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TECHNICAL ARTICLE—PEER-REVIEWED

Maintenance Error Detection Procedure and A Case Study of Failure Analysis Locomotive Diesel Engine Bearings

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Abstract This paper presents a maintenance error detection algorithm. Proposed algorithm is used to determine failure analysis of a locomotive diesel–electric engine. Although the inspected engines had been performing normally up to the maintenance sequence, the problem occurred after the maintenance and resulted in a complete stop of the engines with the high losses on-site. In failure cases, before focusing on technical problem narrowing down possibilities were required. After initial analysis, many possibilities were eliminated and the problem was determined with less effort on shorter time. Engine bearings were investigated to diagnose the problem. The origin of the problem was diagnosed and determined using SEM techniques and on-site inspections. The results show that the shot peening technique used in engine block cleaning operations caused the deterioration of the engine. Oil filters were damaged and could not hold shot peen particles. The oil filter and engine bearing have been examined with SEM and EDS analyses to determine the source of the particles. Some of the found ferrous particles had a spherical shape of 300–1000 μm. These particles and the high pressure created by the engine's oil pump used to cool the system caused severe abrasive wear.

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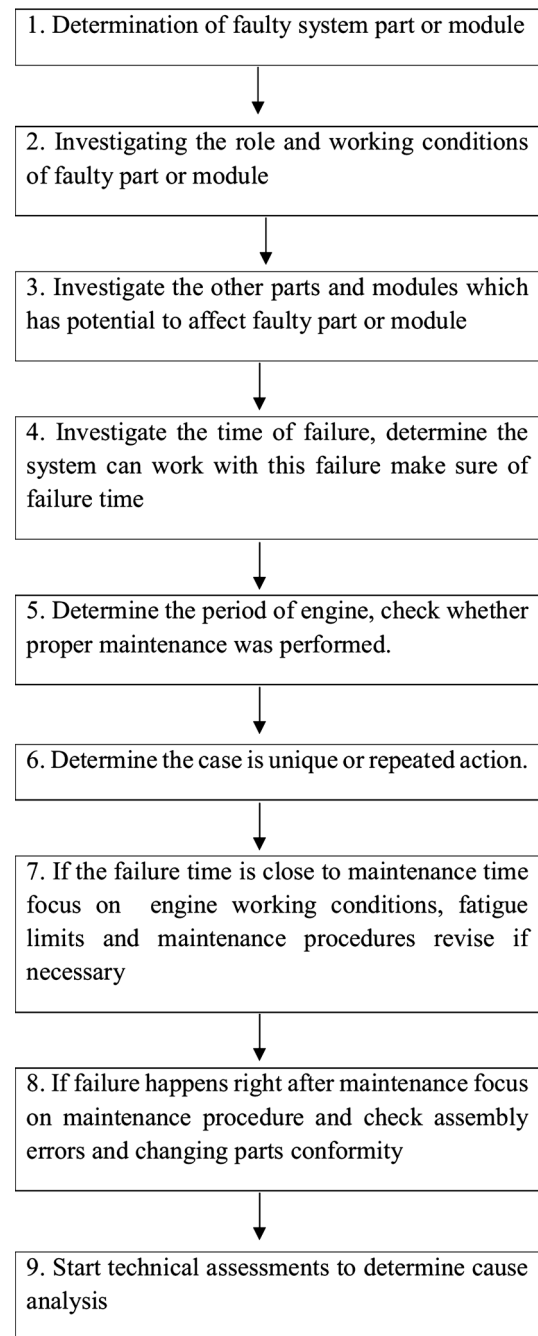
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Introduction

Maintenance activities are carried out using different methods such as periodic replacement of spare parts, oil change, remachining of some components or instantaneous vibration monitoring. Prognostic maintenance becomes more important lately. Even though it may be an unwanted situation, damage may occur in some conditions without control. Damage analysis is performed in such cases to identify and eliminate the source of the problem and to facilitate running of the existing machine system. In addition, probable causes must be investigated in order to prevent the problem from reoccurring in the future. In this manner, failure analysis is a fundamental step for most maintenance operations. Similarly in transport industry, this issue requires so much importance. Trains are one of the most efficient means of transportation. This efficiency is achieved through properly designed infrastructure including efficiently designed railway tracks. Trains are driven by locomotives that can be powered by electricity or diesel fuel. While electricity powered locomotives are considered the most efficient locomotives, it is not always possible or feasible to use them. In such cases, diesel-powered electric locomotives and engines can be used. In this case, investigated engine was a diesel–electric engine TLM16V185 model, had 16 cylinders and can generate 11,280 Nm torque. The service conditions of the train included severe stress, vibrations, dust, environmental changes, climate changes [1].

