Reliability Evaluation of an Oil Cooler for a High-Precision Machining Center

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KEYWORDS : Reliability evaluation, Reliability prediction, Reliability test, Failure mode, Failure distribution

Improving the reliability or long-term dependability of a system requires a different approach from the previous emphasis on short-term concerns. The purpose of this paper is to present a reliability evaluation method for an oil cooler intended for high-precision machining centers. The oil cooler system in question is a cooling device that minimizes the deformation caused from the heat generated by driving devices. This system is used for machine tools and semiconductor equipment. We predicted the reliability of the system based on the failure rate database and conducted the reliability test using a test-bed to evaluate the life of the oil cooler. The results provided an indication of the reliability of the system in terms of the failure rate and the MTBF of the oil cooler system and its components, as well as a distribution of the failure mode. These results will help increase the reliability of oil cooler systems. The evaluation method can also be used to determine the reliability of other machinery products.

Manuscript received: May 12, 2006 / Accepted: December 4, 2006

1. Introduction

Reliability has commonly been used as the testing standard to determine the performance quality demanded by users.[1] This trend has had an effect on machine parts and the machine tools industry, where quality had been neglected, and has introduced a change in the manufacturing environment in which the concept of reliability has been adapted to the design steps of existing design and production processes based on simple production and safety parameters. Reliability uncertainty is one of the major reasons why products are disregarded by the market.[2]

Because most machinery companies conduct only rough tests without recourse to scientific data, users cannot trust the reliability of such products. In a machinery system and structure of machine tools, the ability of each component is linked to every other component so that the system is dependent on the reliability of each individual component. This in turn determines the overall system reliability.[1,3]

In this study, we propose a methodology for obtaining reliability prediction and testing a given product to provide a quantitative evaluation of oil cooler. These weak points of the oil cooler are identified from the results and a method to improve its reliability is presented.

2. Principles and failure mode of the oil cooler system

The latest machine tools incorporate high-speed machining and have a highly efficient production capacity. However, the problem of heat due to the friction of spindle, the high-speed transfer table, and high-load devices on the machine tools is evident in such machinery. This heat generation leads to irregular heat distribution in the entire structure of the machine tools, which has severe effects on the precision of the machining process and weakens the machine durability. Thermal error is an important factor in the loss of accuracy in machine tools, accounting for about 70% of the total errors made with machine tools.[4,5] To control these factors, the components responsible for heat generation are cooled using an oil cooler system. Thus the reliability of the oil cooler system is linked to the overall reliability of the machine tools. Fig. 1 illustrates the principle of an oil cooler system.

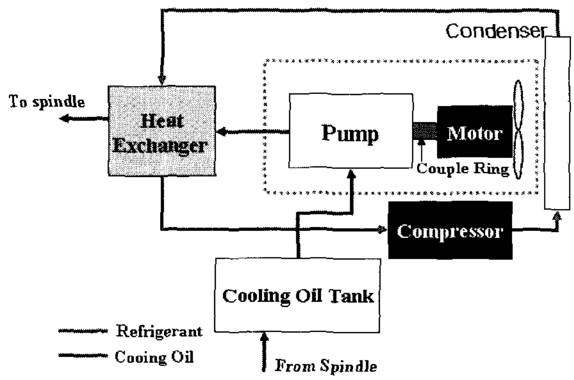


Fig. 1 Cooling principles of an oil cooler system

A reliability evaluation of an oil cooler system was performed on a 1,000-kcal-capacity on/off type oil cooling system, which is widely used for the thermally controlling machine tools because of its simple structure and ease of use. The system consists of six subsystems and 62 components, as shown in Fig. 2, including a control component that performs the on/off motion for the cooling action, electric components that supply electricity to the oil cooler system, a cooling oil circulation component through which the cooling oil that dissipates the heat generated by the various components flows, a refrigerant pipe part where the refrigerant is compressed by a compressor, and an evaporation component in which the cooling oil and refrigerant meet and exchange heat.

