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Assessment of the Tool Post Reliability of a High-Stiffness Turning Machine

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Abstract

Reliability refers to the ability of a part, device or system to conduct an intended function in a given condition for a certain period of time. A mechanical system or structure such as a machine tool exercises the capacity of the entire system with regard to the various constituent parts that are connected to each other; as such, the reliability of the parts constituting the system determines the reliability of the entire system. A tool post is a device designed to efficiently provide the tools necessary for the processing of a turning machine: the parts used in a hard turning machine which requires higher stiffness must provide greater reliability. For the purposes of this study, the reliability of a tool post, which has the highest failure rate of a turning machine system, was assessed. In order to conduct a reliability assessment of a given tool post, reliability prediction using a failure rate database, weak point analysis, the manufacture of a reliability tester and the calculation of reliability testing and quantitative reliability criteria were also carried out. By so doing, the failure rate, the MTBF (Mean time between failures) and other factors could be calculated. Furthermore, the results can also be applied to other parts of the turning machine or to a reliability assessment of a sub-system by using the suggested assessment method.

Keywords: Reliability assessment; Reliability prediction; Failure rate database; Tool post; Mean time between failures; Failure rate

1. Introduction

A production method to which the concept of reliability is applied has recently been used, rather than simple design and production focusing on the functions in all industrial fields (Saleh, 2006). Reliability refers to the ability of a part, device or system to conduct an intended function in a given condition for a certain period of time. Products that are produced according to such a method meet the customers' requirements in terms of both quality and function. In particular, a mechanical system or structures like a machine tool which exercises the capacity of an entire system in which the many constituent parts are connected to each other; as such, the reliability of the parts constituting the system determines the reliability of the entire system. Therefore the reliability of each part is very important (Lee, 2006).

A tool post is a device that efficiently and automatically provides the tools necessary for the processing of a turning machine, and the precision of such a device is the core unit that ultimately determines the precision of a processed product. According to the relevant analyses, a tool post is known to have the highest failure rate among the subsystems that constitute a turning machine system

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(RAC, 1991). In particular, a tool post used in relation to processing in a processing system - which requires high stiffness, such as that provided by a hard turning machine-requires higher reliability (Kim, 2005). In general, the reliability assessment of the electronic parts is conducted on the assumption that the failure rate (according to the bath-tub failure rate curve which is generally used) remains the same during the useful life of the electronic parts (Lee, 2001; Lee, 2006). However, although the failure rate of the mechanical parts tends to increase, it is an essential to obtain as much information on the reliability of mechanical parts as possible, all the more so because we don't currently have much information on the failure rate of mechanical parts (Wang, 1999; Lee, 2003).

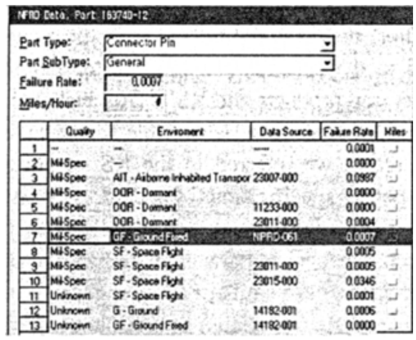
In this study, with regard to the reliability assessment of the tool post used in a hard turning machine, the quantitative calculation of reliability and the calculation of the reliability information of the mechanical parts were conducted by forecasting their reliability and analyzing their weak points using the failure rate of the mechanical parts; manufacturing a reliability tester for the reliability testing of a tool post; carrying out a reliability test for the measurement of such functions as stiffness, repetition and angular resolution; and calculating the quantitative reliability criteria, and so forth.

2. Reliability prediction

Reliability prediction refers to the efforts made to enhance the competitive power of a product in the market and to prevent losses caused by unexpected accidents, mainly by checking the reliability of the product's design according to its development state or by forecasting the reliability of a prototype, thereby enhancing its reliability before production starts (Moasoft Inc., 2002). The reliability prediction methods include FMEA (Failure Mode and Effect Analysis), FTA (Fault Tree Analysis), Worst Case Analysis, performance assessment and the field data method (Customer Service Data), and the failure rate database method, and so on. To conduct reliability prediction effectively, data (information on the failure rate) on the failures of each part is desirable. Unlike electronic parts, there is no clear definition of the failure mode and known reliability data for mechanical parts. Therefore, in this study, we conducted a reliability prediction using the NPRD95 (Non-electric Part Reliability Data 95), a database containing information on the failure rate of mechanical parts (Lee, 2003).

