Bearing-Eye: a measurement and analysis platform for rolling contact fatigue in rail-axle bearings

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Abstract

Rail-axle bearings deteriorate with time and usage through rolling contact fatigue (RCF). Currently bearings are replaced during maintenance schedules (on-time) or when a bearing has failed. This has implications, such as service delay, derailment and fire with risk to life. Condition monitoring (CM) has been applied to rail-axle bearings to detect a change in monitored parameters, but it is not yet capable of directly quantifying the severity of the damage, sometimes leading to premature extraction.

Understanding the relationship between the RCF damage and the CM data (true calibration) requires a measuring device able to quantify the RCF damage. This paper describes the principles of the BEARING-EYE, a new instrument built to map and interpret the surface damage observed in failing rail axle bearings.

This ability to interpret the RCF damage and report this as a simple numeric output will transform the CM into a diagnostic/prognostic tool able to determine from CM parameters how long bearings could be left running safely thus avoiding unexpected failures. Consequently, the maintenance programs will change from 'on-time' to 'on-condition'.

Keywords: *rail-axle bearings, bearing degradation, rolling contact fatigue, condition monitoring, surface measurements, metrology, 3D Digitisation, artificial intelligence.*

1 Introduction

Rail-axle bearings deteriorate with time and usage through rolling contact fatigue (RCF). Currently bearings are replaced during maintenance schedules (on-time) or when a bearing has failed. This has implications, such as service delay, derailment and fire with risk to life. For many years condition monitoring (CM) has been applied to bearings in general, but also in the rail environment [1].

CM is currently employed in-service as a detection system capable of flagging a change in monitored parameters, but it is not yet capable of directly quantifying the severity of that damage, sometimes leading to premature extraction.

Detailed failure investigations of rail axle bearings, removed from service from Southeastern railway trains after showing higher than normal vibrations, has shown RCF damage in at least one of the two cup races of the outer ring [2,3]. The damage to the static outer ring always spread from the region of maximum loading.

The damage in rail-axle bearings generally presented two types of RCF macropitting: surface and sub-surface initiated. The sub-surface initiated damage or primary damage is believed to be the first damage to appear. This damage develops sub-surface cracks that when reach the surface will free a chunk of material leaving a macropit on the surface. From this macropit secondary damage could then develop during running. These two types of damage have been discussed in detail by Symonds et al. [2,3].

Understanding the relationship between the RCF damage and the CM data (true calibration) requires a measuring device able to quantify the RCF damage. Current recommended good practice includes measuring surface roughness using 2D contact profilometry [4], however this only provides discreet slices. Yusof et al. [5] periodically monitored using an optical light non-contact measuring system a section of the surface of the accessible inner race and of a roller to determine the deterioration pattern. This methodology cannot be used in outer race damaged rail-axle bearings.

This paper describes the principles of the BEARING-EYE, a new instrument built purposely for this project and able to map and interpret the surface damage observed in failing rail axle bearings. This ability to quantify RCF damage will transform the CM into a diagnostic/prognostic tool able to determine from CM parameters how long bearings could be left running safely thus avoiding unexpected failures. Consequently, the maintenance programs will change from 'on-time' to 'on-condition'.

The work was funded by Innovate UK, led by the surface contact measurement specialists Scantron Industrial Products Ltd and built on the research knowledge of nC^2 Engineering Consultancy, an industrial tribology focused department within the University of Southampton, in collaboration with the condition monitoring experts Perpetuum Ltd.

2 Methods

The BEARING-EYE is a measurement instrument (Figure 1) specifically built and developed to analyse the outer ring of rail-axle bearings. The BEARING-EYE is a three-axis cartesian robotic stage with a rotational axis. Each cartesian axis is equipped with an encoder (Renishaw linear optical) with 0.10 µm resolution. The rotary stage is also equipped with a rotary encoder (Gurley Precision Instruments) with a resolution of 0.001°. The motors are controlled by a custom embedded controller connected to a PC for sequencing, data collection and processing. A granite table and heavy-duty box frame provide stability and reduce vibrations. This improves the quality of the scan data. All control electronics are housed in the cabinet below the machine.