The objective of this study is to develop an error detection procedure and apply this procedure to analyze a

high-importance maintenance error. There are some studies about maintenance planning with failure aspect in the literature [2, 3]. Technical analysis was to determine the root cause of the observed failure. The viewpoint of a fault inside a system changes depending on the stage when the failure occurs. It also depends on whether this failure is a unique case or a repeated action. In present case, the severe wear was observed after the maintenance of diesel engine. The maintenance protocol was a routine procedure applied to properly performing engines which have been in service for projected operating time. In previous test cases, similar instances of failure were not observed even in the engines that were in near-maintenance condition. At this point, the root cause analysis focuses exclusively on the maintenance procedure rather than on the manufacturing errors or possible fatigue-related issues. The first possible cause could have been an improper assembly of the engine block. However, after performing all necessary measurements, the possibility of an assembly error was eliminated. The second possible cause could have been an oil pump malfunction or rapid oil deterioration. Although the examination of the oil filters and the samples of used oil did indicate that the filters were pierced in multiple places, no faults were found in the oil pump. This preliminary investigation raised doubts that the cause of the problem might be oil contamination. Researchers have studied the effect of contaminants on performance of ball bearings in previous studies [4–7].

The initial examination was performed on the oil filters that concluded that they were pierced in many places. After this first inspection, the damaged parts were replaced, the engine's oil was changed and the filters were renewed. After the subsequent inspection in a testing facility, the same instances of failure were detected again. At that point, suspicion fell on some sort of contamination that could not be removed by standard cleaning procedures. Another examination was performed on the part of the engine's bearings and oil filters. More specifically, the damaged parts of the engine and the oil filters were examined with scanning electron microscope (SEM) to determine the cause of wear.

Investigation Methods

An algorithm has been developed for the systematic approach in the determination of the problem. Proposed procedure was followed for this case. Maintenance detection procedure is given in Fig. 1. Firstly, visual inspection of the engine was performed. Engine was seized, and faulty parts were determined which were engine pistons and bearings in this case. When the piston and bearings used in this system were examined, it was observed that there are

1. Determination of faulty system part or module

2. Investigating the role and working conditions of faulty part or module

3. Investigate the other parts and modules which has potential to affect faulty part or module

4. Investigate the time of failure, determine the system can work with this failure make sure of failure time

5. Determine the period of engine, check whether proper maintenance was performed.

6. Determine the case is unique or repeated action.

7. If the failure time is close to maintenance time focus on engine working conditions, fatigue limits and maintenance procedures revise if necessary

8. If failure happens right after maintenance focus on maintenance procedure and check assembly errors and changing parts conformity

9. Start technical assessments to determine cause analysis

Fig. 1 Maintenance detection procedure

wear groves in the bearings. Main related parts to damaged modules are oil and oil pump, fuel and fuel pump exhaust system and cooling system. Exhaust system and cooling system were investigated and no fault detected. The cooling system used in this study is oil cooling. A detailed examination of the oil pump system has been decided and implemented. Failure time was determined which was just after the maintenance procedure problem was determined at test runs at the testing plant. Engine maintenance