Failure of an oil cooler system generally occurs in the on/off relay of the control component, which controls the temperature of the cooling oil. Another type of failure occurs when cooling oil is lost because of damage to the coupling that supplies the motor power to the cooling oil pump.

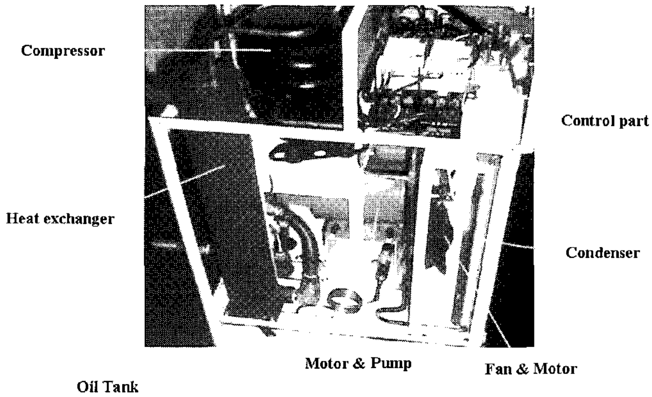


Fig. 2 Structure and composition of the oil cooler system

3. Reliability evaluation of the oil cooler system

To obtain an objective quantity for the reliability of the oil cooler system, we analyzed the working time of the system for the machine tools to which the oil cooler was attached. The system completed an on/off cycle in 8 minutes, during which 5 minutes were spent in the 'on' status and 3 minutes were spent in the 'off' status. The oil cooler system durability, which was defined as the mean time between failures, was predicted based on the life of the relay performing the on/off function for the compressor. The relay was guaranteed for 100,000 operations, and the average durability was given by the manufacturer. To protect the control circuits of the oil cooler, we restricted the length of the on/off cycle to 1 minute. Using this restriction, the objective durability was 13,333 hours. Under typical operating conditions, the durability of the on/off cycle was 16,667 hours.

3.1 Reliability prediction

The proposed reliability prediction method seeks to verify the reliability of a system in accordance with the development phases and identify defects in the preproduction phases so that the market competitiveness of the product can be improved and damage caused by unexpected failure can be prevented.[6] We used the NPRD95 failure database for non-electric (machinery) components and the MIL-HDBK-217F N2 failure database for electronic components to predict the reliability of the oil cooler system.[7, 8] These databases have an exponential distribution. NPRD95, which is a collection and compilation of data accumulated from 1974 through 1994, is the only database that provides the failure rates of individual mechanical components.

The objective system must be modeled to predict its reliability. Basic modeling data includes a parts list, bill of materials, and design drawings. After modeling, reliability information is entered using the failure database. Here, the user selects a failure rate based on the user environment from the parts selection which is set up by part and subpart types. Fig. 3 shows how an example failure rate is selected from NPRD95. In the event that the proper parts are not found, a comparison between relative parts is used. After calculating the failure rate of each part using the failure database, a reliability block diagram (RDB) with cooling oil and refrigerant flow in its center is composed[8] and a quantity used for the system construction are entered. The failure rate of the system is the sum of the failure rates of the individual parts.

$$\lambda_{sys} = \sum_{i=1}^{n} \lambda_i$$

where λ_i gives failure rates of the individual parts

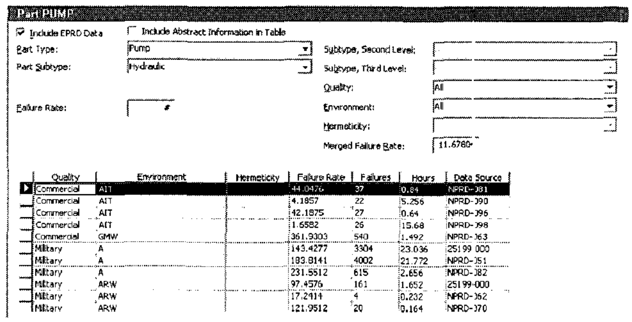


Fig. 3 Example of an NPRD95-based failure information search

The reliability prediction gave a oil cooler failure rate of 73.28 failures/million hours and an MTBF of 13,645 hours. Fig.4 shows the change in reliability of the oil cooler system and the subsystems over time. Among the subsystems, the reliability of the control component declined more rapidly than in other systems, even though it consisted of only four relays.

