Project in railway technology

Damage from electric discharge in axle bearings on trains

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Abstract

A summary of known information on damage in bearings due to electrical currents, with a special focus on railway applications is provided. The process of inspection of a possibly damaged bearing is described. Results are compiled, also providing some suggestions on handling the damage. Finally, all results are connected with each other. Some proposals for solutions of the current problem are given and some points of interest for further research are highlighted.

Keywords: railway, bearing, axle, carriage, electric current, damage, pitting, fluting, wash-boarding, electrical erosion, axle box, bearing box, Electrical discharge machining

Acknowledgements

We would like to thank our supervisor Anders Ekberg for guiding us through the process of creating this report, supplying us with the necessary basics and literature for a good start and of course helping us establish contact with industry experts and connections with companies that are of relevance for the treated topic. Furthermore, we want to thank Roger Deuce from Alstom as well as Per Wessling from SJ for answering some of our questions and giving us more advice on the discussed problems. Last of all we would like to thank SweMaint AB for allowing us into their workshop and showing us the steps of maintaining a train axle as well as opening up several out-of-use bearings and giving one to us for further investigation.

Contents

1
Introduction

1.1 Aim

The aim of this report is to provide a further understanding of the problems caused by electrical damage to bearings in the railway sector. It seeks to answer why and how these problems may occur along with some possible solutions. Finally, it seeks to highlight some real-world problems regarding the subject together with valuable insight from industry experts.

1.2 Background

The amount of people and goods transported by trains keep rising. This leads to an increased necessity of having reliably working rolling stock. However, concern arise regarding the impact of electric current going from the overhead catenary through the train and power electronics into the rails through the axles and how this influences the bearings of the axles and potentially creates problems. In order to optimize the efficient usage of rolling stock and to prevent future problems or accidents, an investigation will be conducted into the extent of this matter.

In the past, there have been several incidents, including severe derailments that were traced back to a fault in the axle bearings. While faults in the tracks and human errors are the cause of most accidents at low speeds, the problem of bearing failures is more frequent at higher speeds where the consequences also can be greater. Bearing failures are mainly due to overheating (by friction or otherwise), the influence of electrical current is not necessarily given [1]. However, electrical current going through a bearing could increase the wear of the material and lead to incidents like that occurring earlier.

1.3 Consequences

Unwanted electrical currents through the bearings have been known to degrade and damage axle bearings on trains under certain conditions. With high-risk items such as axle bearings that may cause a derailment if damaged, a good understanding of all the deteriorating factors plays a crucial role in maintenance and safety. Thus the industry has shown interest in more research on this topic to help improve RAMS (Reliability, Availability, Maintainability, and Safety) in the asset management of trains and locomotives.

2

Theory

2.1 Types of electrical damage in bearings

A large part of electrical damage in metals, and therefore also in bearings, is due to electrical erosion. This type of damage, according to Tallian [2], can be described through the following: "Electric erosion is damage to contact surfaces caused by the passage of electric current."

Other failures or types of damage caused by electric erosion can also be electrical pitting, electric current damage, current erosion, and spark erosion.
Electrical pitting are small craters or cavities on the conductor's surface caused by localized damage brought on by extreme heat. Electrical components can be harmed by excessive or irregular electrical current flow, which is known as electric current damage. Current erosion is the gradual degradation or wearing away of a conductor brought on by the flow of electrical current. Spark erosion is surface damage from repeated electrical arcing or sparking that results in material degradation and removal. Another very common occurrence connected with erosion is cratering, where sparks caused by the electric current heat small areas of the metal to a very high temperature. Then the affected material is torn off, leaving small craters in the surface. Furthermore, the material surrounding the crater might get tempered, leading to softening. If the sparks hitting the metal surface are even stronger, and cause higher heating on a larger area, rehardened material (melted by the high electric currents from the spark and then cooled down until solid again) can be created, which can lead to micro-cracks forming in that area [2].

Two different, distinctive appearances of electrical erosion in metals are electric pitting and fluting.
Electric pitting describes surface craters which are approximately conical, that are created by the material melting and then breaking away, as described above. These pits are generally very small and might need magnification to be identified.
Fluting, also called wash-boarding, on the other hand, affects large areas of the metal's surface. It is caused by ongoing electric erosion for a longer time, leading the metal to appear as if it had a surface covered with evenly spaced lines (called flutes or washboard). However, when taking a closer look, it becomes evident that these depressions are in fact lines of pits, with more or less unchanged material in between [2].