The NPRD95 database, which holds collected and edited data accumulated from 1974 to 1994, is the only source of information on the failure rate of mechanical parts. These failure rates follow an exponential distribution (RAC, 1995). In order to search for information on reliability, modeling of the system is required first of all. The basic data for modeling are the parts list, bills of materials and drawing, and so on. Once modeling has been completed, the reliability information should be entered using the failure rate database. For reliability information, the user chooses the failure rate under the usage environment in the part selection set to part, part sub-type. Figure 1 shows an example of a search of the Connector Pin for the failure rate by using the NPRD95.

A tool post, as shown in Fig. 2, is composed of a turret head to which the tools are mounted, a main shaft that supports the turret, a clamping part to fix the rotation of the tool, gears (driveshaft) to transmit power for the rotation of the tool, and electrical sensor parts such as a proximity switch. The turret head has a


NPRD Data, Part 163740-12
Part Type: Connector Pin
Part SubType: General
Failure Rate: 0.0007
Miles/Hour:

	Quality	Environment	Data Source	Failure Rate	Miles
1	--	--	--	0.0001	
2	Mil-Spec	--	--	0.0000	
3	Mil-Spec	AIT - Airborne Inhabited Transpor	23007-000	0.0987	
4	Mil-Spec	DOR - Dormant		0.0000	
5	Mil-Spec	DOR - Dormant	11233-000	0.0000	
6	Mil-Spec	DOR - Dormant	23011-000	0.0004	
7	Mil-Spec	GF - Ground Fixed	NPRD-061	0.0007	
8	Mil-Spec	SF - Space Flight		0.0005	
9	Mil-Spec	SF - Space Flight	23011-000	0.0005	
10	Mil-Spec	SF - Space Flight	23015-000	0.0346	
11	Unknown	SF - Space Flight		0.0001	
12	Unknown	G - Ground	14182-001	0.0006	
13	Unknown	GF - Ground Fixed	14182-001	0.0000	

Fig. 1. Search for information on failure rates using NPRD95.

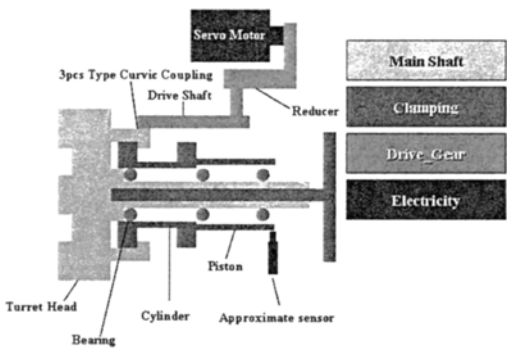


Fig. 2. Classification of parts constituting a tool post for reliability prediction.

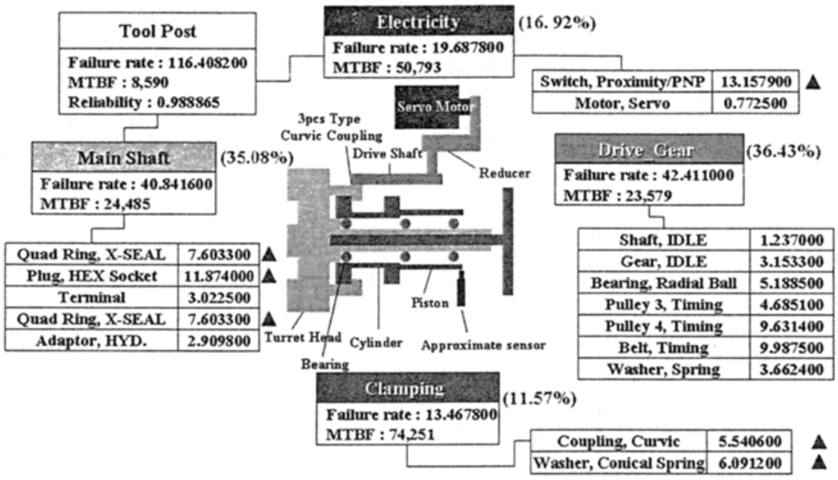


Fig. 3. Analysis of the sub-assembly and main parts of the tool post.

holder into which 12 tools can be inserted and installed.

