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Analysis of the Impact of Selected Factors on Damage to Rolling Bearings of Rail Vehicle Wheelsets

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ABSTRACT

This work attempts to demonstrate the root causes of failure of the bearing of rail vehicle wheel sets. The work presents the recommended methodology for analyzing damage to the bearing of rail vehicle wheel sets. It was important that the end result of the analyzes was to correctly identify the root cause of the bearing failure. The results of the failure analysis of selected bearings showed that the most probable causes of their failure were: irregularities during the maintenance phase (including failure to comply with inspection intervals), lack of sufficient supervision and/or failure to properly secure the bearing pressure cap mounting bolts, intrusion of external contaminants and/or contamination of the lubricant at the stage of installation and maintenance activities, electrical erosion. The above-mentioned possible causes of bearing damage provide important information that allows for better prevention of damage.

Keywords: rolling bearings, bearing failures, rail vehicles.

INTRODUCTION

Rolling bearings of rail vehicle wheelsets are at least a safety relevant components affecting the reliability and operational safety of rail vehicles. This is because rolling bearings are responsible for transferring vertical, longitudinal and transverse loads occurring between the wheelset and the hardware part of the rail vehicle (the bogie frame and the vehicle body with all its equipment). Therefore, damage to the rolling bearings of rail vehicle wheelsets can lead to overheating of the wheelset axle journal. In the aftermath, such damage can lead to axle fracture/breakage and vehicle derailment, events classified as accidents or serious accidents. The discussed scenario of derailment of rail vehicles has materialised in the past, which confirms that damage to rolling bearings can have an obvious impact on rail safety regulations [1]. Rolling bearing failure is a serious problem that affects passenger safety and can generate significant costs for operators (fines, repairs, reduced train availability) [2].

Wheelset roller bearings of rail vehicles are the key interface between the bogie frame and the wheelset. The most commonly used bearing types for this design node are cylindrical roller bearings, tapered roller bearings and spherical roller bearings. At the same time, spherical roller bearings are used less and less due to the risk of internal slippage. However, there is still a high demand for this type of bearing in the maintenance of wheelsets, for which this type of bearing was originally used [3].

The analysis of the causes of rolling bearing failures in rail vehicles has become an important analysed factor in recent years. This is because the European rail transportation system has set itself the goal of improving reliability, availability, durability, high-speed capacity and maintenance [4]. Regarding the classification of bearing damage, the rail vehicle companies refer to the ISO 15243:2017: Rolling bearings – damage and failures – terms, characteristics and causes standard. Figure 1 shows the classification of rolling bearing defects based on the aforementioned standard.

There are few scientific papers that have analysed rolling bearing damage in rail vehicles. However, this issue is very important due to the possible dangers of this type of damage during the operation of rail vehicles. An important issue to avoid rolling damage in the future is to identify the cause of the damage. In the article [6], a vibration-based bearing fault detection analysis was performed. The results of this research may confirm the existence of challenges in detecting rolling bearing defects, particularly in complex mechanical systems [7]. The paper reviews the current state of research on damage diagnostic methods for rolling bearings of rail vehicle wheelsets. Diagnostic methods using vibration and acoustic signals are discussed, as well as diagnostic methods based on bearings operating temperature. The authors, based on an analysis of the work done so far, identified technical areas in bearing diagnostics that need improvement and further research directions that provide new research theses for alternative methods of

