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Study of ball bearings failure modes in an eddy current dynamometer

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ABSTRACT

Eddy current dynamometers are one of the most important equipment of internal combustion engine test cells in powertrain companies. Failure of rolling element bearings in these assets is a common reason for downtime hours of engine test beds. Insufficient information in this field not only imposes unwanted expenses, but also would result in wrong engine testing data. The purpose of this article is the identification and classification of rolling element bearings failure modes in the eddy current dynamometers. This is an essential research for choosing an appropriate maintenance plan in engine testing laboratories. More than 30 faulty ball bearings of different eddy current dynamometers are collected to study different modes in which the bearings actually fail to operate properly. In addition, metallurgical studies have been applied on the failed parts to specify possible root causes of failure. The dynamometers whose bearings are under study have been employed in different engine testing procedures that an eddy current dynamometer is capable of performing e.g. endurance tests, over-speed tests, etc. so that a diversified collection of modes is available which would happen in any eddy current dynamometer. The recognized cases are then classified to prepare a practical basis for condition monitoring of dynamometers using vibration analysis or other methods.

1) Introduction

Engine testing dynamometers are used to accurately measure the torque and power output of engines with putting the engine (specimen) in the variable loading conditions within engine speed and duration range [1]. According to different factors [2] that are out of the scope of this paper, the type of appropriate dynamometer for an engine test cell is chosen.

Eddy current dynamometers convert the mechanical energy of the engine to heat energy using an electromagnetic field. As a result, dynamometer's parts are subject to heat shock loads and also exposed to high temperatures. To dissipate this heat energy, dyno manufacturers utilize water or air cooling systems according to the capacity of the machine. In figure1. a water-cooled eddy current dynamometer connected to an IC engine is shown.

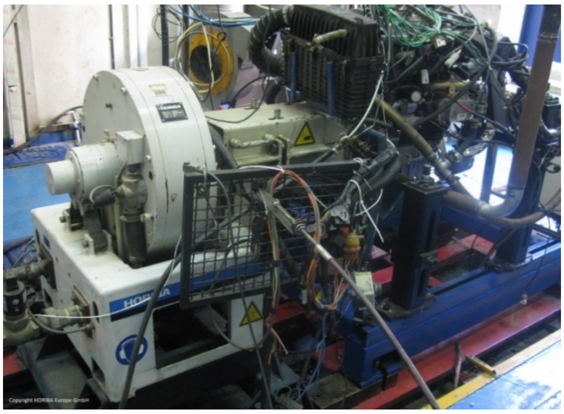

Figure1: An eddy current dynamometer coupled to an IC engine in the engine test bed (Courtesy of IPCO)

Leakage of water in water-cooled dynamometers is one of the most common problems which usually predicates that dyno's cooling chambers and bearings are failed and need to be replaced. Although the bearings remaining useful life before water leakage would be very long, the bearings after water entrance by no means are healthy and reusable.

In engine test beds, the engine is connected to the dynamometer via an elastomer coupling which weakens many irregularities of the engine behavior and damps the vibration transmission to the dynamometer. However contriving these conditions in engine test beds to some extent decreases the influence of the vibrations of an IC engine operation on dynamometer's bearings, still many unpredictable conditions remain. These conditions that are mostly difficult to investigate arise from the complexity of combustion engines operation, or negligence of technical instructions and precautions about engine test bed equipment. Whatever the causes, prolonged exposure to vibration causes the bearings of dynamometers to be prone to premature failure.

Eddy current dynamometers commonly contain angular contact ball bearings to withstand axial and radial loads but in some cases they also include deep groove ball bearings in the rear side. The section view of an eddy current dynamometer is illustrated in figure 2.

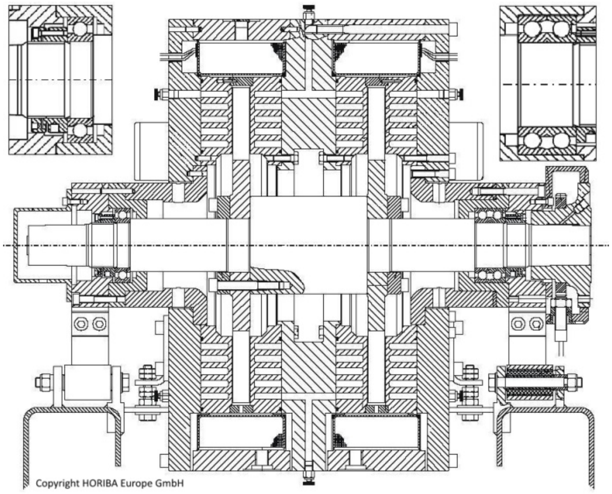

Figure2: Section view of an eddy current dynamometer (Courtesy of Horiba)

To reduce the vibrations of driveline in an engine test bed, manufacturers usually use high precession angular contact ball bearings which are preloaded with a special axial force. Figure 3 shows the components of an angular contact ball bearing used in a dynamometer.