Because most mechanical products are composed of components that are linked to each other by rings, bolts and nuts, we classified the composition of the tool post to a single level for reliability prediction. The reliability information should be searched for according to the standards of the specifications, materials, and usage environment of the constituent parts. For the material-related specifications, we referred to the specifications manual of KS D4301 gray cast iron products and KS D3709 nickel chrome molybdenum steel materials, while for parts-related specifications, we referred to the KS specifications and in-house specifications standard. Because the desired usage environment and specifications of the constituent mechanical parts are not always available, we selected the most similar parts (usage environment, materials and specifications) in consultation with the designer. A reliability block diagram is a method for calculating failure rate-related reliability by expressing the flows of energy, matter and information shown by the system (Wang, 2004). In this study, where the tool rotation of the tool post is regarded as the main function, the main parts were put together by series connection.

For the prediction results, the MTBF of the tool post was estimated at 8,590 hours and the failure rate at 116.408200 failures/million hours. The reliability prediction conditions involved an operation temperature of 30℃ in a GB (Ground Begin) and GC (Ground Controlled) environment. With regard to the sub-assembly, the highest failure rate is found in the

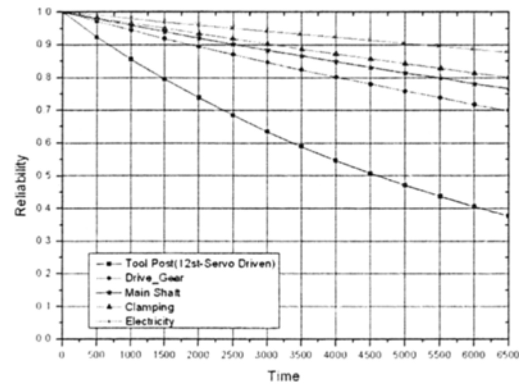


Fig. 4. Reliability change of the tool post and sub-assembly over time.

drive-gear, whose failure rate is 42.411000 failures/million hours, while the lowest failure rate is found in the electricity parts, whose failure rate is 19.687800 failures/million hours. The failure rate being in inverse proportion to the MTBF in an exponential distribution, the result means that the mean time between failures of the drive gear is shortest and the failure rate of the electricity parts is longest. Figure 3 illustrates the failure rate of the sub-assembly of the tool post and the weak points and failure rate of the main parts. The percentage of each blank indicates the failure rate of each sub-assembly when it is assumed that the failure rate of the tool post is 100%. The Timing Belt, Pulley and Radial Bearing of the Drive Gear, which has the highest failure rate, have a high failure rate and therefore can be expected to be weak parts. As they also have a high failure rate, the Proximity Switch, Quad-Ring (X-Seal), 3 piece type curvic coupling and the Proximity Sensor of the electric parts are expected to break down during actual operation.

Figure 4 illustrates the change in the reliability of the tool post and the constituent sub-assembly over time. The sub-assembly that reliability declines sharply is drive gear because the failure rate of the timing belt of the drive gear has a relatively higher failure rate than the other parts. In addition, we found that the reliability of the sub-assembly was almost equal to the failure distribution rate derived from actual customer service data.

3. Manufacture of a reliability tester and reliability testing

3.1 Tool post reliability tester

The failure of a tool post is the failure of indexing and clamping, which are the most important functions of a tool post. This is thought to be the result of a malfunction of the proximity sensor, which senses clamping or leaks caused by wear and tear of the sealing parts. In addition, damage to the main shaft, the defectiveness of parts assembly, the wear of parts due to the repetition of loads, and the backlash caused by loads asymmetry due to biased tool installation also lead to failure. Therefore, the angular resolution, repetition degree, stiffness and flatness of a tool post are very important elements of function and reliability. Table 1 shows the assessment items for a reliability assessment of a tool post. The reference data are made by machine tools maker.

Angular resolution and repetition are measured using an angle encoder, and if the values fall outside the reference value, then curvic coupling wear, O-Ring wear and oil pressure decrease are forecast. In the case of wear of the curvic coupling, the stiffness of the tool post decreases. For this measurement, the wear of the curvic coupling can be measured by inflicting loads with a load cell, measuring the transformation value and the stiffness change. Equally, the proximity sensor bracket vibration and temperature increase caused by continual operation can be measured using an accelerometer sensor and thermocouple.