Some different types of damages caused by electric erosion are described by Tallian [2]:

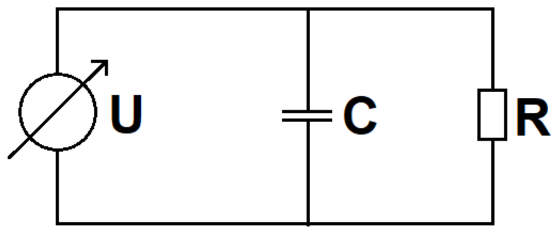
- Electrical erosion pitting: A rehardened layer is built up on top of an overtempered one at the pit bottom surface after an overheating of the metal. This creates extremely noisy bearings which can fail quickly due to fluting or spalling. Electric erosion pitting is caused by sparks, generated by current flowing through the bearing and penetrating the surface of the metal causing a localized removal of material and the creation of craters or pits.
- Electrical erosion pitting combined with a shallow entry spall: Electric erosion leads to pits, which can form a cluster, and in turn create a spall. The surface is melted or eroded by sparks, which create pits. If these pits occur close together, spalling can take place. This causes the bearing to fail due to rapid progressing of the deterioration.
- Electrical erosion pitting combined with multiple spalls: This is caused by a line of electrical pits, that can be detected along a larger circle. It makes the bearing extremely noisy and strongly increases the wear. It is again created through electrical pitting, this time occurring along a line rather than throughout the surface or in the vicinity of one point.
- Electrical erosion pitting combined with glazing, scratch and kinematic wear marks: This damage is created through long-term pitting with low currents, leading to a high number of craters. Over time, the higher edges of the pits get rolled down (because of the movement of the bearing), which is called glazing. The wear marks occur due to different imperfections in the material, which are worsened by the considerable surface harm brought on by electrical erosion.
- Electrical erosion pitting combined with sharp individual dents from metal debris: Electric erosion can remove small pieces of the metal from the surface. If these small pieces are then rolled over through sparks heated (melted) material, they form sharp dents in the surface. The raised edges of these dents can then again be rolled down, leading to additional glazing (as before).
- Electrical erosion pitting combined with a corrosion stain: A large pit can be created by a high current passing through the bearing while it is stationary. Corrosion stains can then occur on the roller path. This leads to an immediate bearing failure and makes it unusable. However, this is not a damage caused by normal usage and is therefore not relevant for the topic of this report.
- Electrical erosion fluting: Evenly spaced depressions transverse to the rolling surface are created by continuous current flow above a minimum strength, leading at first to pitting and in the course of that to the fluting. This makes extremely noisy bearings and leads to a quick failure of the bearing due to a strongly increased wear. The reasons for this phenomenon are not fully known yet, however, it is believed that the vibratory conditions lead to more current flow at minimum separation points, creating a self-reinforcing scheme.
- Electrical erosion fluting combined with glazing: Flutes are created with dense cratering in them. These craters have sharp, raised edges, that are rolled down (glazed) while the bearing is in use. This leads to additional surface distress and as before to strongly increased noise and material wear. Again, the reason for this is not completely clear, but is said to arise from the vibrations of the

bearing.
It is generally accepted that continuous spread of electrical damage on the bearings happens when the train is in motion while individual surface defects and craters are created when the train is standing still or moving very slowly [3].

2.1.1 Damaging currents in bearings

Axle bearings on trains can be of several designs but are all steel grease-lubricated roller contact bearings [4]. During low-speed operation there exists a metal-to-metal contact path between the inner and outer raceway and the bearing has a lower impedance. During medium and high-speed operation the grease forms a film that separates the rollers from the inner and outer raceways and the bearing has a higher impedance given insulating greases are used [5, 4, 6, 7].
Electrically, a roller bearing can be thought of as an ohmic resistor and a capacitor in parallel. In figure 2.1, U represents the potential across the bearing, R represents the resistance, and C represents the capacitance [5, 8, 7]. This combined effect of the capacitance and the resistance of the bearing is referred to as the impedance of the bearing.