Fig. 2 Locomotive and examined diesel–electric engine
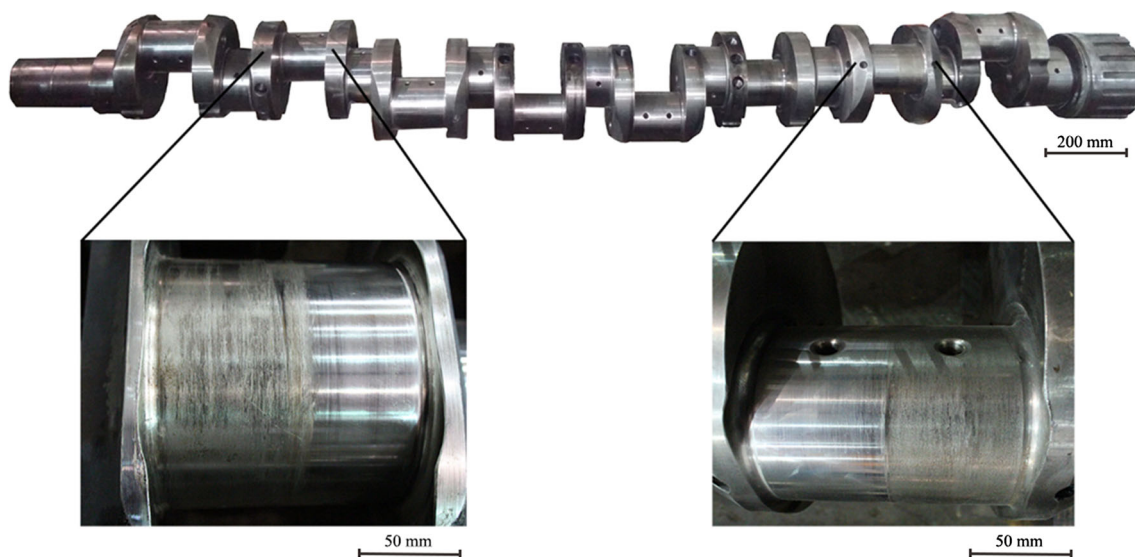
Fig. 3 Crank shaft failure

procedure was investigated. Similar type of failure was observed at more than one engine, so this case could not be classified as unique case. It was a repeated action.

Failure time is just after maintenance, so maintenance procedures were investigated. Possible assembly errors were checked. Then, technical assessments were started to determine the cause of engine failure. Engine's bearings were chosen for further examination based on visual assessment and transportation ease. Then, the engine's bearing was cut into pieces to represent observed different wear types. Finally, the contaminants were collected from the oil filters. The examination was performed with using SEM and energy-dispersive X-ray spectroscopy (EDS) analysis. Investigated locomotive end diesel–electric engine is shown in Fig. 2.

Observed Results

Visual Examination

Firstly, visual inspection was performed on the crank and the engine's bearing. Figure 3 shows failed engine crank-shaft. Severe marks of abrasive and adhesive wear were observed.

Figure 4 shows some of the engine's bearings taken from the failed engine. The image demonstrates multiple scratches along the bearing in the direction of the crank's motion. These scratches were fairly deep, and some of them were so deep that resemble deep grooves. In addition to these groves, the image shows obvious pitting zones. The engine's oiling system contains many particles and contaminants. The pitting zones show the area with the

