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RELIABILITY ANALYSIS OF MACHINING CENTER BASED ON THE FIELD DATA

ANALIZA NIEZAWODNOŚCIOWA CENTRUM OBRÓBKOWEGO W OPARCIU O DANE TERENOWE

Machining center is the complex machinery, with high level automation and complicated structures, so there are lots of failures. When a random failure occurs, the failed machining center stops and causes a production line or even the whole workshop to stop functioning. The frequent failure leads to the low levels of reliability and production rate. In order to help users and manufacturers optimize maintenance policy to improve the reliability for machining center, this paper presents descriptive statistics of the failure data and develops the failure trend using power-law process, simultaneously establishes the routine inspection and regular inspection as well as the sequential preventive maintenance under maintenance cost constraints. The proposed model could be a useful tool to assess the current conditions, predict reliability and optimize the machining center maintenance policy.

Keywords: *failure analysis, machining center, maintenance policy, power-law process, repairable system.*

Centrum obróbkowe to skomplikowany mechanizm o wysokim poziomie automatyzacji oraz złożonej konstrukcji, w związku z czym ulega licznym uszkodzeniom. Przy wystąpieniu przypadkowej awarii, uszkodzone centrum obróbkowe przestaje działać i powoduje zatrzymanie linii produkcyjnej a nawet całego oddziału produkcyjnego. Częste awarie obniżają poziom niezawodności oraz tempo produkcji. Aby pomóc użytkownikom i producentom zoptymalizować politykę utrzymania ruchu w celu poprawy niezawodności centrów obróbkowych, w niniejszym artykule przedstawiono statystyki opisowe dotyczące danych o uszkodzeniach i opracowano trend uszkodzeń w oparciu o proces spełniający prawo potęgowe. Jednocześnie ustalono zasady rutynowej inspekcji i okresowych przeglądów, jak również sekwencyjnej obsługi zapobiegawczej przy ograniczonych wydatkach na utrzymanie ruchu. Proponowany model może być użytecznym narzędziem dla potrzeb oceny aktualnych warunków oraz przewidywania niezawodności w celu optymalizacji polityki utrzymania ruchu centrum obróbkowego.

Słowa kluczowe*: analiza uszkodzeń, centrum obróbkowe, polityka utrzymania ruchu, proces spełniający prawo potęgowe, system naprawialny.*

1. Introduction

With the increasing development of high-speed and high-precision technologies, machining center is becoming the main equipment for advanced manufacturing technology. It is a typical electromechanical product mainly composed of mechanics, electronics and hydraulics, etc. In most cases, machining center is usually used in production lines for mass production, thus it fails more often than NC lathe [14].

Machining center is often regarded as a repairable system, so it can be restored to an operational state by some maintenance actions such as corrective maintenance (CM) and preventive maintenance (PM) [5, 6]. There is a failure-repair-failure cycle with the ability to repair a failed repairable system. Depending on the features of the repairable system, the distribution of the times to the first failures may not be the same as that of the times between successive failures. Therefore, the traditional life distribution models are not appropriate for the reliability analysis for the repairable system [1, 7].

Failure point process models are characterized by isolated events occurring at instants distributed randomly over a time continuum. So we can use point process models to describe failure process for the repairable system.

Machining center during the whole life acts with many failures which may result in the production of an entire workshop being halted. How does one improve the design of machining center? How does one find out the failure causes for the machining center? Which trends do the failure times follow? Is there an optimal maintenance policy for machining center? The above problems need to be solved to improve the reliability of machining center. This paper studies the failure analysis as well as failure trend model of machining center.

2. Brief description of machining center

The machining center discussed in this paper employs Mitsubishi 64m digital control system with digital AC servo system which has high-precision mode G61.1 and high-speed machining mode G05P3. The CNC system and some electronic components, such as relays, transformer and contactor switches are fixed in the cabinet. The spindle is driven by AC spindle motor, with speed varying from 60 to

8000rpm. The three feeding motions are driven by AC servomotors through ball screws and controlled by CNC simultaneously. In order to raise productivity, there is an automatic tool changer which includes 20 cutters [4].

The machining center is not only appropriate for cutting components such as plate, shaft and rod parts, but also for processing mold parts.

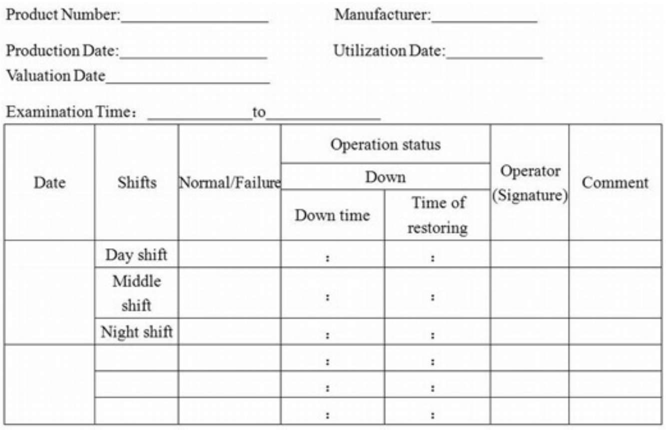
3. Data collection and analysis

3.1. Data collection

Data collection is the basis of failure analysis. The more detailed and truly the failure data is, the more accurate the analysis result is. Tables of operation records and maintenance reports are made in order to collect failure data in a unified format [13]. The operation records table should contain the following information:

1. Product name, product model, product size and manufacturing number.
2. Production date, start date of utilization and valuation date.
3. Other information about operation.

