improve the reliability of CNC machine tools. In these cases, both the manufacturers and users take the reliability and availability of CNC machine tools as two of the important factors. Therefore, the manufactures pay more and more attention to them.

In this study, a statistical analysis of failures data of the CNC machine tools field trace experiment for about 5 years was carried out. The failure causes statistics and the failure cumulative time trends of CNC machine tools and its key parts whose failure cumulative times follow the power law process (PLP) were determined. Furthermore, the maintenance strategy calculated under the reliability limitation was presented for the key parts of the CNC machine tools.

Methods

(1) Failure Analysis of CNC Machine Tools

The machine tools studied in this paper are machining center which include electricity spindle which is the stator of the servo motor, three slide axes named *X*, *Y* and *Z* feed axes of which are driven by three servo motors and Mitsubishi 64m digital control system. The spindle with continuous speed change is driven by AC motor directly with speed varying from 60 to 8000 rotates per minute. All of the servo motors are controlled by CNC simultaneously. The structure of machining center is shown in Figure 1.

In order to improve the reliability level and optimize the maintenance strategy of machine tools, the manufactures must collect lots of failures data, and then the research problem is how to gather the machine tools failure data. The operation records table and maintenance reports table for machine tools are made in a unified format for gaining the failure data as in (Wang, *et al.*, 1999) and (Yang, *et al.*, 2013). The failure data are stored in a database by the sales staff or the specialized staff of manufactures.

The failure data of machining centers analyzed in this paper were derived from the field practical application and these machining centers were used in a typical representative auto manufacturing company of Fist Auto Works of China. The failure and repair data were collected during a 5 year period and collected more than 200 pieces of data which were the basis of failure analysis.

(2) Model of Non-Homogeneous Poisson Process
In order to build a more accurate reliability model, assume that machining center is a repairable system, which undergoes repair and can be restored to an operation by some maintenance policies as in (Hsu and Shu, 2010) and (Jiang and Murthy, 2008). Therefore, the distribution model of the time between the first two failures is not the same as the time between the subsequent successive failures, in other words, the time between failures are not mutual independence. So the common modeling approach can't be applicable to the repairable system reliability analyses as in (Ascher and Feingold, 1984) and (Jiang and Guo, 2012).

A stochastic point process is characterized by isolated events occurring at instants distributed randomly over a time continuum. So we can use a stochastic point process to describe failure procedure of the repairable system. A common procedure for analysis of a set of data of a repairable system as in (Bo, 1997) seems to be as follows. The repairable system is observed from instant t=0, and let T_1, T_2 ... denote the sequence of ordered failure times. So let X_1, X_2... denote times between failures, thus $X_i=T_i-T_{i-1}$, i=1, 2, ..., n.

Non-homogeneous Poisson process (NHPP) is one of the most widely used stochastic point process. The intensity function of NHPP is given by $\lambda(t) = \alpha\beta t^{\beta-1}$ (1)

The reliability at time t with respect to the first failure is equivalent to the probability of no failures at time t: $R(t) = \exp(-at^{\beta})$ (2)

For the intensity function given in Eq. (1), if β<1, the system is improving over time. If β>1, the system is deteriorating over time, as might be observed under minimal system repair.

Eq. (1) provides the cumulative expected number of failures, denoted by m(0, t):