Figure 2.1: Simple circuit diagram of a bearing



The oil-film thickness (and therefore also the impedance of the bearing) changes with regard to temperature, grease starvation, speed, load, type of grease, geometry, and surface finish among other factors [5, 8, 4]. This means that different currents and voltages affect the bearings differently depending on all the factors mentioned above. When the bearing is stationary or operating at low speed the bearing will typically not experience arcing electric discharge machining (EDM) currents due to lower resistance caused by the metal-to-metal contact [9, 6, 5].

When discussing damaging bearing currents a commonly used term is the "apparent bearing current density" J_b which is the relation between the peak current through the bearing $\hat{I}_b$ and the Hertzian contact area A_H [9, 6].

$$J_b = \frac{\hat{I}_b}{A_H} \tag{2.1}$$

Generally, a bearing current density of less than 0.1 A/mm^2 is deemed safe for direct and low-frequency alternating currents [10, 9].
The Hertzian contact area A_H of a given wheelset bearing can be calculated as seen in [11], however accurate calculations of the Hertzian contact surface of a rotating

bearing are difficult since they depend on surface roughness, load, and on the oil film thickness [11, 6].

During high-speed applications, where the inner and outer raceways are electrically separated and the impedance of the bearing is predominantly capacitive, EDM and capacitive bearing currents (dV/dt currents) can occur. EDM currents can happen when the potential over the bearing exceeds the breakdown voltage of the grease between the bearing elements. This can create very high current densities due to the very small affected area of the arcing[5, 6, 7]. Under this state of electrical breakdown of the grease, the bearing impedance goes from being mostly capacitive to mostly resistive again. It's also been shown (on other bearings) that electrical breakdown of the grease can be caused by field strengths of over 29 volts per micrometer of lubricating film thickness but can be sustained with field strengths as low as 10 $V/\mu m$ [7]. SKF suggests a maximum of 0.5 V over the bearings in order to prevent damage due to EDM currents [10].

2.1.2 Possible further consequences

Because the before-mentioned types of damage due to electric current passing through a bearing may in some cases be very small, one could be tempted to say that they could not have a great impact on the reliability and lifetime of the bearing. However, the small defects can lead to further, larger consequences. By not noticing the damage and therefore not replacing the bearing after an appropriate time, the defect can keep on growing until a bearing failure takes place. As a consequence of the small electric crates (which can be microscopic) described before, these faults can add up to create washboarding and fatigue cracks in the rolling elements or raceways of the bearing. Further, this could lead to either rolling elements getting stuck or breaking, which brings an extremely high risk of the bearing overheating. Furthermore, the build-up of bigger craters, spalls, or depressions on the raceway without noticing it for a long time could lead to the bearing rim breaking and possibly causing a derailment of the railway car [10]. As seen in several incidents, an overheated or damaged bearing can cause fatal accidents, for example recently in Ohio [12]. It is also to note that electrical arcing in the bearings can affect the bearing grease, which can also drastically shorten the grease and bearing service life [4, 10, 6].

Recalling that damage through electrical currents going through a bearing can occur already if the voltage exceeds 0.5 V and is expected to be potentially harmful at an electric current density of more than 0.1 A/mm^2, which are extremely small values compared to typical currents connected with the railway industry, it is necessary to be very careful in inspecting these types of damage and not neglecting any possible problems, as the potential outcome could be fatal [10].

2.1.3 Plausible causes

Effects like EDM damage due to tribocharging or other similar forms of self-induced electric charge are not deemed plausible. This leaves only the electrical system of the train/locomotive and the infrastructure of electrified railways as probable causes for the electrical damage to wheelset bearings.