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Fig. 4 Macroimage of bearing failure
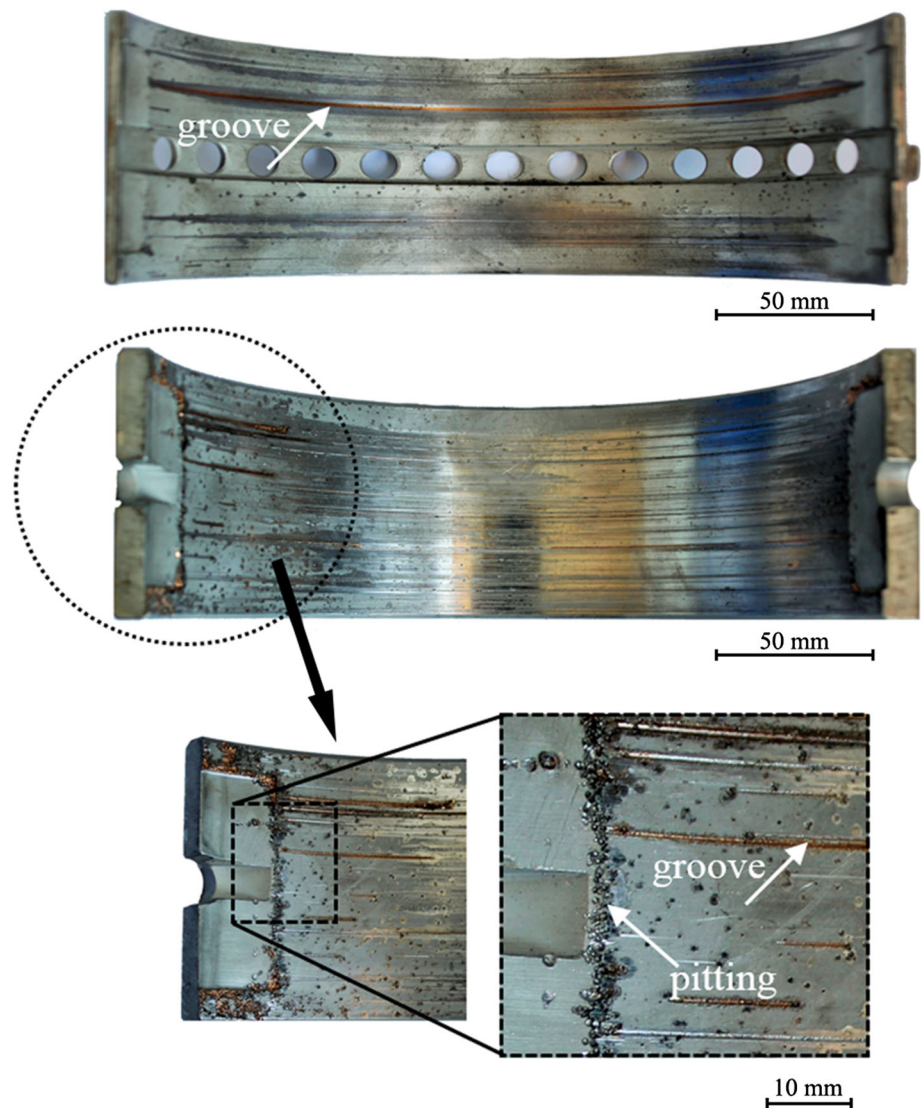
sign of erosive wear. Presumably, this erosive wear in the engine's bearing parts happened due to the problems originating from the high-pressure oiling system. Oil with particles and contaminants circulates in the engine at a pressure of approximately 5 bars. These pitting zones are concentrated around the oil inlet and outlet areas. The dimensions (width and depth) of the scratches and grooves vary. Although the difference could be appreciated even with a visual inspection, a more detailed analysis was done by using SEM. Usually, this type of wear regime occurs in the presence of harder particles that likely have caused the severe abrasive wear observed in the engine's bearing parts. In order to determine the origin of wear, SEM analysis and previous bearing failure cases were investigated to compare the engine's bearings visually [8].