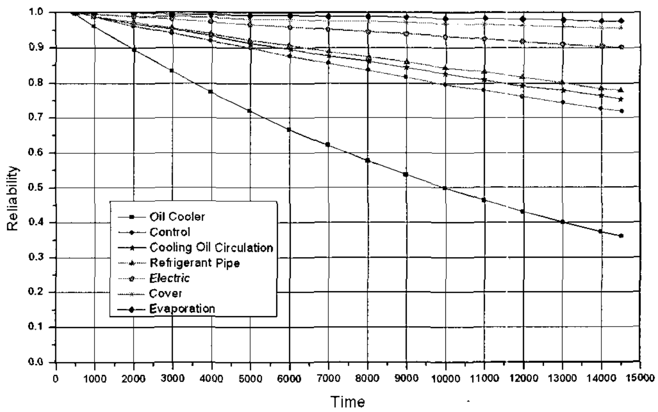


Fig. 4 Change in reliability of oil cooler system over time

Table 1 shows the results of the reliability prediction for six subsystems. The failure rate for the control, cooling oil, and refrigerant pipe components accounted for 84% of the entire failures. Thus the reliability of the oil cooler system could be greatly improved by reviewing the subsystems.

Table 1 Results of the reliability prediction for the oil cooler system

Sub-system	Failure rate (failures/million hours)	MTBF (hours)
Control Component	23.68	42,222
Cooling Oil Circulation Component	19.99	50,005
Refrigerant Pipe Component	17.89	55,867
Electrical Component	7.35	136,003
Evaporation Component	1.29	774,954
Cover	3.06	326,947
Oil Cooler System	72.38	13,645

3.2 Reliability test-bed and reliability test

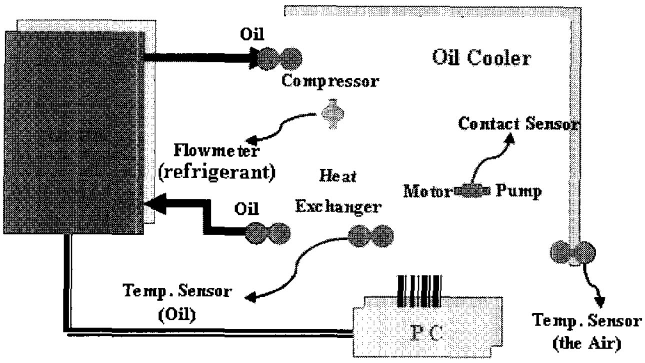
3.2.1 Reliability test and test-bed items

The six items considered in the oil cooler system reliability test were determined by analyzing customer service data of the manufacturer. These items are listed Table 2.

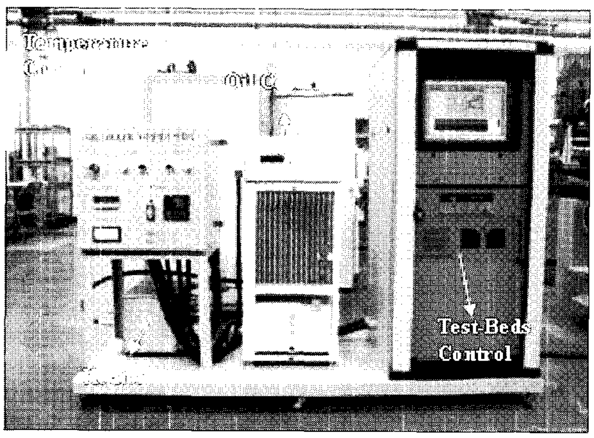
Table 2 Reliability test items

Items used in the reliability test	Test method
·Temperature sensor	·Test with a precision temperature sensor
·Controller	·Examine the driving signal of the compressor
·Breakage of the coupling motor and pump	·Examine the contact sensor
·Overload of motor and condenser	·Examine the alarm lamp
·Leakage of refrigerant (welded part)	·Test with a manometer
·Flow meter	·Calculate the cooling capacity