Table 1. Evaluation items for the reliability assessment of a tool post.

Items	Source of Failure	Reference Value	Remark
Angular resolution	Worn out of Curvic Coupling and O-Ring	0.01°	Indexing and accuracies
Repetition	Same as above	0.005°	
Flatness	Assembling status	5 um	
Stiffness	Worn out of 3 piece type Curvic Coupling	200 N/um	Worn out of gear teeth
Vibration	Clamping Error		Detecting error of approximate sensor

In order to measure the aforementioned items, we made a reliability tester for the structure, as shown in Fig. 5. The tester is divided into a drive part, measurement part, control part and supporting part. The drive part is composed of a servomotor to drive the tool post, a hydraulic device and lubricating device; the measured data are processed in the PC. The supporting part is composed of a surface plate on which the tool post reliability tester is installed, and a bracket to which the sensor is fixed. In the study, we also used a surface plate on which a damper is installed. Figure 6 shows the tool post reliability tester which was actually made for this study.

3.2 Assessment of the performance of the tool post

We measured the performance of the tool post in order to determine the optimum operational conditions for reliability testing. This was conducted so as to define a failure by consecutively measuring perfor-

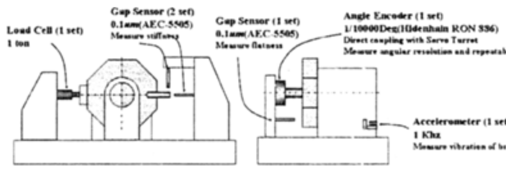


Fig. 5. Composition of a tool post reliability tester.

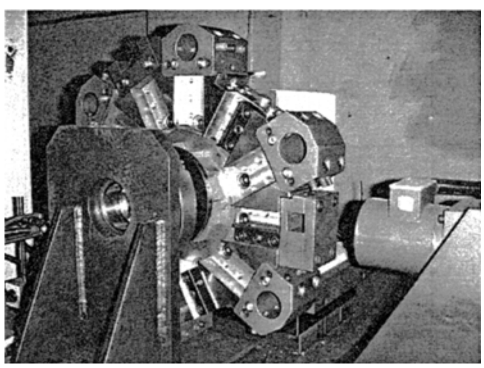


Fig. 6. Tool post reliability tester (actually made for the purposes of this study).

mance in a long operation.

3.2.1 Oil pressure and stiffness/repeatability

The stiffness of the radial direction of the tool post is determined by the change of the oil pressure on the curvic coupling. The oil pressure applied in this study is 20~70 kg/cm^2 and the strength inflicted by the load cell is 400 N. In the test, the stiffness decreased noticeably in oil pressure below 40 kg/cm^2 and remained fixed for oil pressure of more than 40 kg/cm^2. Figure 7 illustrates the change in stiffness according to the change in oil pressure. The optimum stiffness for maintaining the stiffness of a tool post requires oil pressure of at least 40 kg/cm^2.

Moreover, oil pressure also has a great impact on repeatability. If oil pressure is too low, repeatability declines because of the low clamping force of the curvic coupling. However, the use of too high a level of oil pressure is not desirable in the structural aspect either. Figure 8 illustrates the change of repeatability according to oil pressure. Oil pressure proved most desirable at 50 kg/cm^2 if we consider repeatability; because repeatability meets the basic value in oil pressure over 50 kg/cm^2 and fails to meet the basic value in oil pressure below 50 kg/cm^2.

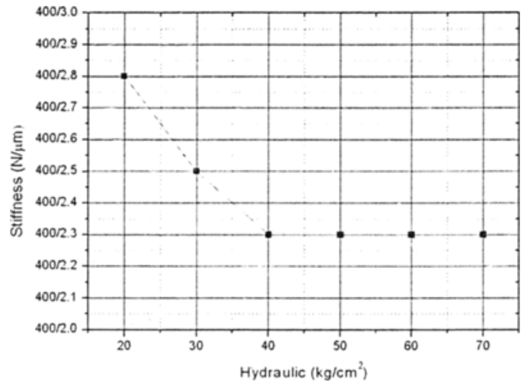


Fig. 7. Stiffness according to oil pressure change.