SEM Examination

According to ISO 7146 [9, 10], abrasive wear is caused by contamination of the systems. This contamination might include damaged particles, natural contaminants (such as dust, soil, etc.), deteriorated chemicals and foreign materials. These contaminants flow with oil inside the hydrostatic oiling system and might cause severe scratches and grooves. These particles might also adhere to the bearing surface or deform it. Figure 5 shows the SEM microimages of the examined samples. These SEM images prove that there were many scratches with different sizes and depths: (a) width of scratches was about 200 μm, (b) 500 μm, (c) 150 μm and (d) 800 μm. The depicted morphology of the grooves shows that the bearing surface was chipped off by the abrasive particles. In some areas, the
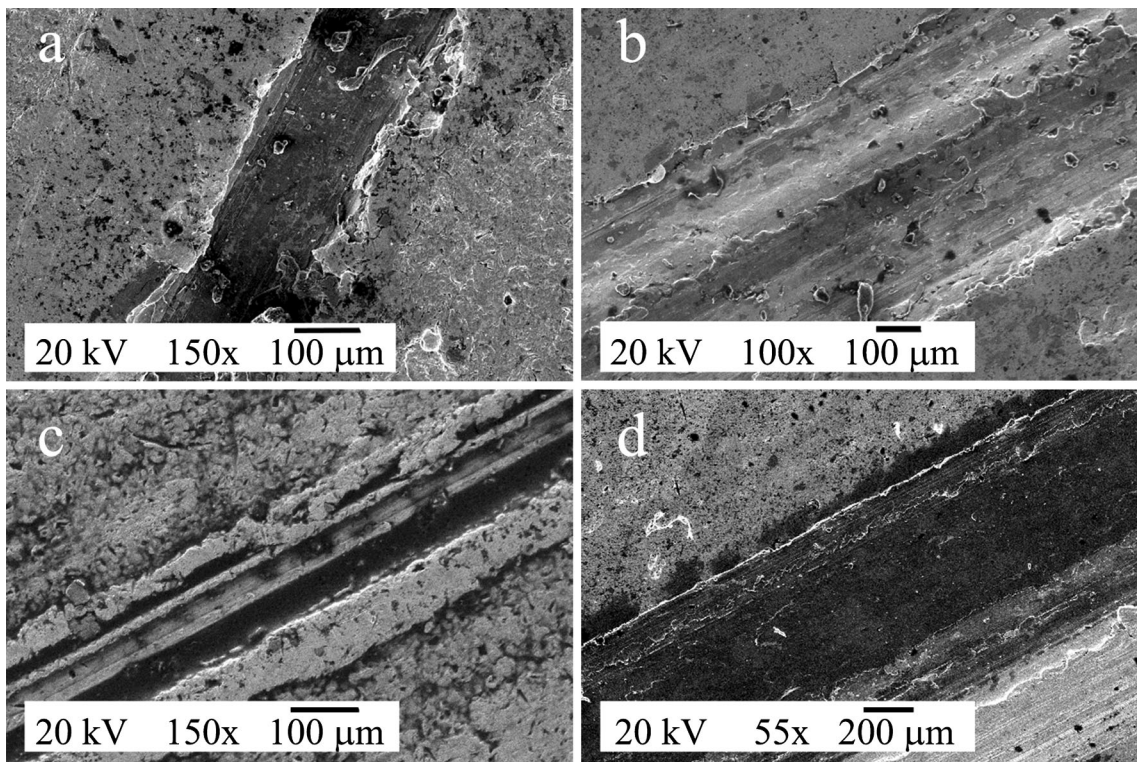
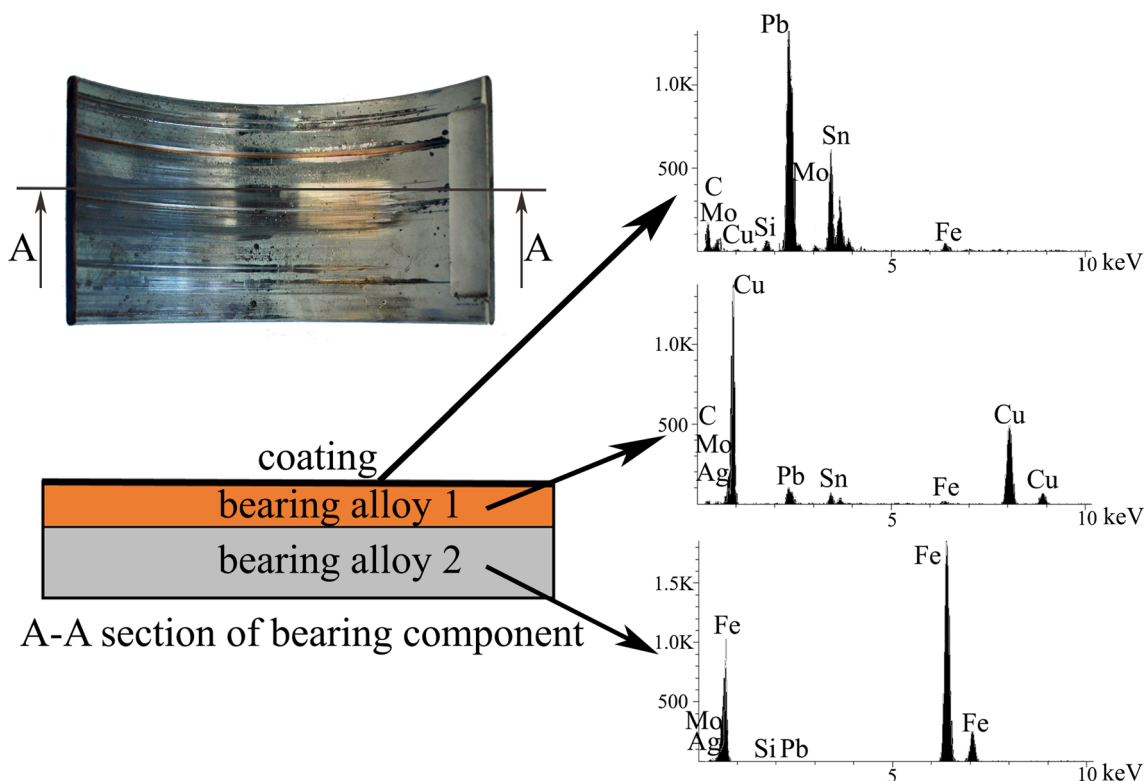Fig. 5 SEM images of wear morphology
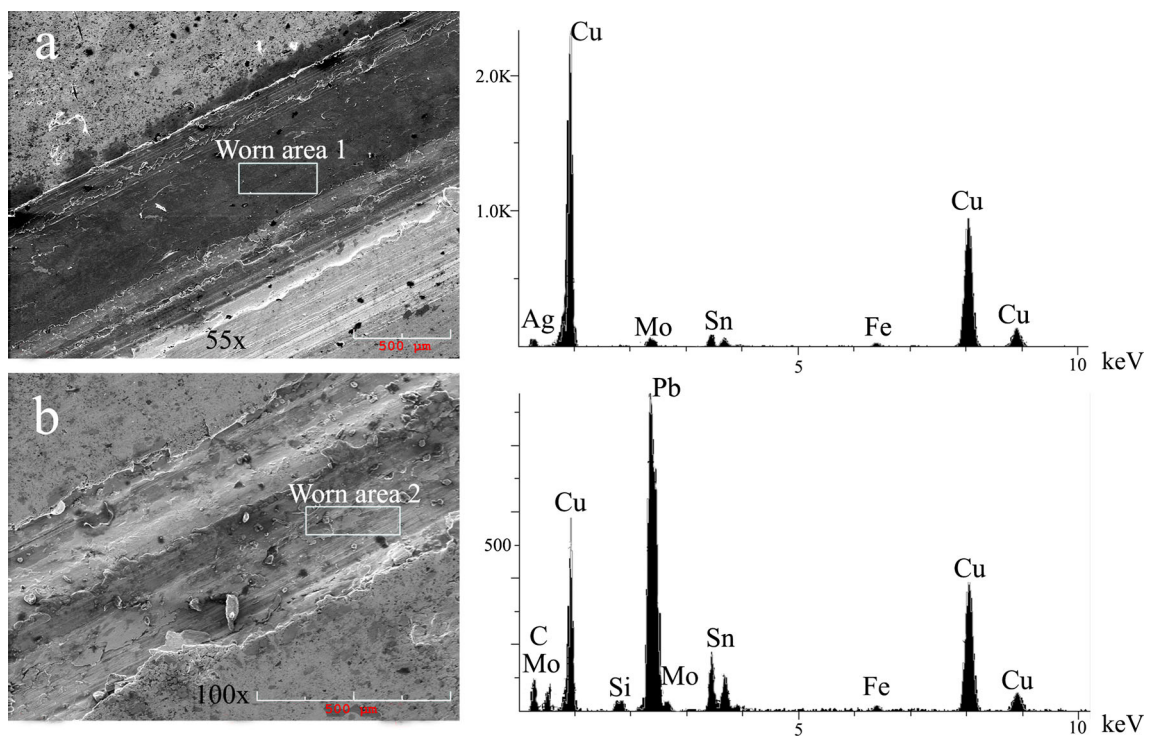
Fig. 6 EDS analysis of wear sections