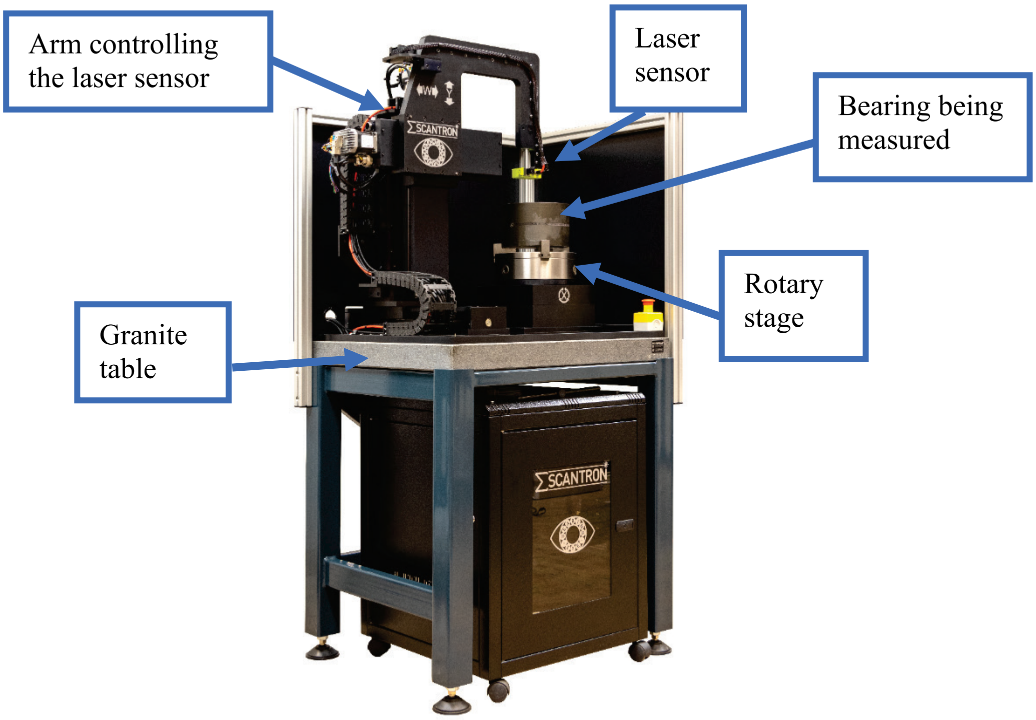


Figure 1: *The BEARING-EYE measurement system.*

The bearing is mounted onto a chuck on the rotary stage. The laser sensor is mounted on the armature above. The sensor can be placed inside or outside the bearing using the three-axis robotic stage. In order to measure the races of the outer ring the bearing is placed onto the rotational stage and the sensor is positioned within the outer ring of the bearing. A scan strip is performed as the bearing is driven through one revolution, then the vertical stage is moved down to measure subsequent strips. At each measurement position, the sensor is triggered to take a measurement and the encoder values are captured. From this a detailed point cloud of data is collected for later analysis. The data analysis and visualisation are performed using a software developed by Scantron.

The BEARING-EYE can be equipped with a variety of sensors; currently a 3D high resolution 95.010 blue laser line sensor has been evaluated and its properties are listed in Table 1. The sensor projects a laser line onto the surface, captures an image using a camera and then uses triangulation techniques to derive distance from the sensor to the surface.

Three bearings, removed from service from Southeastern trains after identification by Perpetuum Ltd., were imaged using a DSLR camera and then scanned by the robotic BEARING-EYE. For comparison the bearings (referred in this work as A, B and C) were also analysed by a human expert using a Zeiss Stemi 200C macroscope with oblique segmented LED lighting identifying the regions of sub-surface and surface initiated RCF.

Line Length	~11 mm
Vertical Resolution	0.37 – 0.45 µm
Lateral Resolution	5.6 – 6.8 µm
Points per line	1920
Measurement Speed	~700 Hz
Measurement Range	5 mm
Stand off	23.5 mm

Table 1: *Characteristics of the laser triangulation sensor; figures have been provided by the manufacturer, except for the measurement speed. This is determined by the parameters needed to measure the surface (such as laser intensity and exposure).*

3 Results

Three bearings were chosen as typical examples of the RCF found on rail-axle bearings, see Figures 2. The time and miles the bearings run before extraction, listed in Table 2, clearly show that damage could happen at any time.