A precision temperature sensor was installed in the same position as the oil cooler system temperature sensor to test its accuracy. The signal that drives the compressor was used to test the controller. A body-type sensor was attached to the coupling that links the motor and the pump to breakage, while an alarm lamp was used to detect electrical overload. Leakage of the refrigerant (R-22 gas) caused by cracks in the pipe welds were identified using a manometer installed at the entrance of the compressor to measure any changes in the refrigerant pressure. Finally, the cooling capacity was evaluated by measuring changes in temperature using a flowmeter installed in the cooling oil pipe. Fig. 5 shows the test-bed for the reliability test of the oil cooler system.



(a) Construction of the reliability test-bed



(b) Developed reliability test-bed

Fig. 5 Test-bed for the reliability test of the oil cooler system

Precise sensors were installed in crucial positions to scan the temperature of the inflow and outflow of the cooling oil. The test-bed consisted of a heater, temperature control, and test-bed control. The temperature of the cooling oil was increased by the (capacity of 3,000 kcal/hour) rather than by increasing the revolutions of spindle. This facilitated control of the temperature and heat according to the desired test conditions by means of a control computer. Manual and automatic test methods were used. In the manual mode, the tests was performed under given temperatures and heating conditions, while in the automatic mode, various test conditions such as the temperature and heating time, were preset. It was also possible to set the initial value of the required factors. The acquired test data were saved in the control computer as a file. When the cooling oil temperature exceeded 60℃, the heater turned off automatically. The test-bed was used to provide remote monitoring as a safety device.

3.2.2 Test conditions and results

The representative operational modes of general machine tools were broken down into three steps. The conditions of the reliability test used for the oil cooler system are listed in Table 3. The first step warmed the machine tools and involved the shortest on/off cycle for the oil cooler system compressor. Under such conditions, control of the cooling oil temperature could be assured. The heater was in the off mode during this step. For the second step, the spindle of the machine tools revolves without processing and cutting force was not applied. During this step, the heater provides 1,000kcal/hour, which was the general cooling capacity of the oil cooler system. A cutting force was applied in the last step, and the cooling oil temperature was suddenly increased by accelerating the spindle very quickly. One test cycle (three steps) required 4 hours to complete.

Table 3 Conditions of the reliability test for the oil cooler system

Test Conditions			Status
Step	Heat (kcal)	Time (min)	
1	0	30	· Operator with heat turned off · Check features of control temperature for the oil cooler system · Shortest term of the on/off motion under normal temperature · Warm up the machine tools
2	1000	120	· Continuous heat addition · Continuous revolutions of the spindle · No cutting force
3	1500-1800	90	· Rapidly increase the temperature · Rapidly accelerate the spindle · Cutting force applied

The change in the cooling oil temperature for the inflow and outflow is shown in Fig. 6. The temperature initially decreased because the heater was turned off during the first step. The second step involved revolving the spindle without a load. Here, the oil cooler system decreases the cooling oil temperature, induced by the revolution of the spindle. Machining was introduced in the third step, increasing the temperature of the cooling oil. We analyzed the cooling capacity and the temperature-control following capacity by monitoring the change in the temperature of the cooling oil between the inflow and outflow. As shown in the figure, the oil cooler was loaded more than its cooling capacity during the third step so that it could not maintain the preset temperature but instead varied in accordance with the inflow cooling oil temperature.

The maximum cooling capacity of the system was approximately 1,200 kcal/hour. Fig. 7 shows the change in the cooling capacity of the oil cooler system over time. The cooling capacity of the third step was less than that of the second step because the cooling load was larger than the capacity of the system. Under such conditions, the expansion valve was fully open, and the superheating of the refrigerant at the evaporator outlet exceeds the design valve.