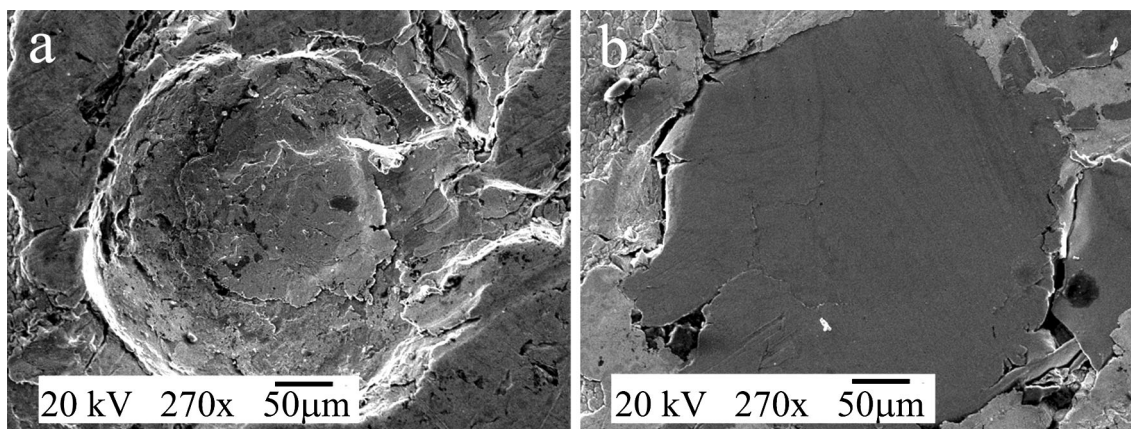**Fig. 7** EDS analysis of the cross section of the bearing component