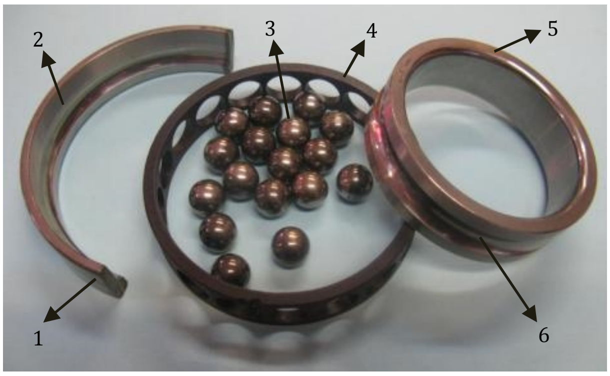

Figure 3: Components of a ball bearing; 1-outer ring, 2-outer race, 3-balls, 4-cage, 5-inner ring, 6-inner race.

Study of ball bearing failure modes in different cases has been elaborately noticed in the literature. Bhushan [3] would be the first researcher who studied and identified bearing failure and damage modes in detail. His studies formed the basis of bearing failure modes analysis for other researchers. Widner et al. [4] considered the causes of bearing premature failure and illustrated the most common bearing failure modes. They also classified bearing damage modes. In addition to these studies, some researchers have taken investigative approaches to finding bearing failure causes. Most of these studies have focused on a particular failed machine.

Bhat et al. [5] studied the failure of a ball bearing in a military jet engine. The bearing failure mode was flaking that was a result of incorrect mounting at last repair. Villa et al. [6] analyzed the failure of a ball bearing used in a jet engine gearbox drive assembly. They investigation showed that despite the signs of overloading, the existence of foreign material in the bearing was the cause of bearing components failure. Upadhayay et al. [7] addressed the general mechanisms that contribute in fretting failure of rolling element bearings.

Budinski [8] documented the failure of a ball bearing used in a helicopter turbine engine that had failed in work and resulted in a hard landing of the helicopter. The failure modes indicated that the bearing had failed due to electrical arcs. Pitting and material transfer were the most evident signs of failure.

There are quite a lot of studies like the aforesaid investigations which are omitted for brevity.

Dynamometer bearings fail because of different reasons. Identification and classification of these bearings failure modes have many advantages that some of them are:

- Recognition of failure frequently repeated modes and their symptoms to better describe the defects.
- Using changed appearance and geometrical properties of defects in state-of-the-art techniques such as vibration analysis to predict failures before break-down.
- Root cause analysis of failures and proactive maintenance implementation.
- Having a better understanding of defects' initiations and propagations.

2) Failed bearing samples

When it comes to bearing failure, it means that the bearing cannot meet "the intended design performance" due to a defect or damage [9].

In this research, more than 30 faulty ball bearings both angular contact and deep groove types from 11 failed dynamometers are collected to study the failure modes of bearings.

Despite the fact that the preliminary cause of any failure is the criterion of failure modes classification, distinguishing between causes and symptoms is not always easy [9].

Bearing manufacturer companies worldwide have classified bearings general failure modes which are available in the net. However, no study has particularly focused on dynamometers' bearings failure in the literature yet. When defects exist in a bearing, high level of vibrations on bearing outer ring and bearing high temperature conditions can be detected.

This paper tries to fully cover the classification of these defects and in fact, the failure modes of ball bearings to give the reader a better insight into bearings failure in an engine testing dynamometer. In the next part, the common failure modes of ball bearings in an eddy current dynamometer are studied in detail.

3) Failure modes

Amongst several faulty bearings collected for this study, 5 bearings which were the best samples are selected. Each of these bearings has a complete collection of defects that repeatedly exist in other samples. Besides taking macroscopic photos from failed bearings, SEM images are given to better describe the defects. The failure modes are compared to that of classified modes in Iso standard [9]. Other authoritative literature [3, 4, 10-12] and guidelines of genuine bearing manufacturers are also used to accurately define these failure modes.