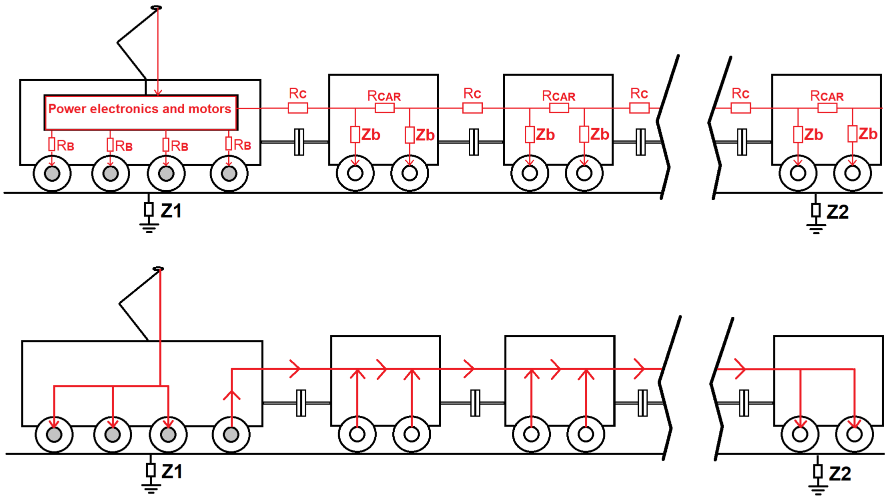
2.1.3.1 Freight cars

Axle bearings in freight cars are typically not insulated, nor brushed, this is true for every rail car in Sweden [13]. One tested theory on why electrical erosion of the bearings happens on freight cars is that a bad ground connection of the grounding rail at the locomotive causes electrical currents to pass through the train couplings in similar ways as shown in figure 2.2. This phenomena could be exacerbated when locomotives without isolated couplings and freight wagons with low resistivity through the bearings are used in conjunction [13, 14, 3].

In [13, 14] it was examined in detail how the current flows (including through the couplings) through iron ore trains in the north of Sweden hauled by Bombardier's IORE-locomotive where the freight cars axle-bearings had experienced a sudden uptick in electrical damage.
That specific locomotive had several carbon brushes for the return current from the drive system as well as one brushed axle at the rear end of the locomotive that was used to ground the train chassis and the locomotive coupling to the track. This created a low-impedance path for the return current in the track to also flow through the train's couplings. This together with bad grounding of the track (several faulty ground connections and a broken electric connection between two sections of the rail) and newer and heavier train cars (large currents and slimmer oil films in the bearings due to the higher axle loads and newer bearing types) caused a high current to flow through the couplings and through the last car(s) into the ground rail and thereby damaging the bearings [13, 14, 3]. This specific unwanted current path for the return current is shown in yellow in figure 2.2.

These unwanted current paths through the bearings of the train cars can also occur when the impedance to ground at the locomotive (in the figure represented by Z1) is higher than the impedance to ground at the end of the train (in the figure represented by Z2). A heavier train and fast changes in speed also increase the current load, therefore also the voltage drop in the rail. Heavy axle loads, higher temperatures, and lower speeds decrease the insulating oil film in the bearings and therefore also reduce the impedance through the bearings (in the figure represented by Z_b) allowing current to flow more easily through them [14].

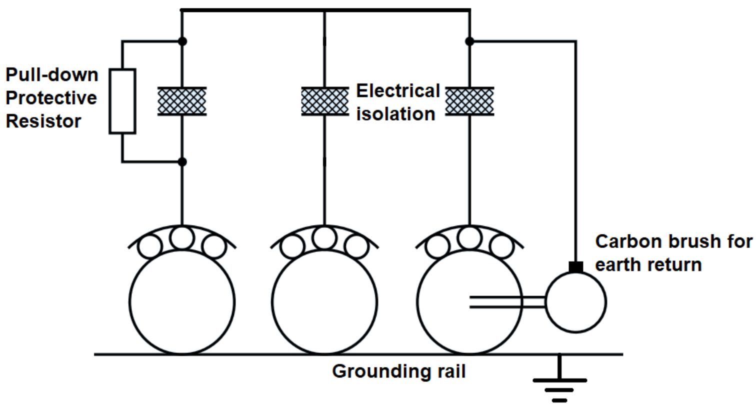
Figure 2.2: Plausible current paths through train cars