Bearing	Mileage (miles)	Time (months)
A	108,984	9
B	253,985	58
C	47,815	11

Table 2*: Life of chosen bearings prior to removal.*

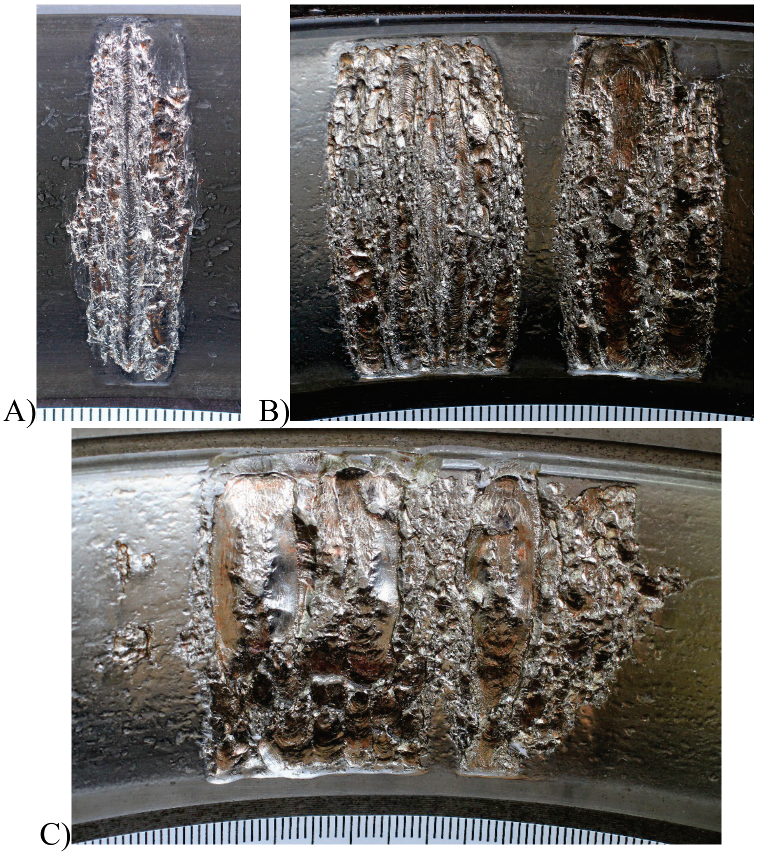
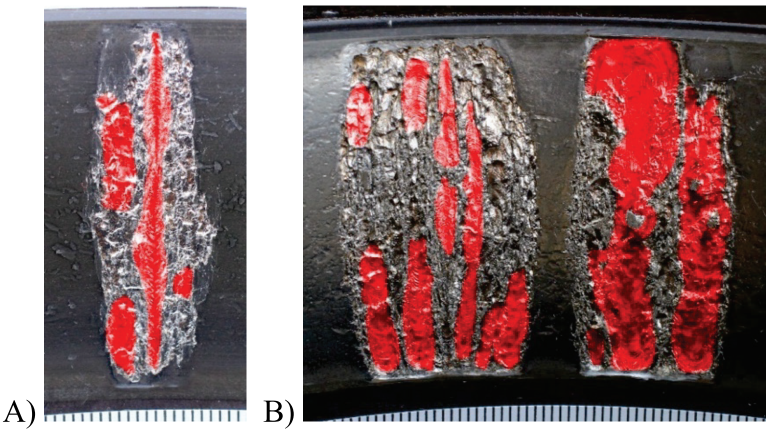


__Figure 2:__ Images of the damages on rail-axle bearings A, B and C.

Figures 3 shows the same bearings after they have been digitally highlighted in by the expert to distinguish between the sub-surface (coloured in red) and the surface-initiated part of the damage; this part of the work is based on previous research, detailed in [3].



C) 

Figure 3*: Analysis by the expert showing in red the areas of sub-surface initiate damage of bearings A, B and C.*

Figures 4 and 5 show examples of scans performed using the BEARING-EYE system. During a scan of one race approximately 640 million scan points (~12 Gb of data) are captured as point clouds, each comprising an (X,Y,Z) position and an intensity value. The point cloud is then converted by merging the overlapping scan data into an image representation of the whole bearing race. This image consists of approximately 86 million points, equivalent to an 86 MP camera image. A zoom in of the scan is shown in Figure 4.