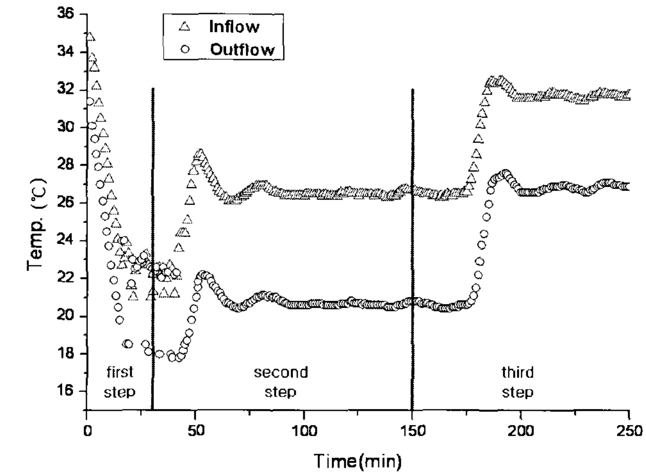


Fig. 6 Change in cooling oil temperature over time (each step)

Therefore, when the refrigerant is compressed under such conditions, the pressure in the condenser rose, degrading the cooling capacity of the oil cooler.

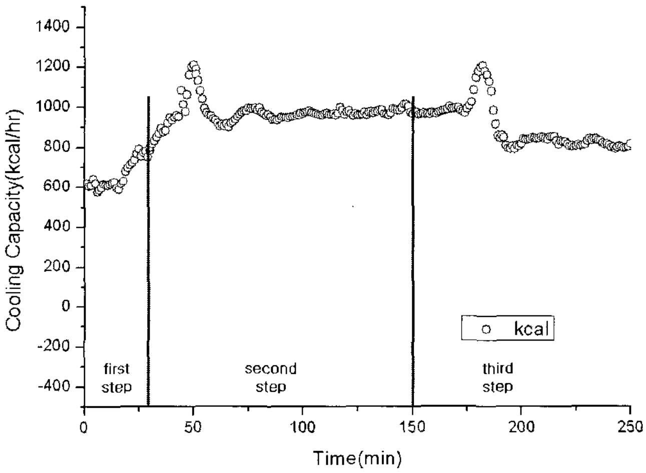


Fig. 7 Change in the cooling capacity of the oil cooler system over time

The failure rate, MTBF, and failure distribution of the oil cooler system were calculated by using the test data from the developed reliability test-bed. The function and parameters of failure distribution were inferred using the gathered data. The suitability of failure distribution was determined using the Kolmogorov-Smirnov test or χ^2.[9,10] This showed whether the inferred failure distribution function accurately represented the actual distribution of the test data distribution.

We performed two reliability tests for the oil cooler. These gave failure time 12,312 and 11,113 hours, which were attributable to the durability of the relay in the control component. After the first failure, the component was repaired by considering the oil cooler as a repairable system and its reliability was tested again. The failure distribution was analyzed using a Weibull distribution (η=11,997.282, m=23.418), and an MTBF of 11,722 hours was obtained. Since m in the Weibull distribution was grater than 1, it may be presumed that the failure of the oil cooler occurs in the wear-out phase.

4. Conclusions

In this study, we proposed a methodology for evaluating and obtaining quantitative predictions of the reliability of oil cooler. The weak points of the oil cooler were identified from the results so that its reliability could be improved. The finding can be summarized as follows:

(1) Reliability predictions were obtained based on known reliability data of the oil cooler system. The results obtained were similar to the data reported by customer service department of the oil cooler manufacturer.

(2) The reliability predictions were performed using the failure databases NPRD95 and MIL-HDBK-217F. The MTBF of the oil cooler was estimated to be 13,645 hours. The MTBF of the control, cooling oil circulation, and refrigerant components were shorter; the parts in these components were weaker and had higher failure rates.

(3) Failure data were obtained twice. These failures were caused by a malfunction of the control component. Using these data, the failure distribution of the oil cooler, which followed a Weibull distribution, was calculated. The MTBF was estimated to be 11,111 hours.

(4) For more reliable reliability evaluation would be obtained if the number of tests were increased.

(5) Reliability improvement methods were determined using the proposed reliability evaluation methodology. These included a redesign of the control component, an improved welding method for the refrigerant system, and the replacement of weak components.

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