The above information should be recorded in the Fig.1 operation records table.



Product Number:_________________ Manufacturer:____________
Production Date:_________________ Utilization Date:___________
Valuation Date___________________
Examination Time：____________to_____________

Date	Shifts	Normal/Failure	Operation status		Operator (Signature)	Comment
			Down			
			Down time	Time of restoring		
	Day shift		:	:		
	Middle shift		:	:		
	Night shift		:	:		
			:	:		
			:	:		
			:	:		

Fig. 1. Operation Records Table

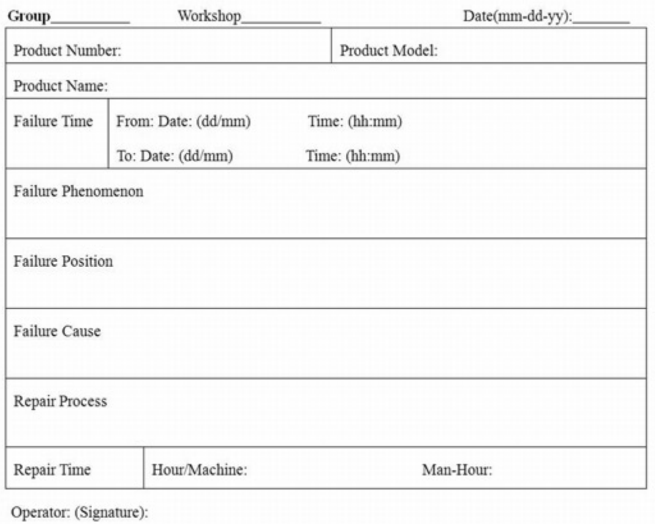
The maintenance reports table should contain the following information

1. Failure date and time
2. Failure phenomenon
3. Description of the failure cause
4. Repair process and repair time
5. Other information about machining center failure

The above information should be recorded in Fig.2 maintenance reports table.

The failure data is stored in Excel sheets, and then the time between failures can be obtained by the function of "TEXT (value, format_text)".

Every failure is categorized as spindle system (SS), CNC system (CNCS), electrical system (ES), hydraulic system (HS), tool magazine (TM), lubrication system (LS), screw and guide system (SAGS), servo system (Servo), changeable table (CT), pneumatic system (PS), guard system (GS), cooling system (CS), swarf conveyor (SC) or clamping accessory (CA) based on the function sharing, function independence and convention division principles.



Group__________ Workshop__________ Date(mm-dd-yy):________

Product Number:		Product Model:
Product Name:		
Failure Time	From: Date: (dd/mm) Time: (hh:mm) To: Date: (dd/mm) Time: (hh:mm)	
Failure Phenomenon		
Failure Position		
Failure Cause		
Repair Process		
Repair Time	Hour/Machine:	Man-Hour:

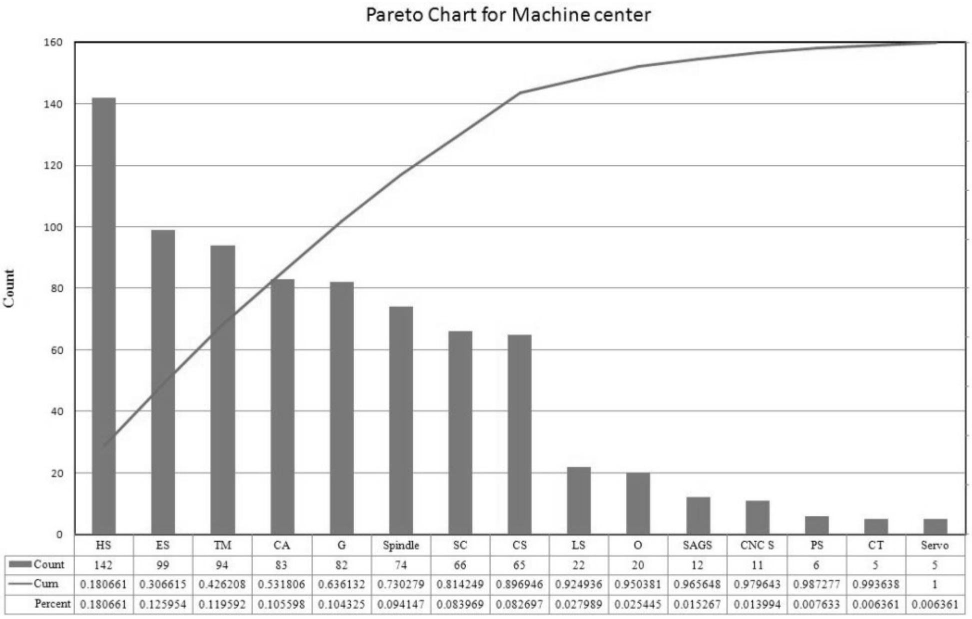
Operator: (Signature):

Fig. 2. Maintenance Reports Table

3.2. Failure analysis

The failure data analyzed in this paper were derived from practical application of twelve machining centers which were manufactured by Dalian Machine Tools Group located in northeast of China. These machining centers were used in a typical representative company of FAW (Fist Auto Works of China) and were traced over the time from 2005 to 2010.

