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Main failure mode of oil-air lubricated rolling bearing installed in high speed machining

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ABSTRACT

The failure mode of rolling bearings is closely related to its operating conditions. In this study, a batch of rolling bearings, which have failed after a certain service period under oil-air lubrication, were collected and the failure modes of the bearings were analyzed. A statistical analysis showed that abrasion and not fatigue is the main failure mode of the collected bearings. The main failure mode for the inner and outer rings of rolling bearings in oil-air lubrication was abrasion, burn-up, corrosion, fatigue and indentation respectively. The causes of abrasion, burn-up, fatigue, indentation and corrosion failure mode were analyzed by visual inspection and the elemental composition of the raceway material of the failed bearings was analyzed by energy-dispersive X-ray spectroscopy. The domination of abrasion failure mode in rolling bearing under oil-air lubrication might be due to the existence of haze particles in the lubrication air.

1. Introduction

Rolling bearings are among the most important parts of modern manufacturing machines. Sometimes they are used in hostile environments. For instance, if a rolling bearing is used in mining equipment, it is exposed to the external environment, which leads to the aggregation of solid particles in the lubricating medium. Considering elastohydrodynamic lubrication theory, the thickness of lubricating oil film between the rolling body and the raceway is usually less than one micron. Depending on the particle size and type of material of the contaminant, these particles may enter the contact area, and the rolling bearing is likely to fail.

In recent years, the mechanical failure caused by contamination has attracted increasing attention [1–3], and important reviews of the mechanical failure caused by contamination have been recently published [4–6]. These articles summarize all potential modes of mechanical failure caused by contamination. The failure mode of failed bearings is often related to the roughness, hardness, size and type of contaminant. In general, contaminants can cause abrasion, indentation, burn-up, corrosion and other failure modes, which have different characteristic features.

Indentation is one of the most common failure modes and has been experimentally studied by several research groups [7,8]. Theoretical studies of indentation failure are frequently based on a force analysis [9]. Other scholars used the finite element method to analyze indentation failure [10,11]. If a bearing suffers from indentation failure, then fatigue failure mode is also likely to occur. Abrasion is another common failure mode, which has also attracted much attention [12–15]. Burn-up failure can also be related to the shapes and properties of haze particles. Some scholars have studied the lack of lubrication caused by such particles, which may result in lubrication film rupture [16–19]. On the other hand, the frictional heat and thermal strain generated in the contact zone through these particles has been studied as well [20–24]. Corrosion failure is also very important, and the corrosion is usually caused by the exposure to other liquids. Many scholars have studied the chemical action of contaminated liquids leading to the failure of mechanical structures [25–28].

The failed bearings examined in this study were collected from maintenance shops. Typically, these bearings are installed on the main shaft of high-speed machining tools. During operation, they are generally lubricated by an oil-air mixture. Wu et al. have studied the thermal deformation and static stiffness of oil-air-lubricated bearings [29]. Jiang et al. have studied the temperature stability of oil-air-lubricated bearings [30]. Weck et al. have studied the minimum lubrication of oil-air-lubricated bearings [31]. However, so far, there is no report on the failure mode of oil-air-lubricated bearings.

However, in these studies, the bearings were operated under laboratory conditions, and the particle size, shape and material were selected by the researchers. Furthermore, in a laboratory simulation, the contaminate conditions are also far from the contaminate conditions of practical manufacturing. For oil-air lubricated bearings, the influence of the hydraulic oil cleaning and air cleaning processes on the

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bearing failure is highly important [32]. In our study, we collected a large number of failed bearings from maintenance shops to determine the main failure modes and mechanisms in practical bearing applications, which can have great engineering significance.

2. Statistical analysis of the failed bearings

2.1. Description of the failed bearings

For this study, the authors collected a total of 108 sets of failed angular contact ball bearings. There were seven main types of failed bearings, i.e., 7005, 7006, 7007, 7008, 7009, 7205, 7206. Among these seven types of bearings, the largest outer diameter was 75 mm, the smallest 47 mm. The largest inner diameter was 45 mm, the smallest 25 mm. The thickness ranged from 16 to 12 mm. In all cases, the contact angle was 15°.

Angular contact ball bearings are typically installed on the main shaft of high-speed machine tools, and the bearings are generally lubricated by an oil-air mixture. The revolution speed of the high speed spindle is usually controlled via a frequency converter and a circulating water pump is used to cool the main shaft, whereas an air compressor is used to provide compressed air to the oil-air generator. The oil-air generator continuously injects the lubricating oil into the compressed air pipeline in the form of oil droplets. The oil-air mixture produced by the generator is then used in the high-speed main shaft bearing for lubrication. The operator can adjust the amount of oil injected per unit time. The oil-air lubrication device used in this study was equipped with a filtration system with a filter diameter of 5 µm.