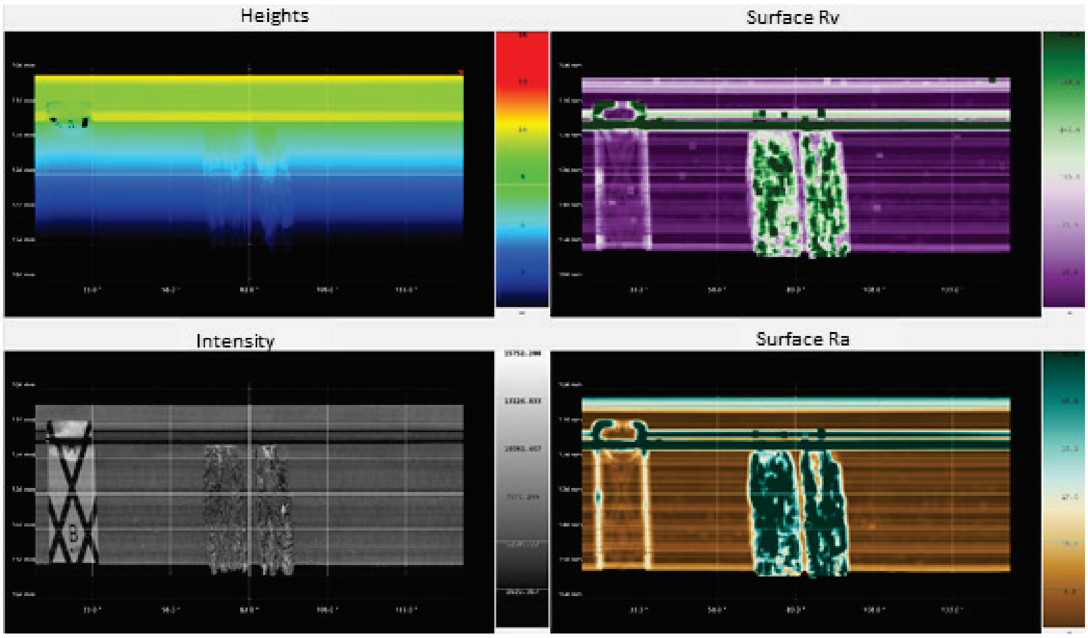


Figure 4: *Visualisation of part of the scan data of bearing B. The four views show the measured height, the surface finish analysis related to Rv, the intensity data and the surface finish analysis related to Ra.*

The height map (Figure 4 top left) is then statistically analysed to produce maps of the surface finish related to Rv (Figure 4 top right) and intensity (Figure 4 bottom left) and Ra (Figure 4 bottom right). Surface finish measurements are computed for small region areas using a moving window approach. These help to analyse the RCF damage and also to highlight pitting and minor surface damages. The intensity data (Figure 4 bottom left) represent a visual photograph of the surface. The scan can be zoomed in even more to provide multiple coordinated views of the data for analysis.

Visualisation in 3D of the collected point cloud data is shown in Figure 5 (whole scan and close-up view). In this instance, the colour of the points is derived from the intensity scan data. However, it is also possible to display the point cloud rendered with colours derived from the surface finish measurements or other data. To aid with visualisation, the apparent surface height has been exaggerated. The close-up view clearly shows the density and completeness of the scan data.