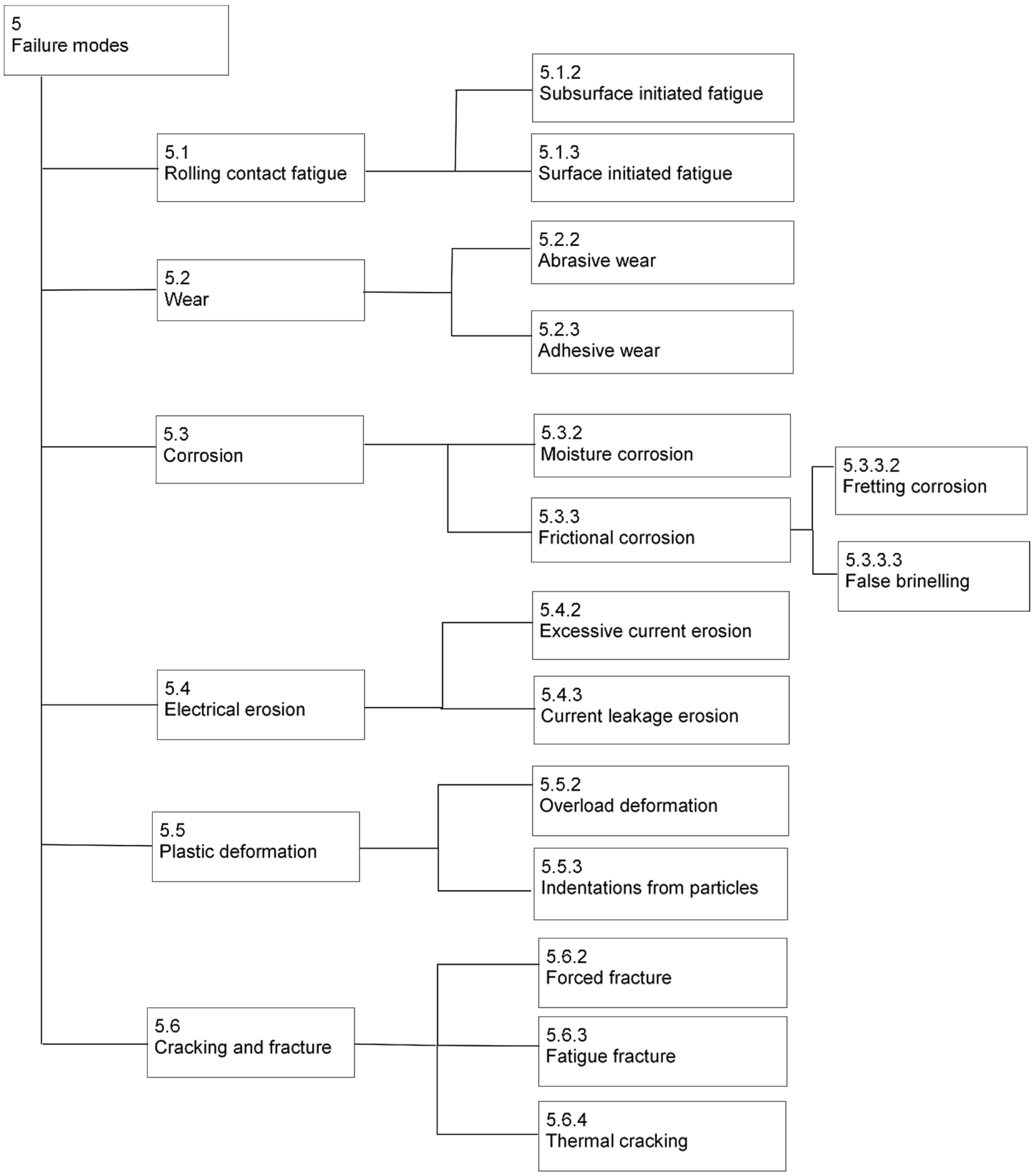

Figure 1. Classification of bearing failure mode [5]

diagnosing bearing damage. It was found that in the future, train rolling bearing diagnosis technology will also integrate various sensor data and systems, especially under increased capacity and complex operating conditions.

For an example of an analysis of bearing damage sources see [8]. This paper presents the application of a vibration signal processing technique to the determination of damage indicators for rolling bearings of railroad vehicles. The presented method allows for assessing the condition of the bearing and monitoring the development of possible damage. The experimental data were obtained by means of a test rig built according to EN 12082:2017 and following the test specifications of the same standard.

In addition, the paper [9] describes the most important causes of rolling bearing failures. In addition to fatigue, they cite several other parameters, such as improper bearing selection for the specific application, insufficient lubrication, vibration, shock load, and environmental factors such as corrosive media, temperature, and contaminated environment, which can cause the bearing to fail before the end of its expected lifecycle. The authors point out that bearing failures can also result from assembly errors, which affect preload, lack of concentricity of bearing components and uneven load distribution, as well as the conditions of bearing operation at excessive loads beyond the design capacity.

On the other hand, in the paper [10] an example of the failure of a rolling bearing of a wheelset of a railroad carriage designed to carry coal is described, which was caused by high temperature and axial force overload. The paper describes in detail the fatigue fracture process on the bearing's outer rings.

Additionally, in order to prevent serious damage to rolling bearings after some time of their operation, methods of diagnosing bearings in real time are being developed. In the work [11], the bearing data of the American Electrical Laboratory "Case Western Reserve University" was analyzed and diagnosed. Based on a fundamental analysis of the causes of damage to rolling bearings of high-speed trains, failure prevention measures and methods can theoretically be proposed to reduce the failure rate of high-speed trains. Finally, the diagnosis results are obtained by using the BP training neural network to accurately diagnose and analyze characteristic data. It was found that the best solution is to use three layers of wavelet packet decomposition to train the BP neural network. Also in the article [12] research on the technology for diagnosing damage to rolling bearings of rail vehicles was analyzed in order to propose a technology to prevent their failure. The analysis of publication data showed that an important phenomenon disturbing the collected data is noise in a complex environment and strong disruptions in train operation, which indirectly affect the quality of data from sensors. It is therefore important to process or quantify environmental disturbances with certainty. Improving feature extraction methods is key to increasing the overall accuracy of train bearing fault diagnosis. Also for rolling bearing failure analysis, a big data management application would be helpful. Here, one of the proposals is the Apache Spark environment, which could be used to process large test data from recorded data from rail vehicles.

In the study conducted, metallurgical tests, including visual observation, hardness test, microstructure test and chemical composition, were performed to describe the causes of damage. From the analysis of the material, it was found that the damage occurred mainly on the outer ring. One of the causes of the damage may have been an increase in temperature due to the constant frictional load on one side of the ring raceway. Another cause of the damage may have been thermal softening resulting from continuous loading, causing a reduction in hardness and tensile stress.