Fatigue

When the dynamometer shaft rotates, a continuous pulsating stress is imposed on the material of the raceways and the balls [13]. Carbides in the subsurface structure of contacting rolling surfaces are considered the weakness locations susceptible to fatigue failure initiation [12]. In fact, fatigue failure initiates with propagation of micro-cracks that finally lead to local fractures. These fractured areas in ball bearings grow parallel to the surface and cause material flaking. Flaking that is also referred to as spalling, occurs due to normal fatigue, i.e. the bearing remaining useful life has ended. However, premature flaking may have causes like external loading heavier than what had been anticipated, or radial preloading because of incorrect fits. Other failure modes e.g. indentations can also result in flaking.

A dynamometer outer race with spalling damage is shown in figure 4. The single spall indicates that the defect is not only the result of Hertzian fatigue, but also arises from the pieces flaked out of the surface. Existence of contaminant foreign objects is also probable [11].

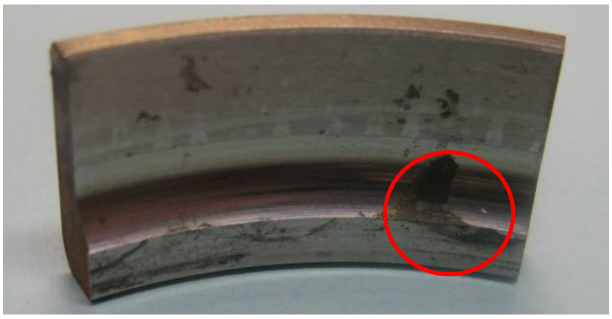

Figure 4: Fatigue damage on an angular contact ball bearing outer race

Fatigue damages during their progress are always accompanied by corrosion. Formation of oxidized surface on damaged area and propagation of micro-cracks are clear in figure 5 [4].

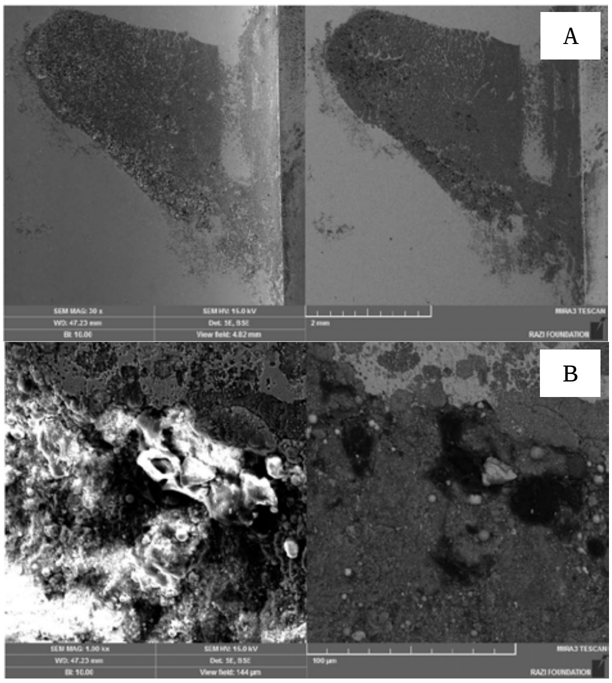

Figure 5: Magnifications of fatigue damage in Figure 4 (Mag: A-30×, B-1000×)

Adhesive wear

High normal and tangential stresses can cause the formation of a metal-to-metal contact on a microscopic scale. This contact can raise a strong welded junction that lead to the adhesion of surfaces. When dynamometer shaft rotates, it causes rupture of adhesive junctions [13]. This phenomenon can occur in other locations near the original area as well. Insufficient lubrication can be one of the main causes of this defect. The bearing raceway and balls are subject to this damage. Adhesive wear can be the cause of other failure modes like spalling.

In figures 6 and 7 this defect in a dynamometer bearing inner race is shown.

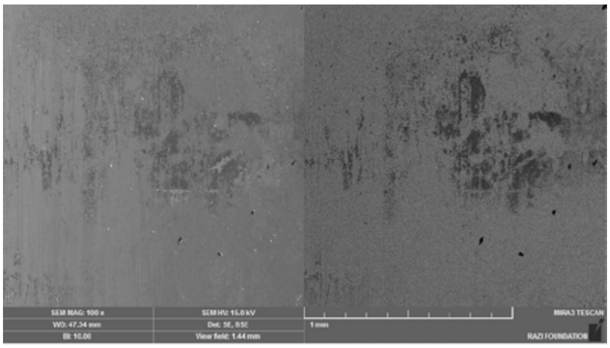

Figure 6: Magnifications of adhesive wear (100×)

Abrasive wear

When the plastic deformation in bearing components causes material removal and wear debris, the interaction of rolling elements and small particles lead to abrasive wear. Contamination of the bearings to foreign particles can obviously further aggravate the condition. Small hard foreign particles cause the surface roughening and accelerate abrasive wear.