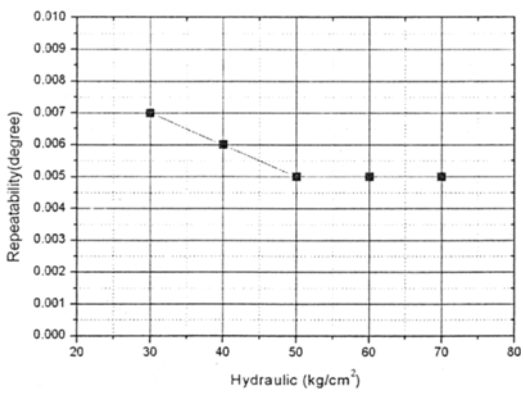


Fig. 8. Repeatability according to oil pressure change.

3.2.2 Angular resolution and thermal expansion

Angular resolution, for which the absolute basis is difficult to establish, is harder to assess in comparison with repeatability precision. Figure 9 shows the average value of index errors by measuring the angles of each index after incessant operation for 8 hours. As shown in Fig. 9, the basic index is 9, but the indexing error does not show a consistent tendency. Given the offset of the encoder value by the basic index as a result of measurement, we can see an indexing error of about 0.03°s. In addition, given that the error does not occur in only one direction, we can see that the error is not caused by the lopsided curvic coupling.

We measured the impact by rotating indexes 3 and 9 repeatedly in order to observe the impact according to the angular resolution. Vibration was measured by an acidometer installed on the bracket used to fix the proximity sensor. As Fig. 10 illustrates, we can see that the impact caused by the clamping of the indexing

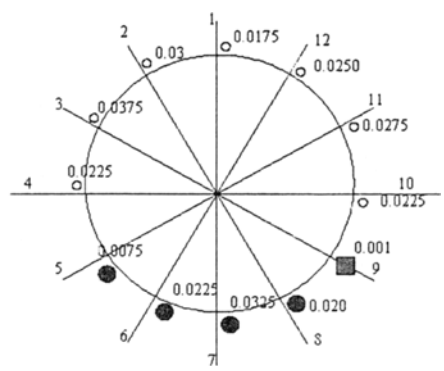


Fig. 9. Measurement of error of angular resolution.

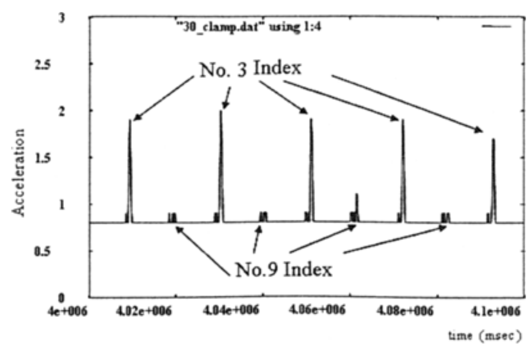


Fig. 10. Clamping impact caused by an error in angular resolution.

indexing of 3 is nearly 10 times higher than that of the indexing of 9, which supports the findings of the angular resolution test above.

If the indexing is conducted incessantly, thermal expansion occurs in the tool post. Thermal expansion can be measured with a gap sensor installed in the radial axial direction. Thermal expansion was found to be 0.5 *um* in the radial direction and 1.0 *um* in the axial direction after 72 hours of operation. In the following consecutive operation, no more thermal expansion occurred.

Therefore, the failure of a tool post can be defined as follows; (1) oil pressure is below 60 kg/cm^2, (2) the repeatability is over 0.005°, (3) the thermal expansion is over 1.0um in the radial or axial direction, (4) tool post is stopped. That is, one of the mentioned items leads to failure of the tool post.

4. Reliability assessment

4.1 Reliability test

Through a reliability test, a variety of results may be obtained depending on the test conditions. In this study, on the basis of the performance assessment conducted above, the reliability test was carried out under oil pressure of 60 kg/cm^2, which is thought to keep the stiffness and repeatability fixed. Although there are other methods, including the eccentric loading, non-loading and consistent loading methods and so forth, for establishing the load condition for the tool post, we adopted non-loading continuous operation for the reliability testing because it was difficult to select the accelerating force. we conducted the operation repeating the rotation and backlash of the tool post index in a sequence of 1→7→4→10, where the operation time of a cycle was approximately 8 seconds, in order to obtain the test results more quickly.