In order to find the weak subsystems, the failures analysis are done and shown in Table 1 which consists of the basic features of repair time, standard deviation (SD) and coefficient of variation (CV). The pareto diagram of the failures is drawn in Fig.3 based on the failure data. In Fig.3, we observe that the HS had the most failures followed by ES, TM, CA, GS and SS and the sum failures of the first six



	HS	ES	TM	CA	G	Spindle	SC	CS	LS	O	SAGS	CNC S	PS	CT	Servo
▬ Count	142	99	94	83	82	74	66	65	22	20	12	11	6	5	5
— Cum	0.180661	0.306615	0.426208	0.531806	0.636132	0.730279	0.814249	0.896946	0.924936	0.950381	0.965648	0.979643	0.987277	0.993638	1
Percent	0.180661	0.125954	0.119592	0.105598	0.104325	0.094147	0.083969	0.082697	0.027989	0.025445	0.015267	0.013994	0.007633	0.006361	0.006361

Fig. 3. Pareto diagram of the failures position of machining center

Table 1. Results of the repair time analysis

Subsystem	Repair time	SD	CV	Subsystem	Repair time	SD	CV
HS	1.73	2.54	1.47	CS	2.29	7.68	3.35
ES	0.93	0.68	0.73	LS	0.92	0.28	0.31
TM	1.66	3.35	2.03	SAGS	4.04	13.44	3.33
CA	1.27	1.33	1.05	CNCS	1.37	1.75	0.5
G	1.28	1.29	1.01	PS	0.86	0.14	0.17
SS	2.65	5.17	1.95	CT	0.8	0.45	0.56
SC	0.98	0.80	0.82	SS	1.41	0.28	0.20

subsystems accounted for 73%. Furthermore, 18% of all failures were observed at the HS. From what has been mentioned above, the HS was a large hindrance to the improvement of the reliability. Effectively, with the development of direct-drive technique of the spindle, it had been simplified greatly and the reliability had been raised remarkably. Compared with it, the ES and TM had been improved little.

The CNCS, PS, CT and Servo had few failures seen from Fig.3. Generally speaking, the reliability of these subsystems was much higher than that of the HS, ES.

3.3.1 Failure analysis of HS

The failures of HS accounted for 18% of all the failures, more than any other subsystem. The failures of HS consisted of damages of pumps, solenoids, valves and hoses. The main failure phenomenon and causes are listed in Table 2. From Table 1 and Table 2, the following observations can be made:

a) The main failure causes of the HS were damages of oil pipes, solenoid valves and oil seal indicating that the outsourcing components were unqualified.
b) The HS-related failures required an average repair time of 1.73*h* which was the fourth longest of all the subsystems. The impact on the availability of machining center was significant.

Table 2. Failure phenomenon and causes of HS

Order	Failure phenomenon	Failure causes
1	Oil leaks from oil pipes	Oil pipes damage
2	Tool doesn't changes	Solenoid valves damage
3	Clamping accessory doesn't work	Damage of oil pipes
4	Oil leaks from cylinder	Oil seal wears out
5	Oil pressure is low	Gear pump damages
6	Oil pressure is not stable	The oil goes bad
7	Changeable table turns slowly	The filter is blocked
8	The hydraulic system alarms	The oil temperature is high
9	The oil leaks from pipe joints	The coupling cutting ferrule is loose
10	The position of the cutter holder is wrong	The reversing valves wears out

3.3.2. Failure analysis of ES

12.6% of all the failures were classified as ES. This category included failures of the electrical devices such as switch, lamp-stand, MCB, power module, relays and limit switch. From Table 1 and Table 3 the following observations can be made:

a) The repair time of the ES was the fourth least of all the subsystems.
b) The repair time was 0.93*h*, with low variability because CV was less than one.

Table 3. Failure phenomenon and causes of ES

Order	Failure phenomenon	Failure causes
1	The spindle moves	The position switch damages
2	Work lights doesn't work	Lamp-stand damages
3	The MCB is off	The MCB damages
4	Clamping accessory doesn't work	The switch damages
5	The machining center doesn't work	The power module damages
6	The fan doesn't rotates	The button damages
7	The fuse wire damages	Water goes in fuse box
8	The power line breaks	The power line exposes
9	1020 alarms	A coil of cooler breaks
10	The processing size is out of tolerance	Reset the limit value
11	1027, 1008 and 1007 alarm	Reset he heat transfer element

Table 4. Failure phenomenon and causes of TM

Order	Failure phenomenon	Failure causes
1	The tool can't be loosen	Damage of button
2	Drop of the tool	The tool arm goes down
3	The manipulator can't work	Damage of proximity switch
4	The tool magazine can't rotate	Damage of rolling bearing
5	The tool changes improperly	The wing piece is locked
6	Drop of the tool when machining	The groove of the catch tool wears out
7	The position of the tool sheath is wrong	Damage of spring of location
8	1024 alarms	The time of changing tool is too long

3.3.3. Failure analysis of TM

Failures of TM accounted for 12.9%. Failures of TM consisted of the wrong position of the tool arm, damages of proximity switch and button. TM failures required an average repair time with 1.66*h*. The moderate repair time was mainly due to the long diagnostic time.