2.1.3.2 Electric multiple unit trains and locomotives

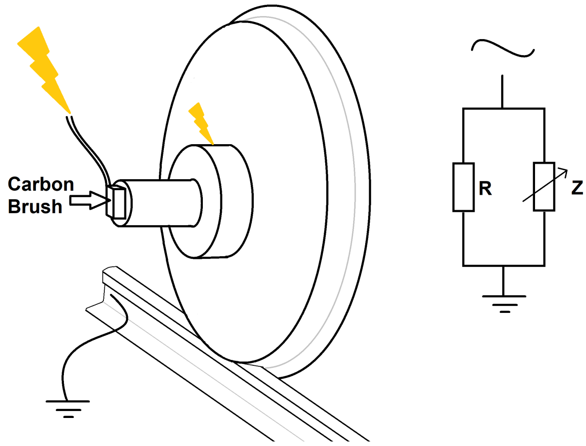
Both electric multiple unit trains or EMUs and electric locomotives use carbon brushes for the earth return. They work as a low ohmic bridge from the train's electrical system to the ground rail [4]. They also use electrically insulated bearings and may use a protective resistor between the outer race of the bearing and the grounding rail through the brushed axles on non-current carrying axles [13, 4]. An illustration of this is shown in figure 2.3.

Figure 2.3: Electrical connection to the grounding rail



If the electrical isolation or the protective resistor were to fail or were designed with too low resistance, a parallel path to ground would form over the bearing. Depending on the resistance of this faulty path to ground (which is likely to change vastly during operation under faulty conditions) enough current could possibly flow over the bearing to cause damage [10]. An illustration of this is shown in figure 2.4 where R represents the resistance through the carbon brush and Z is the varying impedance over the faulty path to ground. Z may vary with oil-film thickness in the bearings along with many other parameters as described in chapter 2.1.1.

Figure 2.4: Faulty ground path through the bearing



Another plausible cause is high dV/dt or EDM currents caused by the high-frequency switching. The effects of high dV/dt currents induced by variable frequency drives and inverters on axle bearings are still not fully understood and might vary between train designs. Whilst electrical damage due to high-frequency switching seems to be more prominent in the motor bearings it can still affect axle bearings under certain circumstances like if the train has a faulty electrical system [15, 10].

2.2 Suggested solutions

Some general suggested solutions to electrical damage in bearings are as follow:

- Conductive grease. Generally it can be said, that damage through electrical erosion increases with decreasing surfaces where the current can flow. In bearings, this means that the electrical erosion increases drastically when a non-conducting lubrication is used. However, although conducting lubricants are available on the market, they are usually designed for lower currents. This means, that for bearings used in trains, the lubricant would not be able to successfully deal with the flow of electricity on its own and protect the bearing in that way.
  Furthermore, even with a perfectly conducting lubrication, it is necessary to make sure that the contact between all the components is good. A problem that could reduce that is the intrusion of a poorly conducting fluid, forming a thin film along the surface of the metal, or the build up of some surface oxide or other deposit [2].
- Electrically insulated bearings (ceramic rollers) such as SKF's INSOCOAT bearings. Though very costly, it would eliminate any electrical damage as a roller of ceramic can not conduct any electricity [10].

2.2.1 Freight cars

A number of possible solutions are suggested in [14] such as:

- Routine maintenance and checking of the grounding of the track.
- Electrically insulated coupling at the locomotive to eliminate the current flow through the train couplings.
- Equip the last car (where most of the current is passing through the bearings) with grounding brushes.
- Equip all cars with smaller, lighter-duty grounding brushes.
- Alter driving style for smoother operation (lower peak currents).
- Install permanent measuring and warning equipment on the loco to warn the personnel of high coupling currents.
- Electrically insulated bearings through conventional means (non-conductive spacers and alike).

2.2.2 Electric multiple unit trains and locomotives

For EMUs and locomotives, the most important part of preventing electrical bearing damage is maintenance and making sure that the brushes, insulation, and potential protective resistors work as they should. More current-carrying (brushed) wheel sets would also decrease the resistance to ground [4].

For damage caused by electrical discharge machining due to high dV/dt currents the following solutions are proposed:

- Usage of isolated bearings [10].
- Revising the electrical system so the high dV/dt (EDM) currents do not form [15].

3

Method

By compiling the different plausible causes and solutions for electrical damage in bearings early, we were able to ask questions to industry experts to gain insight into some of the challenges with implementing the different proposed solutions. These include our mentor Anders Ekberg with many years of experience within the industry and doing research. It also includes a study visit to SweMaint AB that do the renovation of thousands of train car axles every year and email contact and meetings with industry experts from SJ and Alstom.