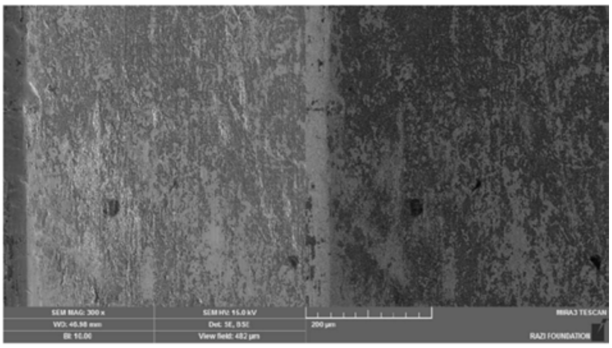

Figure 7: Magnifications of adhesive wear (300×)

Because of coarseness of abrasive particles, the surfaces with this defect are dull and can be easily distinguished. Unpacking bearings just before mounting and using fresh, clean lubricants to some extent can prevent this damage [14]. An outer race with this defect is shown in figures 8 and 9. Pitting also exists in the area.

Figure 8: Abrasive wear in an angular contact ball bearing

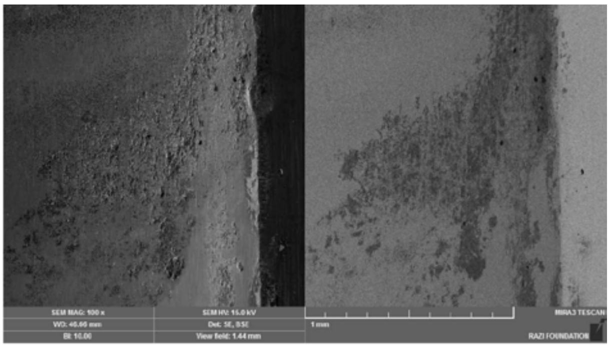

Figure 9: Abrasive wear magnified (100×)

False brinelling

To decrease vibration and noise in dynamometers, dyno manufacturers utilize super precision bearings with fine surface finishes on the order of fraction of micron in the engine side of the shaft-rotor.

Vibrations of environment influence the stationary dynamometers by producing micro-motions in the contact areas of bearing components. A dynamometer in the engine test bed never runs fulltime. The times consumed for New specimen (engine) installations, test cell software/hardware troubleshooting, and all in all when an engine test cell comes to a standstill can be the occasions in which the dynamometer bearings don't rotate but are subject to the vibrations raised from other test cells or even the vibrations of facilities such as spot fans in the very engine test cell.

The lack of lubricant film between balls and races leads to metal to metal contacts and the small relative movements as a result of vibration produce small broken particles and form depression in the raceways. The damage is called false brinelling with marks on the raceways surfaces at the ball pitch and parallel to the shaft axis. In most cases like what is shown in figures 10 and 11, oxidation of the detached particles produces red rust at the bottom of the depressions which is easily noticeable.

Figure 10: False brinelling in the outer race of an angular contact ball bearing

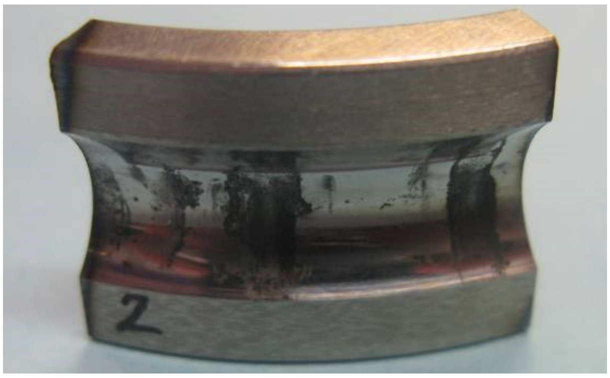

Figure 11: False brinelling in the inner race of an angular contact ball bearing

False brinelling can also be the result of improper transport of bearings. Bearing manufacturers recommend unloading or preloading bearings using safety devices during transport [12, 14].