Table 5. Failure phenomenon and causes of CA

Order	Failure phenomenon	Failure causes
1	Can't find the centering	Damage of pin
2	The CA can't work	Damage of screw
3	The pressure of clamping is too small	Position of location of clamping is high
4	The CA can't work	Damage of the clamping box
5	Oil leaks from CA	Loose of screw
6	The pressure of clamping is too small	Too much iron chipping

3.3.4. Failure analysis of CA

CA failures accounted for 10.55% of all failures. This category of failures included damages of pin, screw and box of clamping. These types of failures needed the machining center to be shut down resulting in long repair time. From Table 5, we can see that:

a) There were 6 types of failure phenomenon and the main failure causes were damages of mechanical components.
b) The failures of CA mainly caused by the mistakes of the users.

3.3.5. Failure analysis of GS

Table 6. Failure phenomenon and causes of GS

Order	Failure phenomenon	Failure causes
1	The guard breaks away	Deformation of guard seriously
2	The guard breaks away	Too much iron chipping
3	The water sinks in the guard	The bolt of protective door is loose
4	The guard of screw breaks away	The welding of guard breaks
5	Drop of protective door	The bolt of protective door is loose
6	Damage of slide guard	The guard is pulled bad
7	The door of guard fails to open	Damage of the guard roller
8	Poor position of work station	Damage of the guard

GS failures accounted for 10.4% of all the failures. This category consisted of loose of bolt and damage of protective guard. The failure causes were the improper length of guard. The repair time of GS was close to that of CA. It was because the failures of GS and CA were easy to diagnose and repair.

3.3.6. Failure analysis of SS

9.4% of all the failures were spindle failures. Spindle failures had the second longest repair time which was 2.65*h*. The SS was one of the most important subsystems of the machining center. The impact of SS failures on processing parts leaded to the poor precision. The failure phenomenon and causes are listed in Table 7. It is found that the failures mainly caused by the poor assemblage.

3.3.7. Failure analysis of other subsystems

27% of all the failures were failures of other subsystems. These subsystems had fewer failures than the first six subsystems. The reason was the technologies of these subsystems were stable and well understood.

Table 7. Failure phenomenon and causes of SS

Order	Failure phenomenon	Failure causes
1	The processing part has poor precision	Radial endplay of spindle
2	No motion	Damage of motor
3	The parallel of processing part is poor	The bearing clearance is big
4	Poor precision of spindle	Wear out of the bearing
5	The speed of the motor is so low	Lubricants of the spindle is poor
6	The PLC alarms	Damage of spindle disc claw
7	Drop of the cutting tool	Damage of spring
8	The spindle doesn't rotate	Oiliness of spindle box
9	Abnormal sound in spindle box	Damage of oil cooler
10	700 or 705 alarms	Loose of cable
11	The spindle doesn't work	Damage of the belt

4. Reliability analysis of machining center

4.1. Model of PLP

Machining center as a repairable system is often modeled by counting processes. A common procedure for analyzing a set of data derived from repairable systems is referred to [8, 10]. The system is observed from instant t=0, and let T_1, T_2 ... T_i denote the successive failure times, X_1, X_2... X_i denote times between failures, thus $X_i=T_i-T_{i-1}$.

The model of NHPP is commonly used in the reliability analysis of complex repairable system with failure intensity function Eq. (1) and cumulative intensity function Eq. (2)

h $$h(t)=\lambda\beta t^{\beta-1} \tag{1}$$

$$H(t)=\lambda t^{\beta} \tag{2}$$

The above intensity function is called the power-law process (PLP). Under the PLP, when $\beta<1$, there is positive reliability growth. That is, the system reliability is improving due to corrective actions. When $\beta>1$, there is negative reliability growth.

4.2. Analysis of failure data for machining center

4.2.1. PLP of HS

The failure data of machining centers analyzed in this paper were collected from 2005 to 2010. All these machining centers were used in two automotive production lines. So assume that the machining centers had the similar using conditions. Table 8 lists the failure data of HS. Denote variable T_k the k^{th} failure time and t_k is its realization.

Let $0<t_{i1}<t_{i2}<\ldots<t_{in_i}$ denote the sequential failures times, then the likelihood function under the minimal repair assumption can be shown as [2]

$$L=\prod_{i=1}^{k}\left\{e^{-\lambda T_i^{\beta}}\prod_{j=1}^{n_i}(\lambda\beta t_{ij}^{\beta-1})\right\} \tag{3}$$

Where k is the number of machining centers, n_i is the number failures of the i^{th} machining center and T_i is the time-terminated data.