The above analysis of the presented selected bearing failures in service in rail vehicle bearings shows that identifying the cause of the damage is inconclusive. Each damaged bearing should be analysed individually depending on the material from which it is made and its function in the construction of the vehicle. Various approaches are at work in the methodology of rolling bearing damage in rail vehicles. A simplified approach, where the condition of bearings is assessed only on the basis of visual evaluation of the condition of the bearing components, without analysis of the system environment, and a comprehensive (extended) approach where the methodology is based, for example, on the one specified in VDI 3822 Failure analysis – Fundamentals and performance of failure analysis, and for bearings additional VDI sheets such as:

- VDI 3822 Blatt 1.1:2021-12: Draft failure analysis – Failures caused by mechanical loading.

- VDI 3822 Blatt 1.3:2017-06: Failure analysis – Failures on metal products caused by tribology working conditions.
- VDI 3822 Blatt 1.4:2011-10: Failure analysis – Failures caused by thermal loading.

The underlying objective of this article is to identify the root causes of bearing node failures of rail vehicle wheelsets. Another goal is to identify areas where special attention should be paid to minimise the risk of derailment of rail vehicles. At issue here is the risk in the aftermath of a broken axle of a wheelset as a direct result of damage to the rolling bearings seated on the axle journals. The study also aims to provide a preliminary assessment of wheelset bearings' criticality. This assessment should be viewed as an evaluation of the potential for defining these components as safety-critical elements, according to regulations implemented under the so-called fourth railway package. This publication's analysis focuses primarily on cylindrical roller bearings and tapered roller bearings, which are most suitable for use in the axleboxesof rail vehicle wheelsets.

The paper presents a recommended methodology for analysing the failure of the bearings of a rail vehicle's wheelset. It was important that the end result of the analyses was the correct identification of the root cause of bearing failure. Such complex studies are not available. From the observations of the authors of this publication, it appears that damage analyses of railway-vehicle-bearing nodes are not carried out in a systemic/structured manner. According to the above, this can lead to the definition of incorrect conclusions of the root causes of bearing failures and, thus, to the faulty definition of corrective and preventive actions.

MATERIALS AND RESEARCH METHODS

This publication's analysis focuses primarily on cylindrical roller bearings and tapered roller bearings, which have the greatest potential for use in the carriage axlebox nodes of rail vehicle wheelsets.

Materials used

Until 2002, Poland had the standard PN-H-84041:1974: Steel, describing the characteristics of rolling bearings. The standard indicates steel with the designation ŁH15 and steel with the designation ŁH15SG as the most commonly used bearing steels. These steels were used, among other things, to produce rolling bearings for rail vehicle wheelsets and were directly indicated in industry standards (BN-71-1131-07 1971) [13]. In this work, damaged bearings made from the equivalent of ŁH15 steel and ŁH15SG steel were analysed. The chemical composition of these steels is defined by the standard PN-EN ISO 683-17:2002 (the version currently in force is PN-EN ISO 683-17:2015-01), which replaced the PN-H-84041:1974 standard. Table 1 shows the chemical composition of these bearing steels.

In addition, an important standard is also PN-EN 12080:2017-10, which specifies a number of requirements that bearings and their components should meet. Table 2 provides a summary of the most important bearing requirements.

Description of research methods

A proper analysis of the causes of damage to the wheelset bearings of rail vehicles should include more aspects in addition to testing and analysis of the bearing. A comprehensive analysis should include, among other things, an assessment of development conditions, load conditions, and geometry of related components. In order to systematize the issue of damage research, a recommended research method for assessing the causes of damage to wheelset bearings has been developed and is presented in Figure 2.

Figure 2 shows schematically the recommended steps that should be used when analyzing the failure of wheelset rolling bearings. The scheme was developed based on the guide VDI 3822 [16] and was applicable to the analyses conducted for this publication. Additionally, the

Table 1. Chemical composition of bearing steels according to PN-EN ISO 683-17:2015-01 [14]

Chemical composition of steel (mass concentration of element, %)											
Grade	C	Si	Mn	Cr	P	S	Ni	Cu	Mo	Al	O
100Cr6	0.93–1.05	0.15–0.35	0.25–0.45	1.35–1.60	Max 0.025	Max 0.015	-	Max. 0.3	0.1	Max 0.05	Max 0.0015
100CrMo7	0.93–1.05	0.15–0.45	0.25–0.45	1.65–1.95	Max 0.025	Max 0.015	-	Max. 0.3	0.15–0.3	Max 0.05	Max 0.0015
100CrMnSi6-4	0.93–1.05	0.45–0.75	1–1.2	1.4–1.65	Max 0.025	Max 0.015	-	Max. 0.3	0.1	Max 0.05	Max 0.0015

Table 2. Key requirements for wheelset bearings from PN-EN 12080:2017-10 [15]

Bearing element	Parameter	Requirement
Rings and rolling elements	Surface hardness	Rockwell hardness (HRC) 57-66 HRC. Difference between rings in a given bearing and between rolling elements - max 4 HRC.
Inner and outer bearing rings	Dimensional stabilisation	Heat treatment to retain dimensional stability for operating temperatures up to at least 150 °C.
Inner rings	Dimensional stabilisation	For rings heated during assembly, dimensional stabilisation up to 200 °C is required.
Rings and rolling elements	Inclusion content	Acceptance criteria in accordance with PN-EN ISO 683-17, Tables A.1 and A.2.
Cage	Material	Steel and riveted brass cages are not allowed. Preferred materials: polyamide PA6 or PA66 reinforced with glass fiber at about 25%.
Complete bearing	Dimensions tolerances and clearances	According to the technical specification.
Complete bearing	Approval procedure	Two approval procedures depending on the degree of innovation/scope of changes - full procedure and simplified procedure. Details are provided in Appendix E of the standard under review.