We also obtained a used freight car bearing from SweMaint AB (of a type that is commonly replaced due to electrical corrosion) for analysis and demonstration purposes.

4
Analysis

4.1 Insight from industry

The different theorized solutions were presented to industry experts as described in Chapter 3. A recurring problem for all proposed solutions was cost. That includes the cost of materials, the cost of maintenance, the installation cost, and the potential downtime during installation.

4.1.1 Specific challenges with potential solutions

- Conductive grease: From the visit to SweMaint it became clear that the type of grease was very important to the longevity of the bearing and the type was strictly specified by the customer or the bearing manufacturer. Many of the bearings they took apart for inspection (of type tapered roller and spherical, not including CTBUs from SKF) had mechanical damage as the main cause for rejects. This means that the property of carrying electricity must not affect any other potential of the grease in a negative way. This would likely also result in a more expensive grease.
- Electrically insulated (ceramic roller) bearings: Again the high cost came up together with a concern of ruggedness (sudden impact loads and alike that can occur during the lifespan of an axle bearing).
- Electrically insulated coupling at the locomotive: Cost and the fact that the industry has been looking to roll out automated train couplings that could also send power back through the train. This could be a problem depending on the future implementation of this technology.
- Equip the last car in a freight train with carbon brushes: The last car in a train is not constant. Making sure that the last car would always be of a certain type would be logistically complicated and time-consuming.
- Equip all freight cars with small light-duty grounding brushes: Expensive and would create another point of failure and requirement for maintenance. It could also be a source of contamination and create wear in many bearings and axle boxes combination. However with sealed bearings inside the axle box this would not be of concern.
- Alter driving style for smoother operation: difficult to implement on many tracks where the time slots between trains are small.
- Installing permanent measuring and warning equipment: Costly, overheating and noise sensors exist today, but from the damage is done.

- Electrically insulated bearings on freight cars through conventional means: Costly and would require a redesign of many components.
- Usage of protective resistors between the bogie and car body to decrease the grounding impedance and or revising the electrical system so the high dV/dt (EDM) currents do not form: We were unable to find any expert to talk to us about this, we assume it would involve a costly redesign on the affected trains.

4.1.2 Other insight from industry

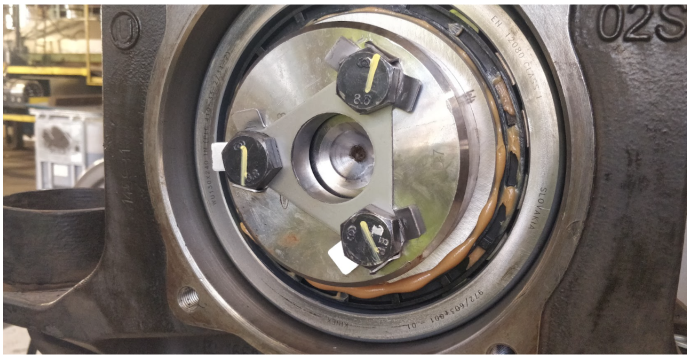
Another insight from our visit to SweMaint AB is the need for a standardized and repeatable way to evaluate the severity of any damage caused by electricity through the bearing. According to the experts at SweMaint they very seldom have any obvious defects from electrical currents in any of the different bearing types they inspect and evaluate further, with one exception. That exception is the new compact tapered bearing units or CTBU's. Those are also the only bearing type they can not or are not allowed to evaluate themselves and have to send away for evaluation. All in all, it costs SweMaint about 2/3 as much to have a bearing evaluated compared to buying a new one outright. The bearings have a very high rejection rate of around 80 % where a majority of the rejected samples were due to stated electrical damage to the bearings. As a result, SweMaint has now stopped sending bearings for evaluation and instead replace them with new ones every time, even when it may not be needed. Not only is this system of evaluation much less economical, it also results in more waste, more carbon emissions, and logistics as the bearings have to be shipped back and forth.