$$m(0,t) = \int_0^t \alpha\beta t^{\beta-1}dt = at^{\beta} \quad (3)$$

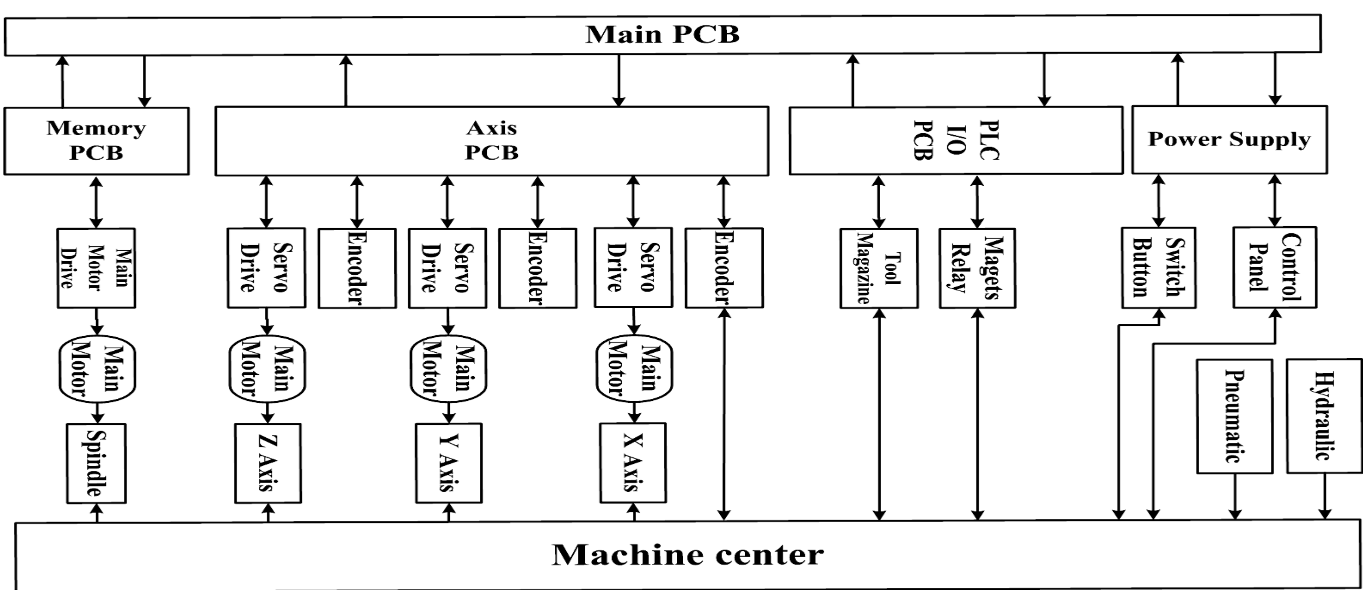

Figure 1: Structure Block Diagram of Machining Center

MTBF of an interval time is given by:

$$MTBF = \frac{t_2 - t_1}{m(t_2, t_1)} \quad (4)$$

The failure data analyzed in this paper were collected for five years. The effect of the power law models of machining center to maintenance policy is very important. So we develop the model of machining center. Tables 1-3 list the failure data of mechanical parts, of machining center. Denote T_k the *kth* failure occurrence time, where t_k is its realization.

The parameters α and β in the intensity function $\lambda(t)$ may be estimated by the maximum likelihood estimation (MLE) and they are given by in (Larry, 1988):

$$\hat{\alpha} = \left(\frac{n}{T_n^{\hat{\beta}}}\right) \quad (5) \qquad \hat{\beta} = \frac{n}{\sum_{i=1}^{n-1} \frac{T_n}{T_i}} \quad (6)$$

2.3 Maintenance Policy

In order to improve the availability and reliability of machine tools, an appropriate maintenance policy should be carried. Therefore, in this section we will select a preventive maintenance policy and solve the optimization model of machining center.

As compared to the whole machining center, the repaired components can be ignored, that is to say the machining center is as old as the old one. Then assume the repair factor is equal to zero.

$$R(t) = \exp[-m(0,t)] = \exp(-at^{\beta}) \quad (7)$$

$$R(t \mid T) = \exp[-m(T+t, T)] = \exp[-a((t+T)^b - t^b)] \quad (8)$$

Where, $(T+t)_i$ represents the *i*th preventive maintenance when R is asymptotic to the special value.

The maintenance policy can be described as follows. Let C_p be the cost of a preventive maintenance and C_f be the cost of a failure. The average cost of per unit time is given by formula (9) as in (Nakagawa, 1986).

$$C(T) = \frac{C_p R(T) + C_f F(T)}{MUT} \quad (9)$$

MUT is the possible working time in one maintenance circle, so it is given by:

$$MUT = T gR(T) + \int_0^T t g f(t)dt = \int_0^T R(t)dt \quad (10)$$

Table 1: The Failure Data of Mechanical Parts

i	t_{1i}	t_{2i}	t_{3i}	t_{4i}	t_{5i}	t_{6i}	t_{7i}	t_{8i}	t_{9i}
1	1044	8642	13205	18338	29073	37200	40741	42501	44805
2	2002	9102	13905	18952	30195	37605	40829	42953	45012
3	2987	9602	14205	20110	30330	37809	41346	43263	45237
4	3698	10980	14670	25213	31387	38210	41473	43456	45427
5	4501	10595	15200	26415	34580	38759	41534	43787	45502
6	5200	10879	15902	26630	35513	39040	41668	43882	45644
7	6021	11200	16502	27181	35976	39203	41746	44001	45835
8	6700	11802	16989	27377	36317	39617	41910	44380	45952
9	7359	12305	17253	28188	36725	40116	42053	44475	
10	8012	12897	17882	28393	37082	40463	42487	44769	