We measured the encoder data and gap sensor data once after 1,000 cycles (that is, measured after 4,000 times of indexing) in order to quantitatively analyze the test results, and conducted 100,000 cycles of consecutive operation.

As a result of the reliability test, three failures occurred in total. In the first failure, the tool post stationed itself completely after about 1.9 million cycles with repeatability rapidly falling after about 1.6 million cycles. We checked the oil pressure of the hydraulic motor supplying the clamping force to identify the cause of the failure, but it proved to be working well, as did the proximity switch. Although

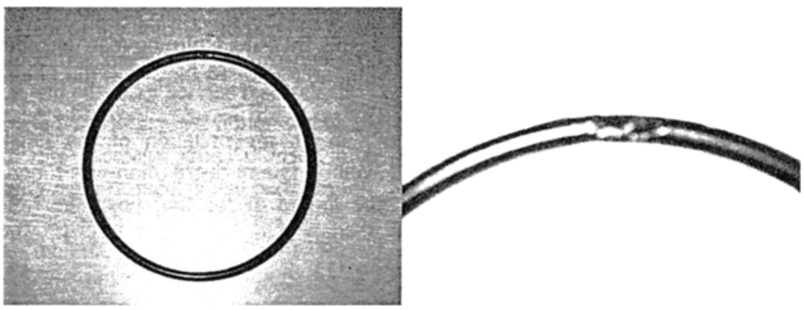


Fig. 11. Damaged hydraulic o-ring.

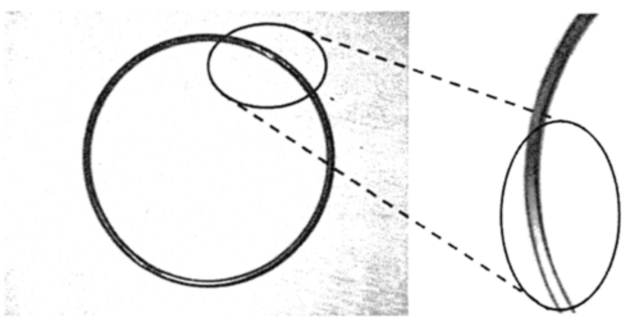


Fig. 12. Worn out of quad-ring.

the cause of the first failure was not found, the most probable cause seems to be the vibration of the bracket used to fix the proximity switch.

The repeatability of the tool post, which started operation after the first halt, was not as high as in the first operation, but we continued the test because it remained within the basic value. In the second failure, the operation stopped after 1.2 million cycles and normal operation resumed after relocation of the bracket fixing the proximity switch, as in the first failure. In this respect, we conducted a deterioration test of the proximity switch, but the life and performance of the proximity switch were not affected by 6 million on/offs. Therefore the abnormal operation of clamping is sure to be caused by the transformation of the bracket fixing the proximity switch. The tool post stopped at about the millionth cycle after readjustment of the proximity switch. As a result of the analysis of the cause of the failure, the hydraulic motor, which was intended to supply the clamping force, wasn't working because the oil pressure was 0 kg/cm^2. Assuming this to be a problem with the hydraulic system, we disassembled the tool post and found, after analysis, that the O-ring, which was intended to transmit the clamping force, had been damaged, and the quad-ring was worn. Figures 11 and 12 show the damaged part of the O-ring and wear of the quad-ring.

4.2 Reliability analysis

We operated the tool post for about 4.1 million cycles for a reliability test, during which three failures occurred. From this, we reasoned that the life of a tool post is about 1.8 million cycles, that of a hydraulic one is 4.1 million cycles, and that the most frequent cause of failure is not the life of the proximity switch itself but the displacement of the bracket fixing the proximity switch.

We analyzed the reliability of the tool post on the basis of the data obtained from the reliability test. The data that should be collected for a reliability analysis include failed parts, failure time, failure mechanism, failure mode, usage conditions and the measures taken against failure, and so forth. Of these, the failure time, usage conditions and number of failures are the important elements to be used in an analysis of the failure rate. That is why we calculated the failure rate of the tool post and MTBF on the basis of the failed parts and on the failure time obtained from the reliability test of a Tool Post.