Then the maximum likelihood estimates (MLE) of λ and β are given by

$$\hat{\lambda}=\frac{\sum_{i=1}^{k}n_i}{\sum_{i=1}^{k}T_i^{\beta}},\ \frac{1}{\hat{\beta}}=\frac{\sum_{i=1}^{k}T_i^{\hat{\beta}}\ln T_i}{\sum_{i=1}^{k}T_i^{\hat{\beta}}}-\frac{1}{n}\sum_{i=1}^{k}\sum_{j=1}^{n_i}\ln t_{ij}\ .$$

In general, these equations cannot be solved explicitly for $\hat{\lambda}$ and $\hat{\beta}$, but can be solved by iterative procedures. Once the estimates $\hat{\lambda}$ and $\hat{\beta}$ are got, the MLE of the intensity function is given by

$$\hat{h}(t)=\hat{\lambda}\,\hat{\beta}\,t^{\hat{\beta}-1} \tag{4}$$

Table 8. Failure data of HS

1	2	3	4	5	6	7	8	9	10	11	12
162	1813	2540	19117	8121	17695	10837	8120	7242	3089	1691	370
19627	18296	11831	22629	12439	20530	13785	10328	14535	3393	1702	1039
28576	27232	12449	32312	17707	20743	22018	20384	15705	13508	9800	1472
28583	44728	14830	32528	21390	26365	23529	32960	23551	16981	10233	2345
31710		15204	35197	23776	26920	23559	34501	25741	26278	14000	3419
31811		15496	35432	24756	28205	25740	35527	26673	44728	15130	5190
36227		16428	37278	27702	29453	26605	43798	35038		22047	5239
36246		20502	38214	27727	29753	35037	44728	44728		22854	6369
36827		21323	38411	29758	29993	44728				25740	13286
37016		26278	38910	29824	36538					25740	14093
37037		44728	44143	29846	40900					26983	15101
37086			44582	30436	41825					27871	15132
38100			44728	35169	43357					29621	16132
38125				41481	43359					30016	16978
38140				44728	44728					35035	17379
38270										44728	17859
38388											18221
38435											19109
38482											19732
39110											20859
39299											21254
40286											26273
40616											44728
42433											
43466											
44209											
44728											

Using the Excel solver [11], the PLP of HS is obtained as below

$$h(t) = 2.66 \times 10^{-5} * t^{-0.27} \tag{5}$$

$$H(t) = 1.68 \times 10^{-5} * t^{1.27} \tag{6}$$

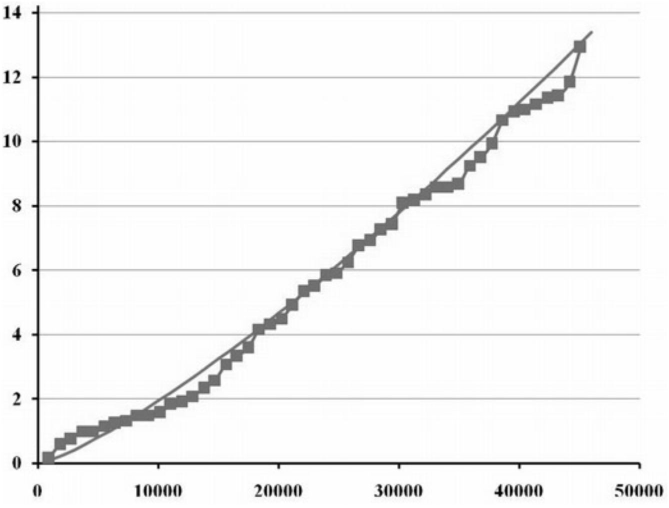


Fig. 4. The cumulative intensity function of PLP for HS data

So the cumulative intensity function is as shown in Fig.4.

4.2.2. Goodness-of-fit test

To determine whether the NHPP is a more appropriate model than the homogeneous Poisson process, a trend test on the failure times is performed [3].

The hypotheses tested are

H_0: The intensity function is constant (β=1).

H_1: The intensity function is not constant ($\beta \neq 1$).

The test statistic is computed from

$$\chi^2 = \frac{2n}{\hat{\beta}} \tag{7}$$

where n is the number of failures and β is MLE the growth or deterioration rate.

Therefore, χ^2=288/1.27=226.77. Since $\chi^2 > \chi^2_{crit,0.05}$, a significant trend is present. According to the above analysis, to perform the goodness-of-fit for the PLP intensity function, the hypotheses are:

H_0: A PLP with intensity $h(t) = \lambda \beta t^{\beta - 1}$ describes the failure data.

H_1: The above process does not describe the data.

The test statistic is computed from

$$\tilde{\beta} = \frac{n-1}{n}\beta \tag{8}$$

where n is the number of failures.

The Cramer-von Mises [8, 9, and 15] goodness-of-fit test statistic is computed by

$$C_M = \frac{1}{12M} + \sum_{i=1}^{M}[(\frac{t_i}{t_k})^{\beta} - \frac{2i-1}{2M}]^2 \tag{9}$$

where M=n for time-terminated data, t_k=T and T is the total cumulative test time for time-terminated data.

For the data provided in Table 8, the test statistic is computed as follows

$$M=144,\ \tilde{\beta}=1.23\ ,\ C_M = \frac{1}{12M} + \sum_{i=1}^{M}[(\frac{t_i}{t_k})^{\beta} - \frac{2i-1}{2M}]^2 = 0.09$$

The significance α=0.05, the critical value is 0.22. Since $C_M<0.22$, H_0 is accepted.

4.2.3. PLP of the other subsystems

The machining center consists of thirteen subsystems in series with automated control system. The PLP of the other subsystems can be obtained and listed in Table 9 by the method mentioned in section 4.2.1 and 4.2.2.