For stationary dynamometers, it is good practice to modify the engine test bed foundation and use air spring systems with required settings to absorb vibrations, and also to rotate the dynamometer shaft to prevent standstill of dynamometers as much as possible. Contriving oil pump beside dynamometers and using oil instead of grease as lubricant will decrease this damage in ball bearings.

The plastic deformation, material removal and oxidized surfaces of detached particles are magnified in figure 12. The bearings races surface out of brinelling marks considerably includes micro-cracks and pitting that can be derived from false brinelling.

This is proved that roller bearings are more prone to this damage than ball bearings. This would be because of the fact that balls freely rotate in every direction. All dynamometers that authors have seen yet contain ball bearings.

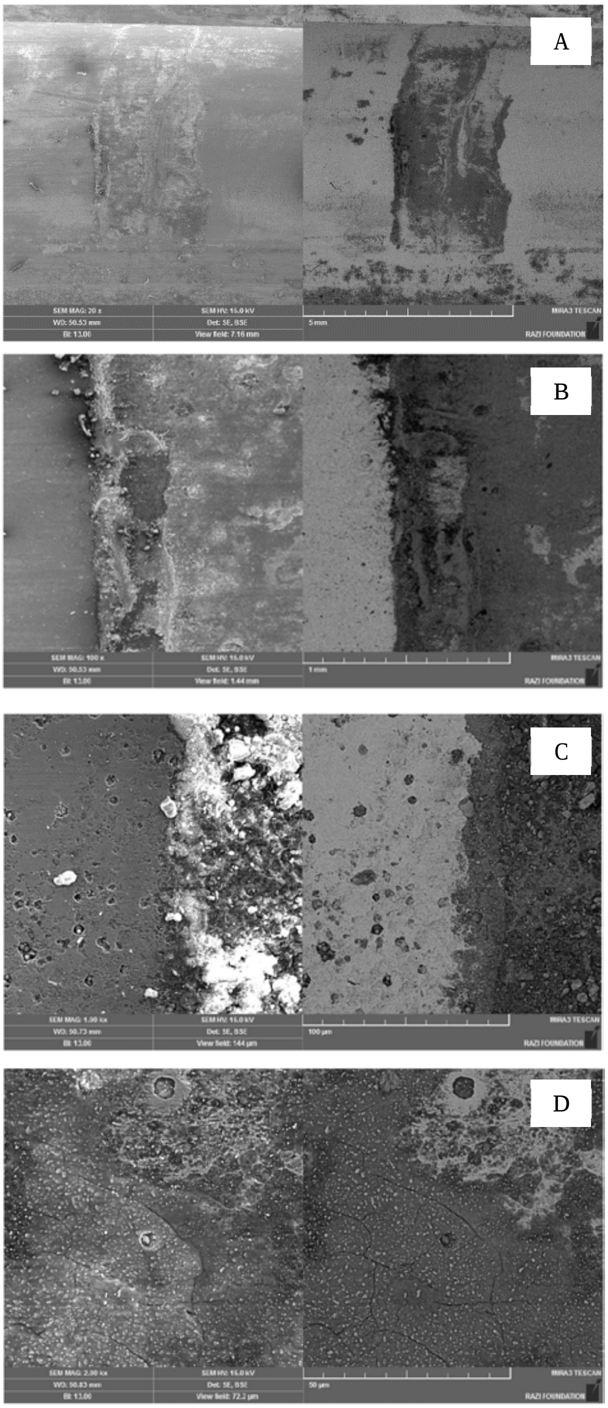

Figure 12: Magnifications of false brinelling damage in an angular contact ball bearing races
(Mag: A-20×, B-100×, C-1000×, D-2000×)

False brinelling marks on balls however don't follow a particular pattern distribution. They are similar to that of outer and inner races in shape but in several chaotic directions. The marks in a ball don't have similar extent. Some are wide, some narrow. It depends that how much the ball has been placed on that state. Figure 13 shows marks directions and their microscopic surface structure. Material detachment and attachment on damaged area form a spongy structure.