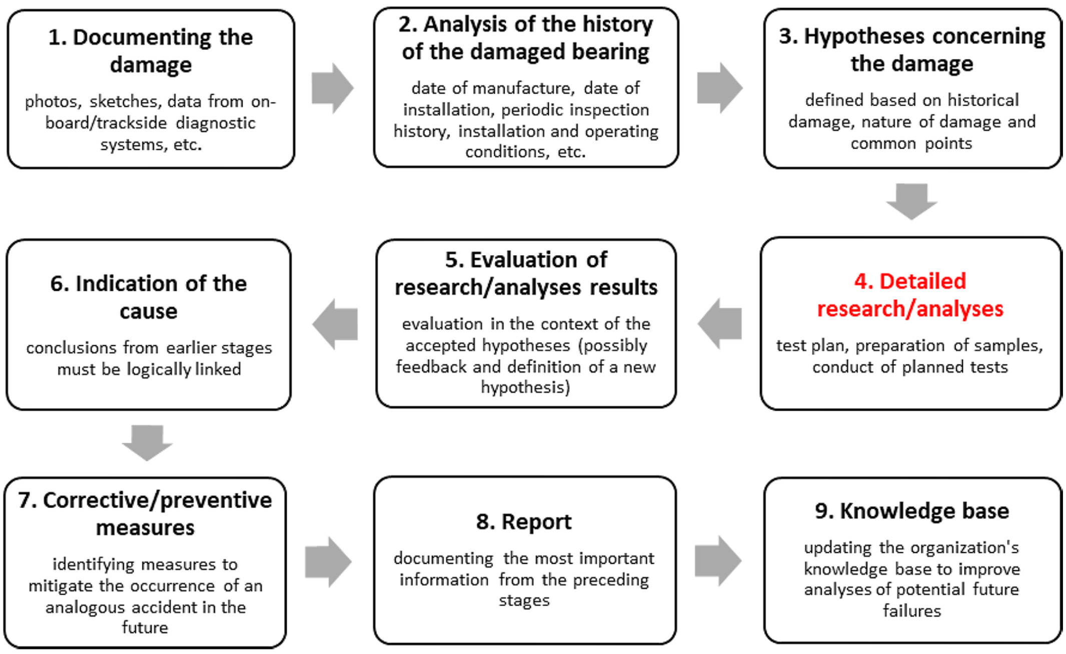

Figure 2. Block diagram of the research method for analyzing the cause of damage to wheelset bearings

guidelines for in-depth investigations/analysis (Step 4, Figure 2) have been further expanded as one of the key steps in determining the causes of failure. The guidelines in this regard are shown schematically in Figure 3.

From the point of view of the correctness of the assessment, it is not required in every case to carry out all the tests/analyses/simulations that are shown in Figure 2. The final research plan may include only selected steps, which requires individual evaluation by the expert team analysing the damage data. At the same time, assessment of the condition of the bearing surface layer, lubricant tests and measurements of basic geometric characteristics (if the condition of the node allows for it), should be carried out in each case and should be considered as basic steps. Table 3 presents a list of the apparatus, tools and software used for detailed studies of damaged bearings, along with an indication of the entities to which each study was outsourced.

The following types of bearings, lubricants and sealing systems were analyzed as part of the study:

- a pair of cylindrical roller bearings NJ+NJP/WJ+WJP 130x240 with polyamide cage – manufactured by SKF/KINEX Companies, Turmogrease 802 grease (Shell Company), non-contact labyrinth seals – 10 cases were analyzed,