Table 9. PLP of subsystems for machining center data

Systems	λ	β	C_M	Cramer-von Mises
HS	1.68×10^{-5}	1.27	0.09	0.22
ES	3.43×10^{-5}	1.17	0.19	0.22
TM	4.08×10^{-3}	0.72	0.12	0.22
CA	2.35×10^{-5}	1.19	0.15	0.22
G	6.40×10^{-5}	1.11	0.21	0.22
Spindle	1.22×10^{-4}	1.02	0.19	0.22
SC	7.65×10^{-6}	1.27	0.21	0.22
CS	1.71×10^{-4}	1.00	0.12	0.22
LS	7.55×10^{-6}	1.24	0.06	0.22
O	1.79×10^{-4}	0.89	0.18	0.217
SAGS	1.73×10^{-4}	0.90	0.17	0.212
CNC S	9.09×10^{-9}	1.77	0.08	0.212
PS	2.01×10^{-7}	1.43	0.09	0.212
CT	1.53×10^{-8}	1.63	0.07	0.199
Servo	1.63×10^{-10}	2.00	0.07	0.199

The critical value of the goodness-o-fit test at 5% significance level is 0.22. Seen from Table 9, almost all statistics C_M are less than 0.22. Therefore, the hypothesis that the models listed in Table 9 can be used to estimate the trends of subsystems, respectively.

4.2.4. Analysis of failure data of machining center

In this section we establish the PLP for the machining center. The failure data were more, so they were not listed here. And the related characteristics are shown in Table 10. Fig.5 shows the cumulative intensity function of machining center.

Table 10. PLP of machining center

λ	β	C_M	Cramer-von Mises
3.41×10^{-5}	1.30	0.17	0.22

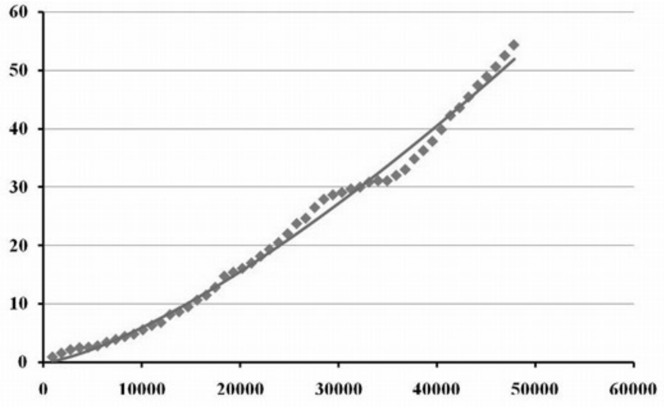


Fig. 5. The cumulative intensity function of PLP for machining center data

According to Cramer-von, the critical value of the test at 5% significance level is 0.22; therefore, the model can be used to estimate the failure trend of machining center.

5. Maintenance policy of machining center

5.1. Preventive maintenance

Machining center deteriorates with usage and can fail. If machining center fails, it would have a great effect on the product performance. In order to guarantee the reliability, appropriate maintenance should be paid on machining center. Actions to control (or reduce) equipment degradation are called PM and PM is classified into two groups – one is periodic PM and the other is sequential PM.

In order to improve the utilization of machining center, the users should develop the items of PM. There are generally two kinds of methods for PM of machining center: one is routine inspection, the other is regular inspection.

The goals of routine inspection of machining center are mainly used to examine whether there is enough lubricating oil, enough coolant liquid and whether the bolts, key connections and V-belt are loosened and whether there are leakage of oil, and so on. The routing testing items are shown in Table 11. There is regular inspection besides routine inspection for machining center. The regular inspection of machining center mainly includes spindle motor inspection, lubricate subsystem inspection, hydraulic subsystem, and so on. The regular inspection items are shown in Table 12.

5.2. Sequential preventive maintenance

As the parameter β=1.30, so the machining centers were in wearout life. That is to say the failure rate became higher with the increasing of the usage and maintenance times when the machining centers were in this life region. In order to improve the reliability, an appropriate maintenance policy should be optimized. Therefore, in this section we will select a sequential PM policy.

Considering the failure rate increasing over time, the failure rate between (i-1)th PM to ith PM can be described in the Eq.(10)[16,17].

$$h_i(x) = \theta^{i-1}h(x+\varepsilon t_{i-1}), 1 \le \theta \le \mu, 0 \le \varepsilon \le 1 \tag{10}$$

Table 11. Routine inspection items

Num	Testing part	Testing items
1	Oil level gauge of the lubricate parts	• If there is enough oil • If the oil is contaminated
2	Surface of coolant liquid	• If amount of the coolant liquid is fit • If the coolant liquid is obvious contaminated • If the filter is clogged
3	Linear guide	• If there is enough lubricating oil • If the scratch chip board damages
4	Pressure gauge	• If the pressure is proper
5	V-belt	• If the tension is proper • If there are cracks and scratches
6	Pipe and appearance	• If there is the leakage of the oil • If there is the leakage of the coolant liquid
7	The moving parts	• If there are noise and vibrations • If the parts move smoothly
8	Panel	• If functions of the switch and handle are normal • If it displays alarm
9	Electric wire	• If there is disconnection • If the insulated coat is wearing out
10	Rotating part	• If there are noise and vibrations • If there is abnormal heat
11	Cleaning	• Clean the surface of the chuck, linear guide and chip machines
12	Workpiece	If the machining center keeps the machining accuracy under the control