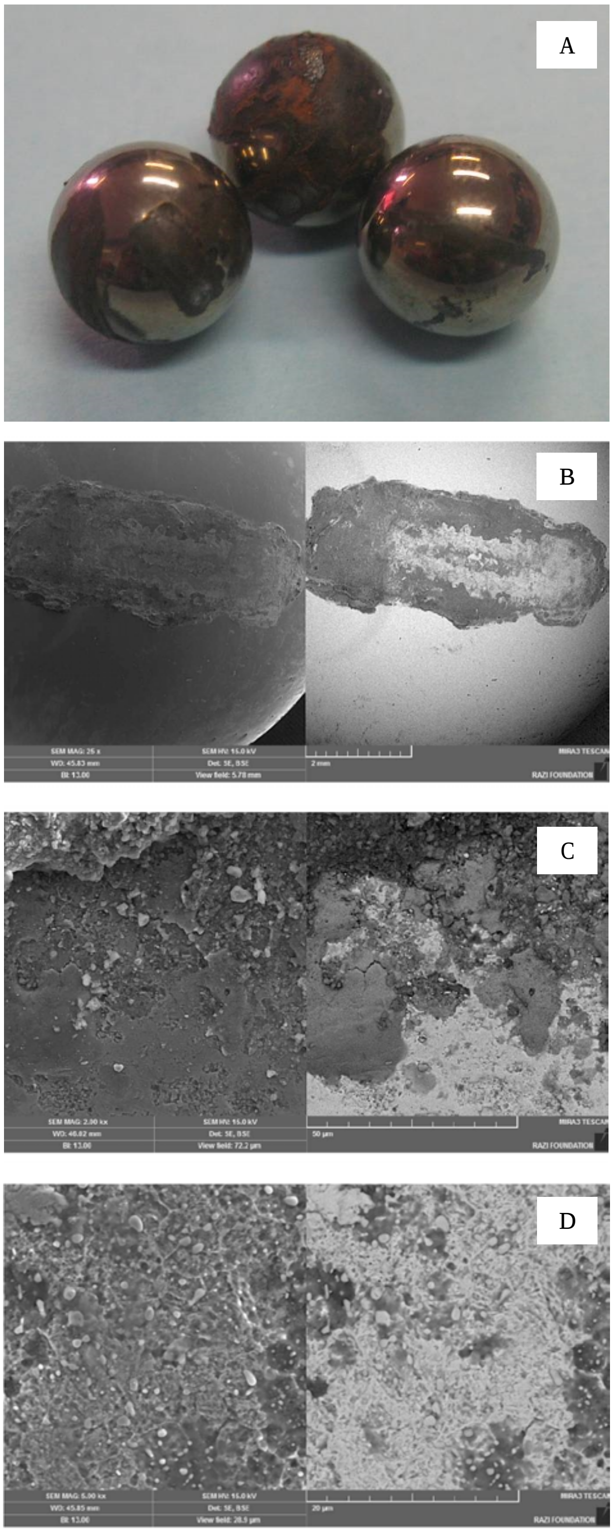

Figure 13: A-false brinelling damage in an angular contact ball bearing ball and B-magnifications
(Mag: B-25×, C-2000×, D-5000×)

Smearing

In smearing, two inadequately lubricated surfaces slide relative to each other under load and consequently the heat of high temperature generated by friction melts the surfaces in contact. Since the material is transferred from one surface to the other surface, the damaged surfaces become meaningfully rough with a torn appearance [12, 13, 14]. In dynamometer, some deep groove ball bearings have been detected to contain this damage as a dark band in the center of raceways which is the contact area of balls and races. Figure 14 shows the inner and outer races of the deep groove ball bearing damaged by smearing.

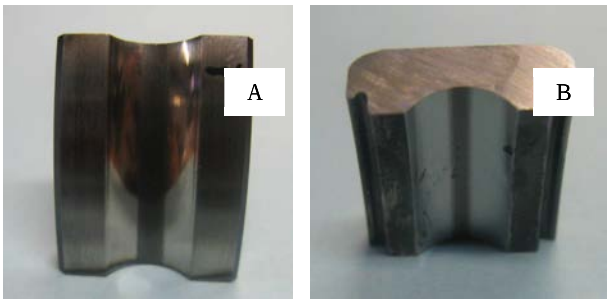

Figure 14: Smearing in a deep groove ball bearing inner race (A) and outer race (B)

The microstructure of this damage is seen in figure 15. The area 1 is smeared surface and the area 2 shows almost no melted or torn material. Using a more suitable lubricant can significantly prevent this damage.