Table 2: The Failure Data of Electrical Parts

i	t_{1i}	t_{2i}	t_{3i}	t_{4i}	t_{5i}
1	2583	16563	27708	35607	42987
2	4693	17799	28734	36154	43602
3	6182	19102	29531	37120	44025
4	8102	20149	30186	37901	44325
5	9152	21201	31820	38200	
6	11071	22520	32634	38702	
7	12703	23521	33200	39210	
8	13901	24205	33811	40250	
9	15023	25044	34719	41002	
10	2583	26051	35197	42051	

Table 3: The Failure Data of Hydraulic Parts

i	t_{1i}	t_{2i}	t_{3i}	t_{4i}
1	2124	14562	28405	42211
2	4201	16000	31633	43988
3	5800	17200	32465	45422
4	6525	18560	34560	46193
5	8014	20012	36042	46937
6	9511	21089	36629	47674
7	9989	22145	36822	
8	11025	23102	37895	
9	12456	24250	38264	
10	13547	26520	40395	

Results

(1) Results of Failure Analysis

The weak parts were found through the failure analysis and the histogram of the failure data is shown Figure 2 drawn in Excel by the statistics method. We can observe that the mechanical parts had the biggest number of failures whose failures accounted for 48.96% of all the failures and followed by it were electrical parts seen from the Figure 2. Therefore, the mechanical parts of the machining center are the large hindrance to the reliability improvement of the machining center.