Figure 13 shows the process of calculating the quantitative reliability. We presumed the function and parameters of failure distribution on the basis of the failure data obtained from the reliability test and conducted a conformity assessment through χ^2 verification and Kolmogorov-Smirnov verification on the basis of the presumed result (KSA, 1992). Then we calculated the reliability index on the basis of the assessment result.

The transformation of the data obtained from the reliability test into test data involves the analysis of reliability of a variety of failures occurring in a sample. We applied the halfway severed data extraction method in the repairable (restoration model) system. For time transformation, we conducted indexing by using a turning machine about three times a minute. Figure 14 illustrates the failure data of a tool post.

For an interpretation of the reliability data, the Weibull failure distribution was found to best explain the failure of the tool post; the failure rate of the Weibull distribution and MTBF calculation are the Eq. (1).

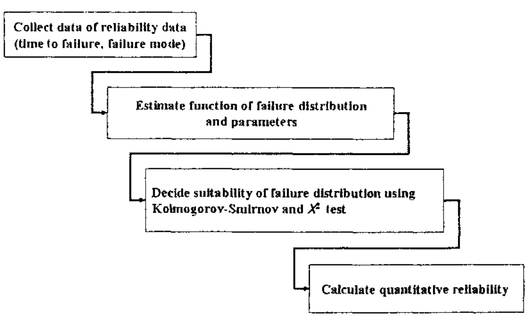


Fig. 13. Quantitative reliability calculation process.

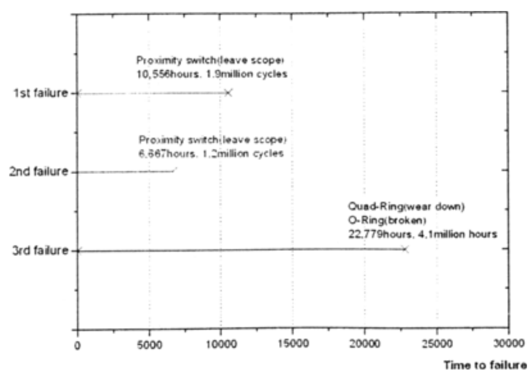


Fig. 14. Failure data of tool post.

$$\lambda(t) = \frac{m}{\eta}\left(\frac{t}{\eta}\right)^{m-1} \qquad MTBF = \eta \times \Gamma\left(\frac{1}{m}+1\right) \tag{1}$$

Being a representative life distribution model, Weibull distribution is used most frequently. Weibull distribution is characterized by the fact that it can express most failure distribution functions including the index distribution according to the parameters, and then calculate the initial failure, accidental failure and wear failure and so on according to m, the shape parameter (Bučar, 2004). The scale parameter η (eta) of the tool post was calculated at 15,166.633, the shape parameter m at 2.109 and the MTBF at 13,433 hours. With a shape parameter m bigger than 1, we can deduce that the failure of the tool post is caused by wear of the parts.

5. Conclusion

In this study, we suggested a method to forecast and assess the reliability of a tool post quantitatively through reliability prediction, reliability testing and the analysis of a tool post used in a hard turning machine. On the basis of the results, we suggest a way to enhance the reliability of a hard turning machine and tool post. The results are as follows:

(1) We conducted reliability prediction on the basis of the reliability data of the constituent parts of a tool post and confirmed that the result is consistent with the reliability test and customer service researched.

(2) We conducted reliability prediction using the NPRD95 failure rate database, which houses information on the failure rate of mechanical parts, and the forecast MTBF was found to be 8,590 hours. Although this is less than the goal life of 10,000 hours of a tool post, it is deemed to be an error due to the lack of information on the reliability (failure rate) of mechanical parts and application of the similar parts comparison method according to the lack of information.

(3) We obtained data on three failures by using a reliability tester; the failures all occurred in the clamping-related parts. As a result of the reliability analysis, the failures of a tool post were found to be best explained by Weibull distribution, and the MTBF was calculated at 13,433 hours by Weibull distribution.

(4) However, to ensure a more reliable test of reliability, it would be advisable to increase the number of reliability tests.

(5) We increased the thickness of the bracket that holds the proximity switch from 0.7 t to 1.0 t, and suggested a way to enhance reliability, such as the replacement of weak parts, namely the Quad-Ring and O-ring.

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