Fig. 8 SEM images of pitting morphology

scratched material became smeared on the side of the grooves as illustrated in Fig. 5c and d.

In this study, EDS technique was used for material characterization. It should be noted that the specimens not specially prepared for this procedure were used to distinguish between practically very different materials. Therefore, it is possible that there is a certain amount of margin of error in the EDS results and percentage of chemical analysis alloys presented. Analyzes made in this context can be said to be semi-quantitative for this practice. The EDS analysis was performed to understand the character and chemical composition of the grooves. Figure 6 provides the EDS samples. Figure 6a shows where (%75.8 Cu, %7.2 Sn, %6.5 Pb and others) elements are concentrated, while Fig. 6b shows where (%36.6 Pb, %29.2 Cu, %13.7 Sn, %8.5 Mo and others) elements are concentrated. The difference in the results of these samples showed that the depth and the level of the wear area were quite different from each other. Figure 7 demonstrates that the examined bearing alloy contains 3 stages. Same analysis procedure was applied to the section of bearing alloy. The EDX analysis of the bearing section provided with the

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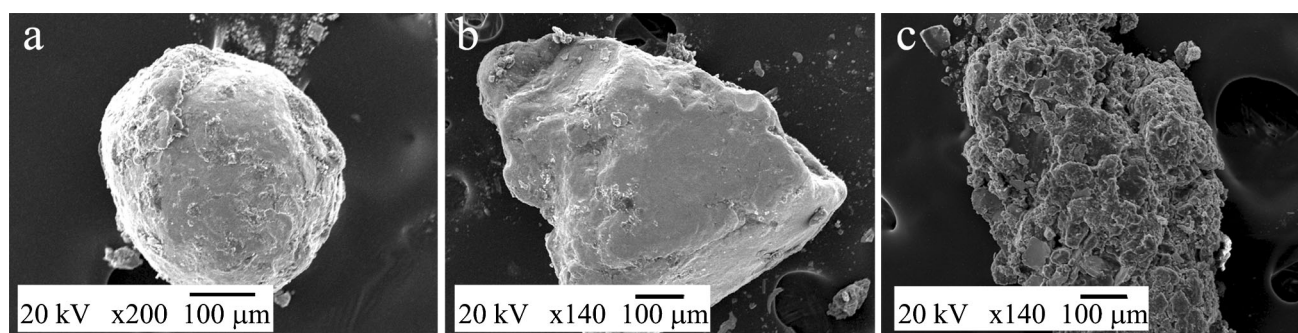
Fig. 9 SEM images of particles

reference results to compare with the worn areas. The EDX analysis of the bearing section is illustrated in Fig. 7. Bearing component was made from three chemically different layers, coating of the bearing alloy contains (%39.6 Sn, %37.4 Pb, %10 Mo and others) elements, the bearing alloy 1 contains (%68.5 Cu, %13.2 Pb, %8.7 Sn and others), and the bearing alloy 2 contains (%92.5 Fe, %3.4 Pb and others) elements. The EDX results in Fig. 6a are in agreement with the chemical composition of bearing alloy 1 in the EDS analysis. From this analysis and Fig. 6a, we might conclude that the wear happened because of the removal of the coating of the engine bearing. This type of wear was excessive for a regular case and can be classified as a severe abrasive wear. In Fig. 6b, the results of the EDS analysis chemically comply with those from the EDS analysis of coating of the bearing alloy and alloy 1. It was concluded that these marks can be classified as scratches or surface deformation because the particles tore the coating of the bearing locally and adhesive wear was also observed.