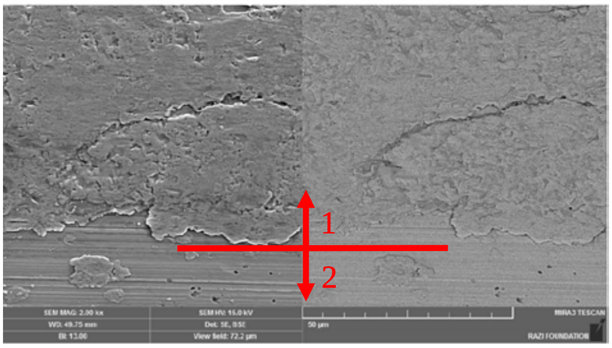

Figure 15: Smearing microstructure in the deep groove ball bearing (Mag: 2000×)

Corrosion

Two types of corrosion are common in dynamometer ball bearings: deep seated rust and fretting corrosion. The first one happens when water or corrosive agents penetrate the bearings in such quantities that the lubricant loses its protective role.

Eddy current dynamometers have a drawback in comparison with other types of dynamometers like AC dynos; the coolant.

The cooling water calls for special treatment to prevent dyno cooling chambers failure. Although decalcification programs in regular intervals help to prevent heat shock loads, still initiation of cracks in cooling chambers and water leakage is inevitably possible. Presence of salt in water can form galvanic corrosion that is called water etching [14]. This would be a reason that dyno manufacturers never permit using salty water as coolant.

Deep seated rust is very dangerous to bearings by initiating flaking and cracks similar to figure 16.

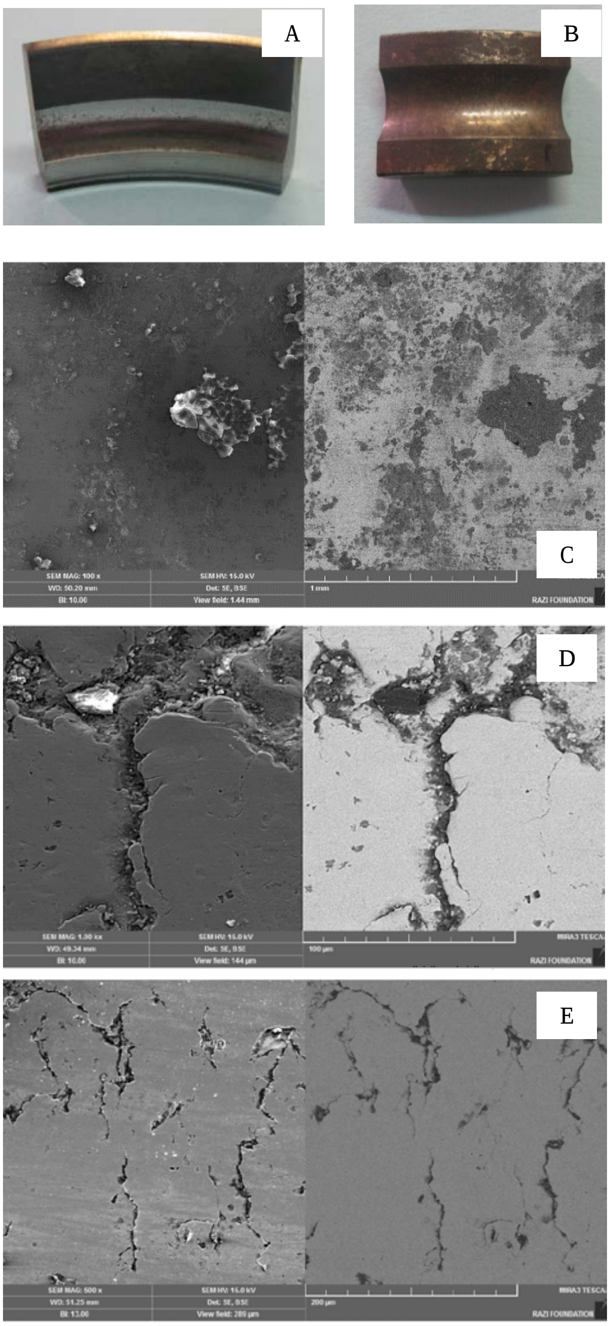

Figure 16: Deep seated rust microstructure in an angular contact ball bearing rings; A-Outer race, B-Inner race, (Mag: C-100×, D-1000×,E-500×)

When the fit between bearing inner ring and dynamometer shaft or outer ring and the housing is too loose, relative movements occur between them which can help to the penetration of the thin oxide film on the surfaces. This is known as fretting corrosion that usually when a dynamometer is repaired and the required fits are neglected, happens.

Cage damage

Identifying the cause of cage damage is on no account an easy case. Defects in other components of bearing which usually go together with cage damage intensify the complexity of the issue [14]. Bearing manufacturers mention certain reasons for cage failure.