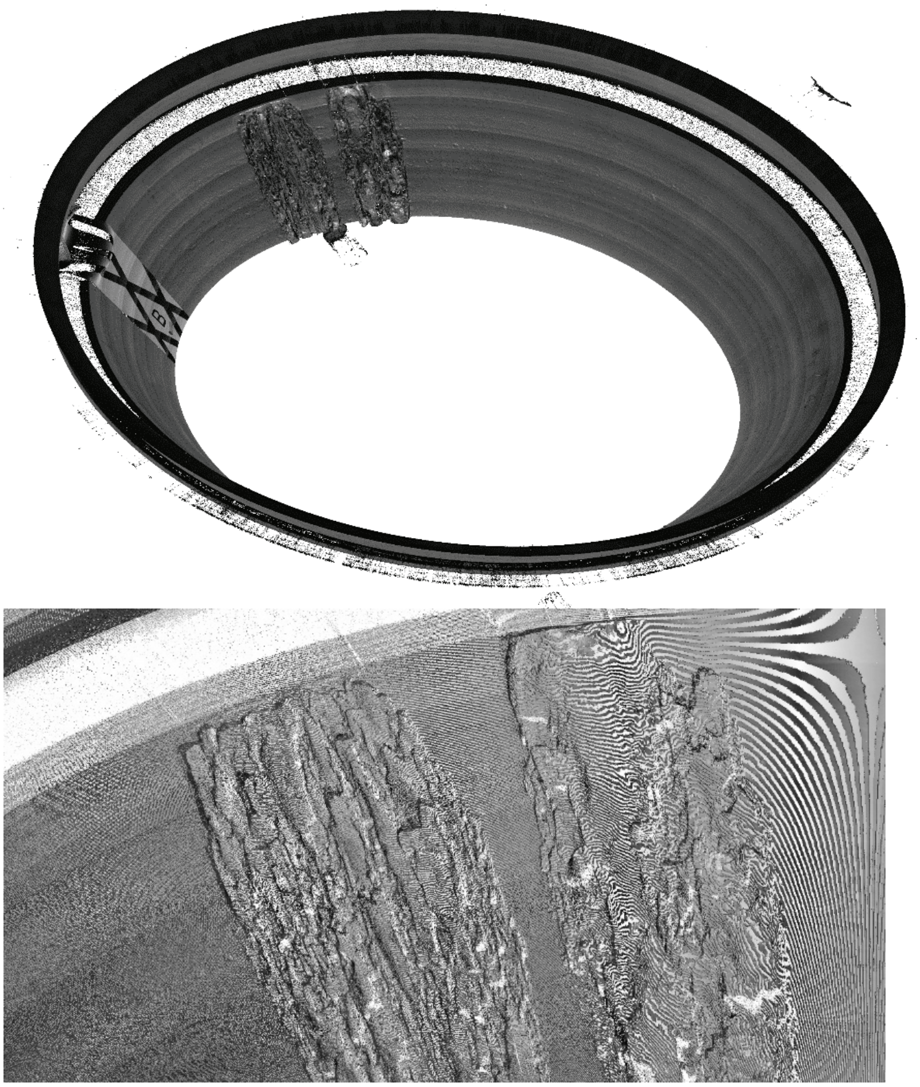


Figure 5: *Visualisation in 3D of the collected point cloud data showing the whole scan and a close-up view.*

4 Conclusions

Preliminary early data captured using the BEARING EYE are presented in Figure 6. The intensity scan data (Figure 6a), unlike the original image of the surface (Figure 6b), is presented unwrapped but still requires refinement as artefacts from the strip and stitching process are clearly visible. The expert analysis (Figure 6c) and the height scan data (Figure 6d) are compared to highlight that the height mapping alone is not the complete answer in identifying sub-surface RCF. Ongoing work will incorporate the roughness mapping and other inputs using a new innovative and intelligent software.

The future work will focus on developing a software based on fractographic analysis, that will interpret the damage severity and report this as a simple numeric output. This innovative software will use machine learning algorithms to analyse the extracted spatial data and will provide a simple numeric output which equates to the severity of the damage. The software tools will include comprehensive data visualisations that will allow analysis of the large volumes of complex, high dimensional data captured.

The BEARING-EYE will help to 'close the loop' in condition monitoring, as shown in Figure 7. By understanding the relationship between the CM data and the severity of the damage, a step change in maintenance schedules from 'on-time' to 'on-condition' could be implemented eliminating the implications of unexpected failures and the subsequent wider economic and environmental impacts.