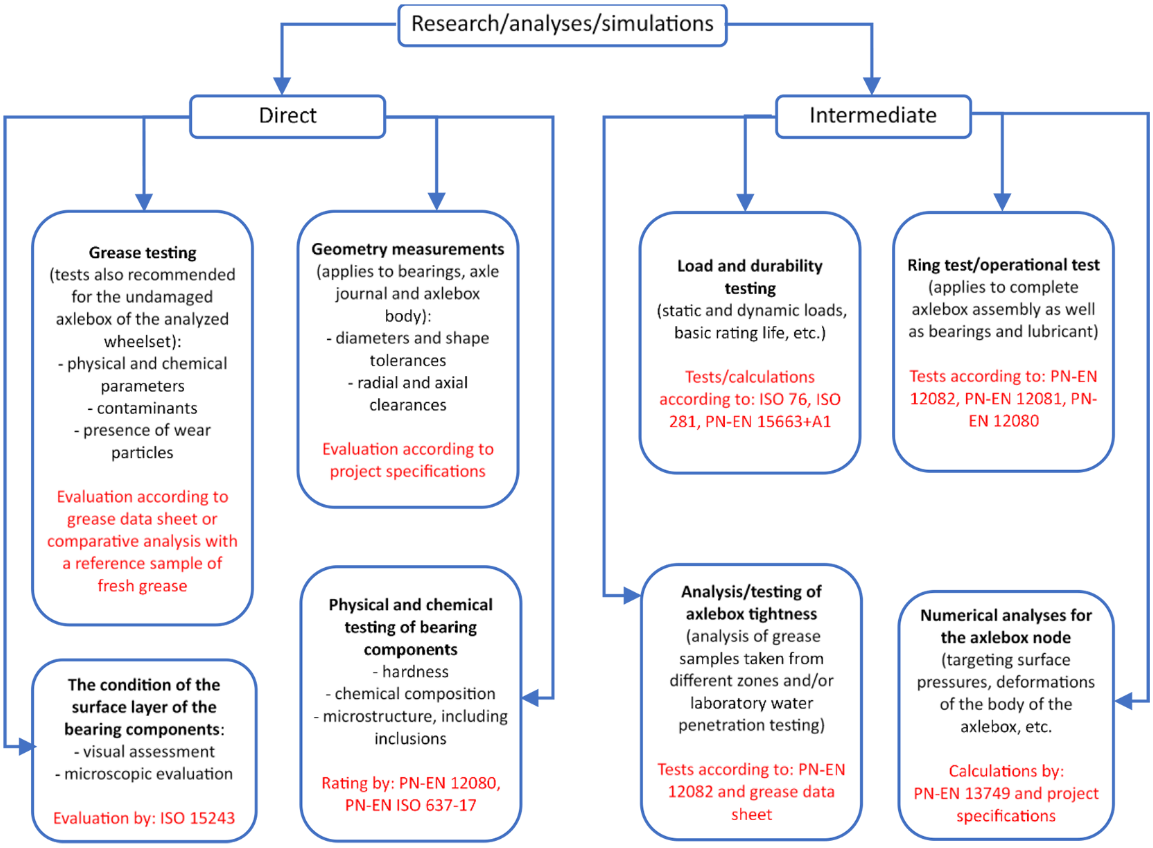

Figure 3. Expanded block diagram of the research method applied for step 4 from Figure 2

Table 3. List of apparatus, tools, and software used in the detailed analysis of the causes of bearing damage

Place	Performed by	Apparatus used, tools, software
Grease test	Ecol Laboratory Ltd.	Apparatus according to test procedures - accredited laboratory meeting the requirements of PN-EN ISO/IEC 17025
Geometry measurement	Research	ROMER measuring arm, as well as diameter and micrometer gauges
Analysis of the surface layer of bearing components	Research	EVO-CAM2 microscope camera, KERN OLM 171 inverted metallographic microscope, Keyence VHX digital microscope
Physical and chemical testing of bearing components	Lukasiewicz Research Network - Institute of Ferrous Metallurgy	JEOL JSM-7200F scanning electron microscope equipped with DEBEN BSE detector and EDAX EDS detector, Octane Elite Super model
	Research	Hitachi PMI Master Pro 2 spark spectrometer. ERNST eDynatest hardness tester with a measuring load of 100 kgf
Bearing life calculations	Research	Analytical calculations based on ISO 76, ISO 281 Analysis using SKF SimPro Quick and SKF SimPro Expert software
Numerical analyses for the axlebox node	Not applicable	Existing analyses dedicated to the projects analyzed were used - ANSYS
A bench test of a complete axlebox node	IMA Materialforschung und Anwendungstechnik GmbH	Dedicated test stand as in Figure 4, accredited laboratory

- compact tapered roller bearing unit (CTBU) 130×240×160 made by SKF Company, MOBILTH SHC100 grease, contact and labyrinth seals integrated into the bearing - two cases were analysed.

In addition, a very important part of the analyses, conducted in parallel with the damaged bearings survey, was a statistic analysis of all hazardous incidents based on data published by the European Railway Agency. Within the scope of this study, hazardous

Figure 4. Rail vehicle wheelset bearing test stand (photo: Laboratory of IMA Materialforschung und Anwendungstechnik GmbH, Dresden)

events were selected whose direct, indirect or primary cause was linked to the failure of rolling stock wheelset bearings. Data from 2002 to February 2023, available on the European Railway Agency website [17], was analysed. The analysed data refers to incidents from all EU member states investigated by National Investigation Bodies - NIBs (in the case of Poland, it is the State Commission for Investigation of Railway Accidents) and is published based on articles 19–25 of Directive 2016/798, including copies of reports of completed investigations, so it is a very valuable and reliable source of information on individual incidents and their direct and root causes [18]. As part of the statistical analysis of hazardous incidents related to damage to wheelset rolling bearings, entries (so-called safety alerts) were published using an IT tool (Safety Alerts IT Tool) provided by the European Railway Agency [19].