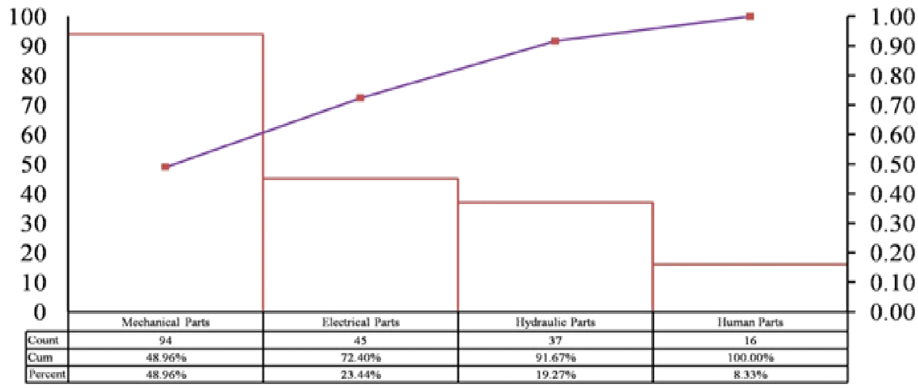

Figure 2: Histogram for the Failures Position of Machining Center

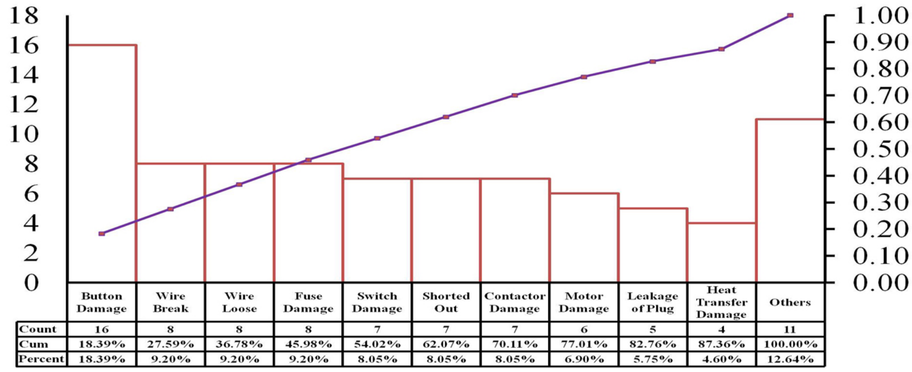

Figure 3. Histogram for the Failures Cause of Mechanical Parts

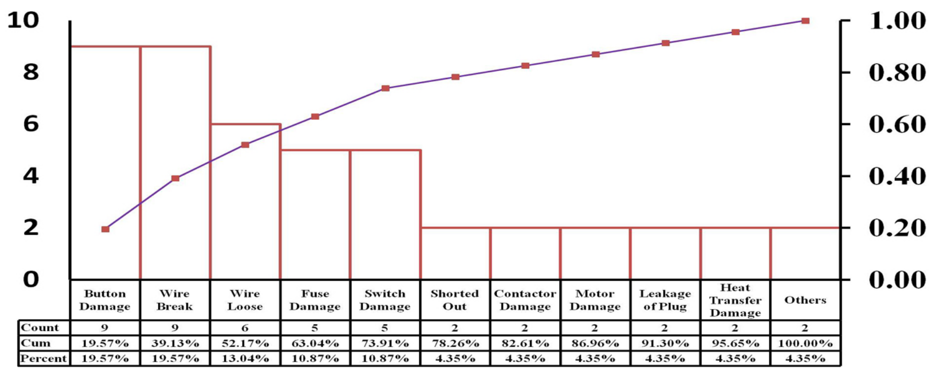

Figure 4: Histogram for the Failures Cause of Electrical Parts

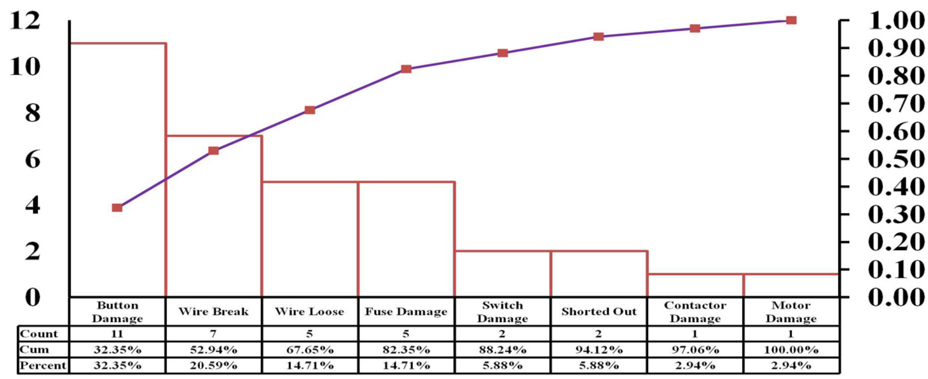

Figure 5: Histogram for the Failures Cause of Hydraulic Parts

In order to distinguish the special causes which have the great influence on the reliability of machining center, the failure causes of mechanical parts, electrical parts and hydraulic parts are analyzed and the results are shown in Figures 3, 4 and 5.

The main cause of mechanical parts was the damage of pin which accounted for 18.4% of all the failure causes of mechanical parts seen from Figure 3. Followed by this cause were adjustment of assemble, burn out, safeguards damage, fall out of bolt, damage of screw and loose of screw. The first seven causes accounted 70%. From the above analysis, the designers should redesign the bolt, screw and pin, especially, choose the more high mechanical strength material or undergo a special heat treatment to improve its mechanical strength. At the same time, the manufacture should set some key processes to enhance the level of assembly.

The main cause of electrical parts was damage of button which accounted for 19.6% of all the failure causes of electrical parts seen from Figure 4. Followed by this cause were break of wire, loose of wire, damage of fuse and damage of switch. The first five causes accounted 73.9%. From the above analysis, the manufacture should enhance the quality of outsourcing and enhance assembly of the connection of wire.

The main cause of hydraulic parts was damage of pump which accounted for 32.4% of all the failure causes of hydraulic parts seen from Figure 5. Followed by this cause were damages of oil seal and reversing valves. The first four causes accounted 82.4%. From the above analysis, the manufacture should enhance the quality of outsourcing of valves and pumps.