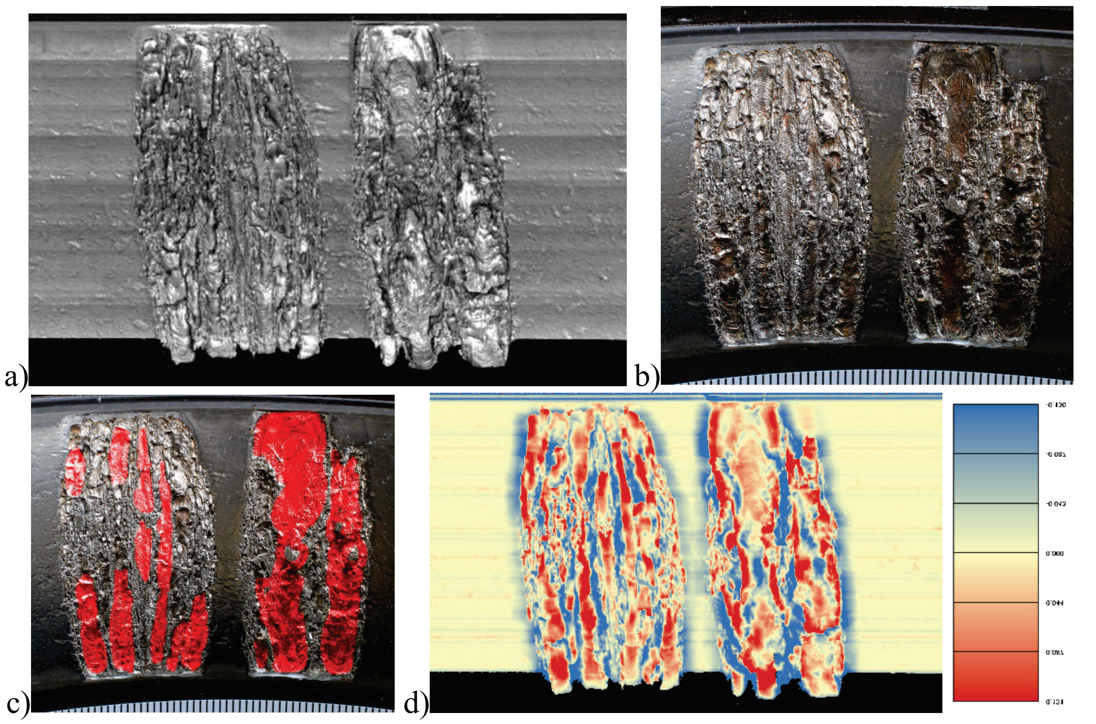


Figure 6: *Comparison of a) the intensity scan data, b) the image of the surface, c) the image of the damage with the primary RCF coloured in red, d) the height scan data for bearing B.*

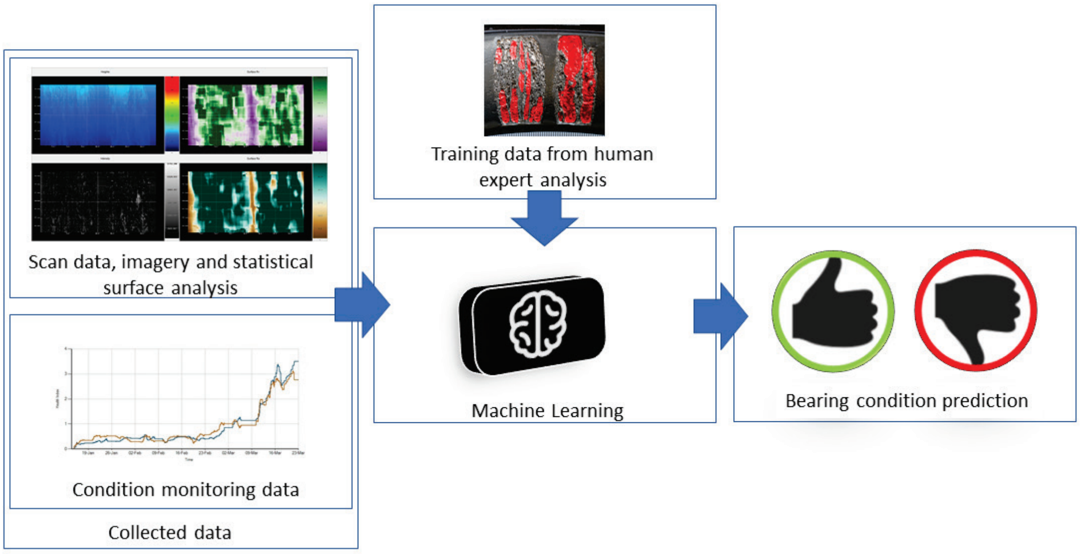


***Figure** 7: Schematic of the BEARING EYE approach to predictive analysis of RCF.*

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