Among several dynamometer failed bearings chosen to study, just one case engaged cage damage which is shown in figure 17. In the angular contact ball bearing suffered from lubricant starvation and was exposed to excessive vibration, the cage is thought to fail due to blockage owing to wedged hard particles between the cage and a ball that prevented the latter from rotation around its axis.

Figure 17: Failure of an angular contact ball bearing cage

4) Results and Discussion

The dynamometers damaged bearings selected for the study, are placed in 7 major failure modes:

- Fatigue (Spalling)
- Adhesive wear
- Abrasive wear
- False brinelling
- Smearing
- Corrosion
- Cage damage

Most of the cases include two or more failure modes accumulated during bearing working service. These defects can provide the initiation of each other's occurrence and can accelerate bearing failure.

There are also some damages like pitting and scratch which are to some degree common in mechanically-in-contact components. The recent defects are ignored in this paper due to the fact that for the generality of bearings they happen.

All failure modes except for the cage damage which is a rare one, happen on bearing components surface or subsurface areas.

Declaring the share percentage of each damage type in a bearing failure is impossible because of several reasons:

At first, we should know the working conditions of the dynamometer. Dyno manufacturers usually recommend a certain working hour for bearings replacement. However, this working hour is a rough criterion and bearings health depends on many other factors like the driveline speed, loads, environment, and etc.

Another reason for difficulty of clarifying the share of each failure mode in bearings' failure would be the test bed in which the damaged bearings are collected; the maintenance system and dedication of personnel to the protection of equipment in the test bed.

The other reason that is very important is the dyno manufacturer. In spite of similar concept of different eddy current dynamometers, each manufacturer employs special bearings, and protection systems.

But as mentioned before, authors attempted to collect a reliably broad community of eddy current dynamometers failed ball bearings which will be applicable for any engine test bed with eddy current dynamometer.

5) Conclusions

Knowing how the bearing failure modes influence the bearing vibration and temperature is necessary for condition-based maintenance systems in engine test beds. The geometrical and physical appearance of bearing defects directly affects the dynamic behavior of bearing components. In this paper, the most important failure modes of ball bearings in an engine test bed eddy current dynamometer were identified and classified. Fatigue, wear, brinelling, and corrosion were the damages with more repetition. Using quality bearings with fresh and appropriate lubricant, and prevention of contaminants entry to bearings besides a predictive maintenance strategy that can detect bearing faults before complete failure can reduce an engine test cell downtime hours and increase dynamometers reliability.

Acknowledgment

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مطالعه حالت‌های خرابی یاتاقان‌های غلتشی در یک لگام ترمز جریان گردابی

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چکیده

لگام ترمزهای جریان گردابی در مراکز تحقیقات موتور، یکی از مهمترین تجهیزات اتاق‌های آزمون موتور بشمار می‌روند. خرابی یاتاقان‌های غلتشی در این تجهیزات یکی از دلایل رایج توقفات اتاق آزمون موتور می‌باشد. دانش ناکافی در این زمینه علاوه بر تحمیل هزینه‌های ناخواسته سبب جمع‌آوری داده‌های نادرست آزمون می‌گردد. هدف این مقاله شناسایی و دسته‌بندی حالت‌های مختلف خرابی یاتاقان‌های غلتشی در لگام ترمزهای جریان گردابی است. برای انتخاب یک برنامه نگهداری مناسب در آزمایشگاه‌های موتور، این یک تحقیق ضروری می‌باشد. بیش از 30 یاتاقان ساچمه‌ای معیوب از لگام ترمزهای جریان گردابی مختلف جمع‌آوری شده است تا حالت‌های مختلف خرابی که در آن‌ها یاتاقان قادر به عملکرد درست نیست بررسی گردند. علاوه براین، مطالعات متالورژیکی روی قطعات معیوب انجام گردید تا دلایل اصلی خرابی مشخص گردند. لگام ترمزهایی که یاتاقان‌های آن‌ها مورد بررسی قرار می‌گیرد در پروسه‌های آزمون مختلفی که یک لگام ترمز جریان گردابی قادر به کار باشد مانند آزمون‌های دوام، سرعت بالا و غیره مورد استفاده قرار گرفته‌اند. بنابراین مجموعه متنوعی از حالات کاری یک لگام ترمز جریان گردابی درنظر گرفته شده است. درنهایت حالت‌های شناسایی شده جهت آماده سازی یک پایه کاربردی برای پایش وضعیت لگام ترمزها با استفاده از آنالیز ارتعاشات یا روش‌های دیگر دسته‌بندی می‌گردند.

اطلاعات مقاله

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