Measurement analysis results

Due to the wide range of research and analysis conducted, this publication only presents selected results, the ones which are most relevant from the point of view of final assessment. As part of the detailed research conducted on twelve cases of rolling bearing damage to the wheelsets of rail vehicles analysed in the study, the following nature of bearing damage was identified, according to the classification presented in ISO 15243:2017:

- surface-initiated fatigue – was identified in 8 out of 12 bearings tested,
- abrasive wear – was identified in 9 out of 12 bearings tested,
- moisture corrosion (corrosion due to moisture/water presence) was identified in 4 out of 12 bearings tested, with signs of corrosion identified for both solutions based on NJ+NJP/WJ+WJP cylindrical roller bearings (open) and CTBU compact bearings,
- fretting corrosion – identified in all cases analysed. Fretting corrosion occurred between the bearing's outer ring and housing as well as between the spacer ring and the bearing's inner ring,
- current leakage erosion – micro craters were identified for 6 bearings analysed
- false brinelling – one case identified,
- indentations from particles were identified in all cases analysed.

Figure 5 shows a selection of the damages described above. Microstructure analysis of 6 samples taken from two randomly selected damaged NJ/NJP bearings showed no abnormalities. The samples were taken from the outer raceways, inner raceways and rollers - one bearing made by SKF, the other by KINEX. The structure of the steel was as expected (it corresponded to the structure typical of bearing steels), i.e. fine-grained martensite and fine carbides - Figure 6. The presence of isolated non-metallic inclusions was revealed. Plastic deformation was noted directly in the raceway zone and rolling surface of the rollers as a consequence of the bearing degradation process.

The lubricant present during the bearing operation was also analysed. Lubricant tests were conducted for all twelve cases analysed. A total of forty-eight lubricant samples were tested. The lubricant for testing was taken from both the damaged bearings as well as from the bearings located on the opposite side of the wheelset from two zones for each axle box (outer zone - from the side of the axlebox cover and inner zone from the side of the wheel). Table 4 shows the test results for two different vehicles with similar mileage, similar loading conditions, and equipped with two

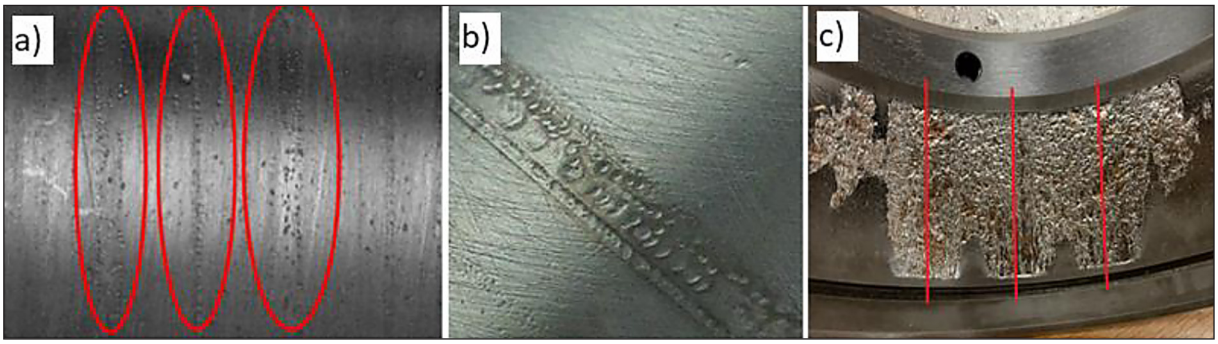

Figure 5. Photographs of sample damage: (a), (b) current leakage erosion, (c) moisture corrosion (photos: P. Biel)

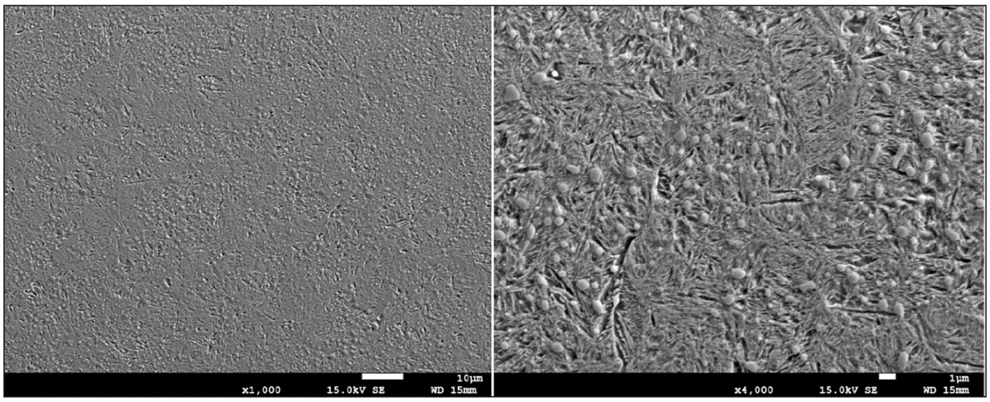

Figure 6. Microstructure of a sample taken from the outer race of an NJ bearing, 100 CrMo7 steel, from SKF Company – prepared by Institute of Ferrous Metallurgy in Research paper report no. N0-0912. Gliwice, 2021