The macroscopic examination of the bearing alloy also exhibits some pitting zones. After SEM examination of the pitting zones, crater like features became evident. Specifically, Fig. 8a shows a spherical cavity and Fig. 8b shows a similar kind of cavity filled with another material. These two cavities have similar dimensions and are probably formed by spherical particles. Most likely, one spherical particle was bouncing in Fig. 8a, while a similar type of particle became stuck in Fig. 8b. The results of the EDS analysis performed in the cavity areas (Fig. 8a) were similar with those performed for the bearing alloy coating (%59.8 Mo, %15.6 Sn, %4.9 Fe, %3.2 Cu and others). However, the results presented in Fig. 8b are different from those obtained for the bearing alloy coating or bearing alloy materials (%95.7 Fe, %0.9 Si and others). Thus, it was concluded that based on the EDS results the particles must be external.

Despite the holes in the engine oil filter, it was decided to examine the filter, and the filtered slurry was filled in a container, and the oil particles were removed, and a precipitate was obtained. The remaining precipitate was brought to the electron microscope for examination. Figure 9 shows the SEM image of particles that were taken from the oil filter. These particles were some of the contaminants found in the lubrication system. Probably, these contaminants caused pitting and scratches. To test this theory of failure, morphology and chemical content of these particles were examined. Figure 9a shows regular spherical particles. This particle was chemically different (%89.3 Fe, %2.1 Si, %3.3 Pb and others) from the bearing alloy and coating. Chemical composition of this particle was quite similar to that in Fig. 8b. When the dimensions of the spherical particle were examined, they were in agreement with previously examined particle dimensions, grooves dimensions and pitting zone dimensions. From this, a theory was established that these particles were accelerated by the oil pump and became stuck in the bearing material. Thus, these hard particles started and propagated the observed abrasive wear. At this point, the identification of the source of these particles was necessary to determine the source of the problem. The origin of this ferrous particles could be in service or fabricated. Their regular spherical shape points to its manufacturing method. The measured dimensions for regular spherical particles vary from 300 to 1000 μm. According to shot peening standard that was used for cleaning purposes of locomotive engines (SAES390), nominal size of particles is 1000 μm and %96 of the particles size must be over 850 μm [9]. Figure 9b shows a different particle though. Not only does this particle not have a regular shape but their EDS results (%84.6 Fe, %2.4 Pb, %1.3 Si and others) also are different from other examined materials. We assume that this particle was ejected from one of the engine parts with the effect of plastic deformation. This particle can be classified as a regular worn particle. Meanwhile, Fig. 9c shows an agglomerated particle that was formed by tiny wear particles and oil additives. EDS analysis of this particle was (%44 C, %21.9 O, %19.6 Fe, %4.2 Pb, %3.8 Si and others). This particle can be classified as a regular contaminant of oil.

Cause Analysis

Although the origin of the particles could be natural (sand, soil rocks, etc.), the SEM tests show that these particles are ferrous and have a spherical shape. This findings support the idea that the particles were manufactured by powder metallurgy. Additionally, these type of particles cannot be worn particles that split from the engine block or the engine cylinders because, usually, such worn particles are oddly shaped as seen in Fig. 9b. After established theory, the engine company investigated the origin of the particles. They concluded that the particles were shot peen particles which were used by one of the suppliers for cleaning purposes. Used shot peen particles were not sifted and had variable sizes. While larger particles were cleaned from the system by a regular cleaning procedure, smaller particles could not be cleaned efficiently and acted as abrasive particles causing the engine's wear. The high-pressure oil pump further aided the wear process by accelerating these particles. The oil filter could not hold these particles, and this is why it was pierced in many places by the effect of shot peen contaminants. As a result, these particles abraded and deformed the engine's block and the wear speed increased dramatically and bearing seizure occurred.

Conclusions

The analysis showed that the retained shot peen particles caused the engine's failure. Because the retained particles had microscopic sizes, they could not be cleaned by the traditional methods. The high-pressure oil pump speeds up the wearing process by accelerating the ferrous particles that could not be stopped by the oil filter. As a result, the engine endured severe abrasive wear before the end of its service life.

Recommendations

1. Ultrasonic cleaning of the engine parts after maintenance eliminates possible residual shot peen particles.

Ultrasonic cleaning eliminates the possibility of any remained contaminants.

2. If shot peen method is required for cleaning, shot peen particles must be sifted before using them for cleaning purposes and a standard chosen [11] to clean with the traditional methods.

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