Table 12. Regular inspection items

Num	Testing part		Testing items	Period
1	Hydraulic subsystem	Hydraulics Pipe joints	• Change the oil, clean the filters • Testing the leakage of the oil	6 mths 6 mths
2	Lubrication subsystem	Lubrication devices Pipe	• Clean the filters • Testing if there are the leakage, blockage and damage of pipes	1 year 6 mths
3	Cooling subsystems	Filter Chips plate	• Clean the chips plate • Change the coolant liquid, clean the filters and water tank	Depends on the situation
4	Pneumatic subsystem	Air filters	• Clean the air filters or change it	1 year
5	V-belt	Belt Pulley	• Test the tension • Clean the pulley	6 mths
6	Spindle motor	Sound, vibration and temperature rise	• Test the abnormal noise of the bearing • Clean the air filters	6 mths
7	Servo motor of X and Z axis	Sound and temperature rise	• Test the abnormal noise of the bearing and abnormal temperature rise	1 mth
8	Clamp subsystem	Clamp devices Cylinder	• Disassemble the clamp and clean it • Test the leakage of the cylinder	1 year 3 mths
9	Panel	Electrical devices Connection screws	• Test if there is odors, change color and damages of interface • Clean the connection screws	6 mths 1 mths
10	Electric subsystem	Limit switch Sensor Magnetic valve	• Test and fastening connection screws again • Test the function and activity of electric devices	6 mths 1 mths
11	X and Z axis	Clearance	• Measure the clearance by dial gage	6 mths
12	Base	Level of base	• Test and adjust the level of base by dial gage	1 year
13	Tool changer	Tool changer	• Test the origin of tool and adjust it	1mths

Where θ is increase factor of failure rate, ε is the repair factor of maintenance.

So the corresponding failure intensity function of PLP and the reliability function are

$$h_i(x) = \theta^{i-1}\lambda\beta(x+\varepsilon t_{i-1})^{\beta-1} \qquad (11)$$

$$\begin{aligned} R_i(x) &= \exp[-\int_0^x h_i(x)dx] \\ &= \exp[-\lambda\beta\int_0^x \theta^{i-1}(x+\varepsilon t_{i-1})^{\beta-1}dx] \\ &= \begin{cases} \exp(-\lambda x^{\beta}), i=1; 0\le x\le T_1 \\ \exp\left\{-\dfrac{\lambda}{t_{i-1}}(\dfrac{\mu+1}{2})^{i-1}[\dfrac{(t_{i-1}+x)^{\beta+1}}{\beta+1}-\dfrac{t_{i-1}{}^{\beta+1}}{\beta+1}-\dfrac{x^{\beta+1}}{\beta+1}]\right\}, i=2,3,\ldots,N; 0\le x\le T_i \end{cases} \end{aligned} \qquad (12)$$

When the reliability reduces to R$_{\min}$, the sequential PM would be carried out. So from the above formula, we can get

$$\begin{cases} \exp(-xt^{\beta}) = R_{\min}, i=1 \\ \exp\left\{-\dfrac{\lambda}{t_{i-1}}(\dfrac{\mu+1}{2})^{i-1}[\dfrac{(t_{i-1}+x)^{\beta+1}}{\beta+1}-\dfrac{t_{i-1}{}^{\beta+1}}{\beta+1}-\dfrac{x^{\beta+1}}{\beta+1}]\right\} = R_{\min}, i=2,3,\ldots,N \end{cases} \qquad (13)$$

5.3. Maintenance cost

Denote the cost of repair by c$_m$, the cost of PM by c$_p$. the cost of replacement by c$_r$. Nakagawa [12] derived the following mean repair cost of N PM periods

$$C(T_i,N) = \frac{c_m\sum_{i=1}^{N}\int_0^{T_i} h_i(x)dx + (N-1)c_p + c_r}{\sum_{i=1}^{T_i} T_i} \qquad (14)$$

The cumulative number of failures during the i^{th} interval of sequential PM is given by

$$F_i = \int_0^{T_i} h_i(x)dx = -\ln R_{\min} \qquad (15)$$

Thus substituting Eq.(15) in Eq.(14) gets Eq.(16)

$$C(T_i,N) = \frac{(c_r-c_p)+N(c_p-c_m\ln R_{\min})}{\sum_{i=1}^{T_i} T_i}, i=1,2,\ldots,N \qquad (16)$$

Our purpose is to seek both the optimal time T_i and number N which minimize $C(T_i,N)$ in Eq.(16). To find an N which minimizes $C(T_i,N)$, we form the inequalities

$$\begin{cases} C(T_i,N+1)\ge C(T_i,N) \\ C(T_i,N-1)\ge C(T_i,N) \end{cases} \qquad (17)$$

Based on the empirical data, c_m=20000, c_p=10000, c_r=550000, R_{min}=0.7, substituting $\lambda=3.41\times10^{-5}$, $\beta=1.3$ in Eq.(16) and Eq.(17) gets the sequential PM periods and the mean cost C(N*) with 82.57. The results are shown in Table 13. The failure intensity function can be seen in Fig.6.