Table 4. Results of tests on lubricant samples

Zone		Vehicle 1, Mobil Mobilith SHC 100 grease, CTBU bearing 130x240x160				Vehicle 2, Turmogrease 802 grease NJ+NJP bearings 130x240			
		Mileage to bearing failure 370,000 km				Mileage to bearing failure 360,000 km			
		Axlebox 1		Axlebox 2		Axlebox 1		Axlebox 2	
		External	Internal	External	Internal	External	Internal	External	Internal
Wear									
Iron	ppm	219	364	8006	11745	13011	6652	1231	268
Chrome	ppm	18	30	210	255	1151	918	18	6
Aluminium	ppm	1.6	4.8	10	17	202	268	3	3
Copper	ppm	87	24	52	137	117	253	126	5
Manganese	ppm	<2	6.6	81	90	2887	1296	14	7
PQ index	-	152	222	75500	>200000	>20000	10000	215	56
Contaminants									
Silicon	ppm	5.8	22	66	101	635	802	16	14
Water content	mg/kg	1062	1310	1516	2314	1820	4720	903	393

different types of bearings. Open-ended cylindrical roller bearings with non-contact labyrinth seals and a second case equipped with CTBU bearings - a compact tapered roller bearing unit with contact and labyrinth seals - are presented. The content of wear particles, including the PQ Index, which indicates the content of ferromagnetic particles regardless of their size, has been shown to correlate with the degree of bearing degradation. At the same time, no noticeably higher failure rate was observed for bearings located on the wheel side, which are more exposed to external contaminants due to the labyrinth seal system. Bearing failures included cases where lubricant testing indicated the presence of contaminants such as silicon (sand/dust from outside) and water, with no cases where the presence of these contaminants was critically elevated, as well as cases for which no elevated contaminant content was found. It should be assumed that in the cases analysed, for which the penetration of contaminants from outside was found, their presence was not the primary cause of the damage but could be an accompanying factor, accelerating the wear process.

In addition, elevated water content was also noted for CTBU-type bearings, against which one would expect satisfactory sealing due to the integrated contact seal system.

Another test performed, which could contribute some information explaining the causes of bearing damage, was a study of chemical composition of the bearings components. Chemical composition testing was performed for all twelve cases analyzed, both for the bearing raceways and for the rolling elements. The test results showed no abnormalities. Table 5 shows selected results of chemical composition tests.

Hardness tests were also performed on bearing components using the ERNST eDynatest hardness tester.. These tests also showed no abnormalities. The hardness of the tested bearing components was in the range of 59-62 HRC, which is appropriate for bearing steels. The tested bearings met the requirements of PN-EN 12080 2017 in terms of physical and chemical properties.

The analysis of the causes of damage to the twelve rolling bearings found that the damage was caused by the following root causes:

- intrusion of external contaminants and/or contamination of the lubricant at the stage of installation and maintenance activities,
- false Brinell imprints (indentations) - damage under shock radial loading,
- electrical erosion in the raceway zone of the bearing rings and the rolling surface of the rollers.

As the presence of water was also observed in the CTBU bearings, not only in the design of the labyrinth seals, but also the washing of the vehicle chassis with pressure washers and directing the water jet directly into the zone of the contact seals and non-contact labyrinth seals should be considered as the cause of water intrusion. False Brinell inprints can be a consequence of the condition of the railroad infrastructure (radial shock loading).

The causes of electrical erosion were not clearly established (no problems were identified on the side of the bracing system, protective resistors on the side of the analyzed vehicles. The condition of the return circuit on the infrastructure side should be considered as one of the possible causes of phenomena of this nature.

Table 5. Results of the study of the chemical composition of damaged bearing fragments

Specification			Chemical composition of steel (mass concentration of element, %)									Grade to ISO 683-17
			C	Mn	Si	P	S	Cr	Mo	Al.	Cu	
Manufacturer SKF	Bearing 1	Outer ring	0.98	0.42	0.31	0.005	0.003	1.8	0.2	0.006	0.05	100CrMo7
		Inner ring	0.96	0.3	0.33	0.006	0.003	1.8	0.21	0.005	0.03	100CrMo7
		Roller	0.93	0.3	0.34	0.013	0.009	1.4	0.07	0.03	0.3	100Cr6
	Bearing 2	Outer ring	0.92	0.35	0.29	0.008	0.005	1.78	0.18	0.008	0.09	100CrMo7
		Inner ring	0.95	0.38	0.32	0.009	0.003	1.8	0.22	0.004	0.1	100CrMo7
		Roller	0.94	0.4	0.31	0.01	0.008	1.45	0.08	0.06	0.18	100Cr6
Manufacturer KINEX	Bearing 3	Outer ring	0.904	1.06	0.577	0.001	0.01	1.48	0.076	0.029	0.03	100CrMnSi6-4
		roller	0.95	1.12	0.616	0.001	0.009	1.56	0.055	0.03	0.03	100CrMnSi6-4