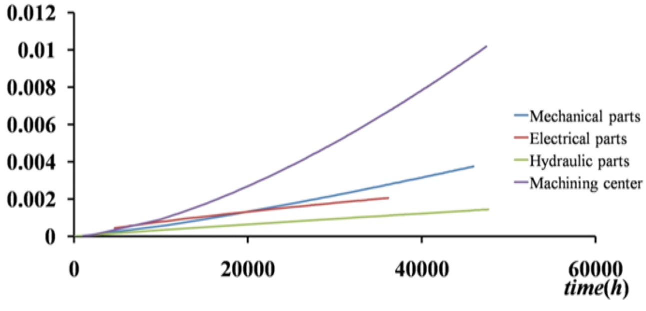

Figure 6: The Intensity Functions for the Whole Machining Center

(2) Failure Trend Models of Machine Center

Using the Excel solver as in (Matthew, 2010), the power law models and MTBF between 5 years of mechanical parts, electrical parts, hydraulic parts and machining center are shown in Table 4 and the four intensity functions are drawn in Figure 6.

(3) Optimal Maintenance Strategy

Based on the empirical data, c_f=30000, c_p=10000, the optimal maintenance strategy is given using the Excel spreadsheet program and shown in Table 5. Figure 7 is the plot of R(T) versus T and Figure 8 is the average cost of per unit time of preventive maintenance. The cost and the time between preventive maintenance time decrease when the preventive maintenance times increases. This indicates that it will have poor effect to users with the increase of preventive maintenance, that is to say frequent preventive maintenance leads to the low availability. So the user should carry the replacement policy, then the time would be longer.

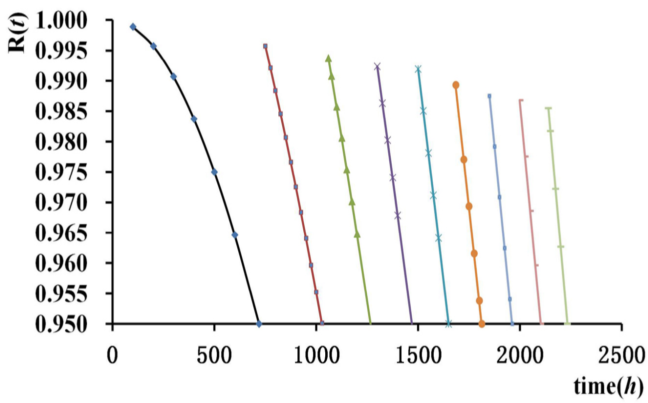

Figure 7: Plot of R(T) Versus

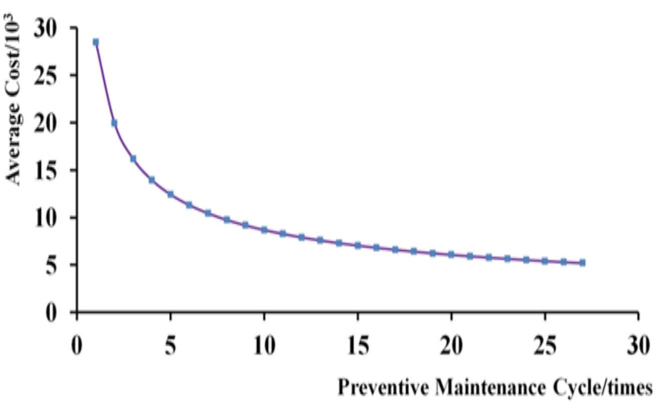

Figure 8: The Average Cost per unit Timeof Preventive Maintenance

Table 4: Power Law Models

Parameter	Mechanical parts	Electrical parts	Hydraulic parts	Machining center
α	2.34×10-5	1.15×10-4	1.17×10-4	1.47×10-7
β	1.41	1.22	1.17	1.94
MTBF(h)	585.76	870.18	1443.19	364.13

Table 5: Preventive Maintenance Time

Num	PM time	Num	PM time	Num	PM time
1	719.58	7	149.87	13	109.112
2	309.03	8	139.80	14	105.12
3	239.10	9	131.56	15	101.54
4	202.64	10	124.65	16	98.31
5	179.23	11	118.745	17	95.37
6	162.55	12	113.62	18	92.69

Conclusions

Through analyzing the field failure data for machining center, gets the following conclusions.

(1) The weakest link of machining center is mechanical parts. The manufacture should enhance the design of pin, screw and protective devices. The customer should take condition repairs into account, such as loose connection, loose of nuts and so on.

(2) The outsourcing components of electrical and hydraulic parts are the main weak parts through statistic analysis.

(3) The hazard rate model of the whole machining center is determined with α=1.47×10^{-7} and β=1.94.

In order to accomplish the growth of reliability based on the field failure data, schedule regular maintenance is an effective method.

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