Table 13. Preventive maintenance period

i	*T$_i$*	*t$_i$*	*i*	*T$_i$*	*t$_i$*
1	1236	1236	13	384	8374
2	959	2195	14	362	8736
3	833	3029	15	341	9076
4	746	3775	16	321	9398
5	678	4453	17	303	9701
6	619	5072	18	286	9987
7	576	5648	19	271	10258
8	534	6182	20	256	10514
9	498	6680	21	242	10756
10	465	7145	22	229	10985
11	436	7581	23	217	11202
12	409	7990	24	206	11408

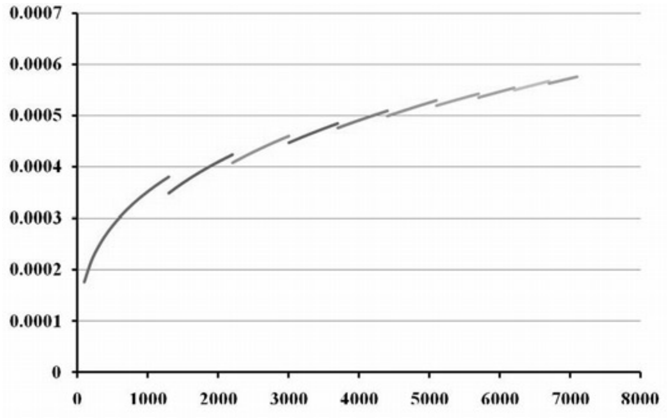


Fig.6. Failure intensity function kth PM for machining center data

6. Conclusion

Synthetical design of reliability should be an integral part of design and management for the effective utilization of product. In this study the field failure data for 12 machining centers over five years were collected and analyzed. The following conclusions can be derived.

- The weakest subsystem of machining center is HS whose failures required the fourth longest repair time. It showed that the repairmen were not familiar with the HS, so the company should conduct repair training for the repairmen.
- The CA had the least failure modes and causes, so it was more likely to improve the reliability of CA. Therefore the manufacture factory of machining center should pay more attention to the design of CA.
- The failures of SS were mainly caused by the poor assembly and therefore the manufacture factory should do static balance test and dynamic equilibrium test to enhance the level of assembly.
- We have developed the PLP with $\lambda=3.41\times10^{-5}$ and $\beta=1.30$ for the machining center. It means the machining center is deteriorating with usage.
- Depending on the limitation of reliability and repair cost, the sequential PM policy was established with the mean cost C(24*) is equal to 82.57.

Finally, we should point out two implementation-related issues. The sequential PM policy is appropriate for the product that is deteriorating over time. The second issue deals with the different using conditions, where relevant PLP and maintenance policies need to be modified. It is an open issue for future study.

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References

1. Ascher H, Feingold H. Repairable Systems Reliability. New York: Marcel Dekker Inc., 1984.
2. Cao JH, Cheng K. An Introduction to Reliability Mathematics. Beijing: Hinger Education Press, 2006.
3. Charles EE. An Introduction to Reliability and Maintainability Engineering. Beijing: TsingHua press and McGraw-Hill Education, 2008.
4. Deng LH, Kuang LJ. Performance Analysis of VDL-1000 Machining Center. Plant Maintenance Engineering 2006; 3, 34–35.
5. Hsu BM, Shu MH. Reliability assessment and replacement for machine tools under wear deterioration. International Journal of Advanced Manufacturing Technology 2010; 48, 355–365.
6. Jiang RY, Murthy DNP. Maintenance: Decision Models for Management. Beijing: Science Press, 2008.
7. Jiang RY, Guo Y. Two Simple Repairable Reliability Models. 2012 Reliability Technology Academic Conference of the National Machinery Industry, Changchun, 20-21 Aug 2012.
8. Larry HC. Evaluating the Reliability of Repairable Systems. 1990 Proceedings Annual Reliability and Maintainability Symposium, Los Angeles of USA, 23 -25 Jan 1990.
9. Larry HC. Reliability Growth Estimation With Missing Data-II. 1988 Proceedings Annual Reliability and Maintainability Symposium, Los Angeles of USA, 23 -25 Jan 1988.
10. Lindqvist BH. Statistical Modeling and Analysis of Repairable Systems. Proceedings of the 1st International Conference on Mathematical Methods in Reliability, Bucharest of Romania, 16-19 Sep, 1997.
11. Matthew MD. Excel 2010 the missing manual. Sebastopol: Pogue Press, 2010.
12. Nakagawa T. Periodic and sequential preventive maintenance policies. Journal of Applied Probability 1986; 23,536–542.
13. Wang YQ, Jia YZ, Yu JY, Yi SF. Field failure database of CNC lathes. International Journal of Quality and Reliability Management 1999; 16(4), 330–340.
14. Wang YQ, Jia YZ, Yu JY, Zheng YH, Yi SF. Failure probabilistic model of CNC lathes. Reliability Engineering and System Safety 1999; 65, 307–314.
15. Won JP, Yoon GK. Goodness-of-Fit tests for the Power-Law process. IEEE Transaction on Reliability 1992; 41(1), 107–111.
16. Wu SM, Derek CC. Preventive maintenance models with random maintenance quality. Reliability Engineering and System Safety 2005; 90, 99–105.
17. Zhou XJ, Xi LF, Lee J. Reliability-centered predictive maintenance scheduling for a continuously monitored system subject to degradation. Reliablity Engineering and System Safety 2007; 92, 530–534.

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