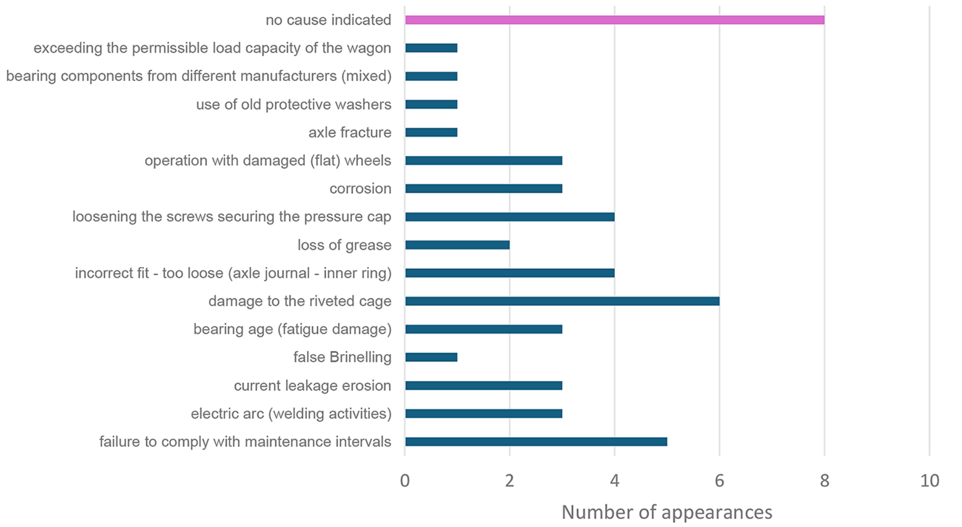

Figure 7. Causes of damage to wheelset roller bearings based on reports from National investigation bodies

Analysis of publication data based on European Railway Agency Sources

The analyses evaluated 3735 investigations conducted by the national investigative authorities of EU member states following accidents within the rail system. At the time of analysis (as of February 28, 2024), 264 investigations had an "open" or "in progress" status, while the remainder had a "closed" status.

Among the analysed incidents, accidents that, according to the committees (NIBs) investigating individual incidents, were associated with damage to the wheelset bearing(s) were selected and analysed in detail. During the period under review, 41 such events occurred, which were analysed in detail for the purposes of this publication. In 35 cases, the axle journal broke due to high temperatures during the final phase of the axlebox node failure, resulting in derailment. Figure 7 shows a detailed summary of the causes of damage to wheelset roller bearings. Causes clearly identified during the study and those deemed most likely by the committees are indicated.

Analyses of security alerts published using the Safety Alerts IT Tool show that 2 incidents related to damage of rail vehicle wheelsets rolling bearings have been reported since 2016. The incident on 25/01/2023 involved a passenger vehicle, and the root cause was the loosening of the bolts holding the bearing inner ring pressure cap, resulting in increased axial play and subsequent bearing failure. The second incident, dated 08/02/2024, involved bearing damage on 8 freight car wheel sets (bearing mileage did not exceed 10,000 km). In the case of this incident, as of 20/04/2024, the results of the analyses of the causes of the accident were not available – the investigation is ongoing.

An analysis of data published through tools provided by the European Railway Agency (a total of 3737 entries were analysed) shows that damage to the rolling bearings of wheelsets can lead to dangerous events resulting in derailment of rolling stock and, therefore, to events categorised as accidents and serious accidents. The most common causes of bearing damage were damage to the riveted cage, irregularities at the maintenance stage, including exceeding maintenance intervals, and loosening of the pressure cap mounting bolts (exceeded axial play). It should be noted that PN-EN 12080:2017-10 does not allow the use of riveted cages in new vehicles.

CONCLUSIONS

The paper attempts to demonstrate the root causes of bearing node failure of rail vehicle wheelsets. The research conducted, and the results of a comprehensive analysis of data published through the European Railway Agency indicate that some of the most significant causes of damage to wheelset roller bearings, which consequently lead to hazardous events, are:

- damage to riveted cages, due to their limited resistance to impact loads;
- irregularities at the maintenance stage (including failure to comply with inspection intervals);
- lack of sufficient supervision and/or failure to properly secure the bearing pressure cap mounting bolts;

- intrusion of external contaminants and/or contamination of the lubricant at the stage of installation and maintenance activities;
- false Brinell imprints (indentations) - damage under shock radial loading;
- electrical erosion.

Regardless of the need to implement measures aimed at eliminating the above-mentioned causes of damage to wheelset bearings, it is also recommended that on-board systems be used to monitor the condition of the structural node in question, using vibration and acoustic signals and/or a diagnostic method based on temperature measurements in the bearing zone. The use of this type of system will significantly reduce the risk of a serious accident in the event of failure of the wheelset rolling bearings. In addition, an action of this nature will allow the capture of failure conditions at the initial stage of bearing damage, facilitating the identification of root causes of failure and thus defining appropriate corrective and preventive actions.

As damage to wheelset bearings led to dangerous incidents categorised as serious accidents, consideration should be given to classifying axlebox bearings as safety-critical components as referred to in the Directive (EU) 2016/798 of the European Parliament and of the Council of May 11, 2016, on railway safety, particularly for rolling stock not equipped with on-board systems for monitoring the condition of wheelset bearings. The final assessment of the safety criticality of wheelset bearings should be carried out in accordance with the rail industry's accepted methodology. In this context, it is recommended to use the technical report CEN/TR 17696 Railway applications – Vehicle maintenance – Guidelines for the identification and management of safety-critical components in railroad vehicles.

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