The percentages of the different bearing types are listed in Table 1, with the bearing type 7006 having the highest percentage at 34.3%.

The percentages of the bearing manufacturers are compared in Table 2. We found that the percentages of HRB and ZYS, the two largest Chinese bearing manufacturers, were slightly higher, up to 81.2% in total. Interestingly, the percentage of the Japanese bearing manufacturer NSK was 10.2%, whereas the percentage of the Swedish bearing manufacturer SKF was very small.

The percentages of the bearing accuracy grade are shown in Table 3. Of the investigated batch of failed bearings, by far the majority of the bearings showed a P4 accuracy grade. The bearings were typically mounted on the spindle of high-speed machine tools, so the accuracy of the bearings is relatively high.

In Table 4, the percentages of rotatable bearings and non-rotatable bearings are shown. If a failed bearing cannot rotate, this indicates that the bearing has been seized. On the other hand, if it could still rotate, this indicates that the bearing has lost its original rotation accuracy, resulting in a non-normal operation. In this batch of failed bearings, 88% of the bearings had lost their rotation accuracy, but could still rotate.

2.2. Raceway failure mode analysis

Harris et al. have classified the different types of bearing failure mode in detail [33]. This classification has been adopted in this study. For identifying the correct failure mode through visual inspection, we compared images of the failed bearings with typical examples found in literature. The causes of the bearing failure are analyzed and summarized in this paper. Typical examples of bearing failure include failure of the outer ring, the inner ring, the cage and the balls.

We used a special tool to disassemble the failed bearings, and then analyzed the failure modes. There are many kinds of failure modes, e.g., fatigue, abrasion, burn-up, corrosion, indentation.

Table 1
Percentages of the different bearing types.

Type	7005	7006	7007	7008	7009	7205	7206
Percentage	12.0%	34.3%	17.6%	14.8%	1.9%	18.5%	0.9%

Table 2
Percentages of the different bearing manufacturers.

Manufacturer	HRB	ZYS	NSK	SKF	Unknown
Percentage	54.6%	26.8%	10.2%	1.9%	6.5%

Table 3
Percentages of the bearings by accuracy grade.

Accuracy grade	P4	P5
Percentage	97.2%	2.8%

Table 4
Percentages of rotatable and non-rotatable bearings.

Percentage of rotatable bearings	88.0%
Percentage of non-rotatable bearings	12.0%

Fatigue is caused through the action of alternating stress on the bearing raceway, resulting in the formation of cracks on the surface of the bearing raceway. Spalling is then caused by crack propagation. After studying all failed bearings suffering from fatigue failure mode, we found that the spalling area of the inner ring is usually larger than that of the outer ring in the same set of bearings because the normal contact stress of the inner ring is larger than that of the outer ring, i.e., the alternating stress acting on the inner ring is larger than that acting on the outer ring. Thus, compared with the outer ring, the inner ring is more prone to fatigue.

Wear can be divided into abrasive wear, adhesive wear, fatigue and chemical wear. In case of oil-air lubrication, the lubrication is generally sufficient and adhesive wear can therefore not occur. Thus, when the bearings were affected by abrasion, it may only be due to abrasive wear. After studying all failed bearings affected by abrasion failure, we found that the abrasion area of the inner ring was usually greater than that of the outer ring in the same bearing set, which suggests that the normal contact stress acting on the inner ring was greater than the normal contact stress acting on the outer ring. According to abrasion theory [34], the abrasion rate is proportional to the normal load. Thus, compared with the outer ring, the inner ring is more prone to abrasion.

The lack of lubricating oil caused sliding friction, which in turn sharply increased the temperature. The high temperature then leads to the burn-up of the bearing. After studying all failed bearings affected by burn-up, we found that the inner and the outer rings burned up in the same fashion. According to the bearing temperature field theory, we found that the temperature difference between the inner and outer ring of the bearing was always very small, i.e., the increase in temperature consistently caused the inner ring and outer ring to burn-up in the same fashion.

The flow of a contaminating liquid into the raceway may cause corrosion. After studying the raceways of all bearings affected by corrosion, we found that the degree of corrosion was similar between the inner and outer rings, and that the corrosion area was often beyond the scope of the raceway (Figs. 1–6).

Larger particles entering the bearing raceway may cause indentation. Only one set of bearings showed signs of indentation. We found indentation of the inner ring, whereas the outer ring did not show indentation.

The statistical data revealed that the main failure mode of the inner rings is abrasion, at 68.5%, whereas burn-up accounted for 13.9%, corrosion for 9.3%, fatigue for 7.4%, and indentation for only 0.9%. The main failure form of the outer rings is also abrasion, at 73.2%, with burn-up accounting for 10.2%, corrosion for 12%, and fatigue for 4.6%.