One possibility is that the CTBUs have a lesser impedance than the other types of bearings allowing for higher bearing currents. It could also come down to how thoroughly they look for imperfections and micro-craters in the bearings as the inspections are done by 2 different companies. SKF mention in [4] that "Any bearing with electrical erosion (craters or washboarding) should be scrapped" but does not go into detail on what counts as a crater. It therefore raises questions about what standards the bearings are held to. A mutually agreed and enforceable standard on what types of defects are deemed acceptable would be needed.

4.1.3 Notable insight

One thing to note is that the CTBUs are already sealed before they are placed in an axle box. Therefore it would not be difficult to imagine that an axle box cover with a built-in light-duty grounding brush could be retrofitted as the concern with particles due to brush wear does not exist. It may also be economical to do so on freight cars with this type of bearing as the cause of replacement is so often attributed to electrical damage. It may also be plausible to use the retaining bracket of the machine screws at the end of the axle as a contact surface (see figure 4.1). This would be preferable as it requires only little re-engineering of a serviceable part that is already replaced every time the bearings are taken off.

Figure 4.1: Bearing box without cover



4.2 Inspection of a CTBU roller bearing

From SweMaint, we have obtained a bearing of type CTBU (see below, figure 4.2). Although this bearing does not show any apparent signs of wear or electrical damage, neither on the outside nor inside, it was replaced by SweMaint. As mentioned above, a large portion of these bearings had been deemed to be damaged after external testing, with a majority of them being declared to possess some kind of damage due to electrical erosion. Of three used bearings of the same type, one was taken for further evaluation. Although the chances that at least one bearing would have signs of electrical damage were high, none of the bearings on display had any damage due to electrical erosion visible to the naked eye. After a good and thorough look at each bearing, the one with the most visible wear was taken for evaluation.

Figure 4.2: Roller elements of CTBU

As said before, at first sight, there are no imperfections visible on the roller elements of the bearing. Although it is possible to see thin lines (or rims) running in circles around all the roller elements, these are not connected to electrical damage but rather form through some kind of mechanical process. These lines however should not have any influence on the performance of the bearing and can therefore be neglected in our further inspections of the involved elements.
Another even closer look however shows extremely tiny holes (or pits/craters), highlighted below in figure 4.3, which could potentially be the result of electric influence on the bearing, in this case as before mentioned the process of electrical pitting. There is (at least up to now) no systematic development of this phenomenon, and it has not processed as far as to create periodical depressions (electric fluting). Unfortunately, it is not possible to see anything more than the tiny holes, so in order to detect other features of electrical damage like rehardened material around the edges of the pits, some rims around the craters or a flattening of those, further up defined as glazing. Therefore, another investigation of the rolling elements using microscopic resolution would be very much useful to better describe the detected indents.

Figure 4.3: Found damage on the roller elements

Regarding the obtained information about the state of the bearing elements it can be said that these pits, just as before the lines from mechanical influence, cannot (yet) affect the performance of the bearing. Testing to find out how these impurities develop if the bearing is further used is necessary. An additional hint would be comparing the time that this bearing had been in utilisation with the time that it might be used onwards from this replacement. Evaluating all of these facts against each other would help to make a prognosis about the safety of further usage of that bearing and also the time until replacement is necessary to avoid any dangers.

5
Results

5.1 Causes

The main causes of electrical damage are:

- Faulty paths to ground through the bearings.
- Bad connections between wheel and rail or axle and brush on current carrying wheel sets.
- High coupling currents in freight trains due to ground potential differences in the grounding track over the length of the train or bad connections through the normal current carrying path.

5.2 Insight from industry

- Many of the proposed solutions to the problem of electrical erosion are difficult or expensive to implement in the real world.
- The percentage of used bearings considered defective due to electrical erosion varies a lot depending on the bearing type and who does the inspection.
- There exists a need for a standardized way to evaluate electrical damage to bearings and to what extent electrical damage is considered acceptable.

5.3 Highlighted potential solutions

- Electrically insulated couplings on locomotives.
- Light-duty grounding brush/contact on one axle box of every freight car. Especially if they use the new CTBU bearings within an axle box.
- Better insulation and grounding on locomotives and EMUs.
- Switch to insulated ceramic roller bearings where applicable.
- Conductive grease.

5.3.1 Some challenges in implementation

- Electrically isolated couplings on locomotives: Costly and maybe technically difficult with new automatic couplings.
- Low-duty grounding brush on one axle box of every freight car: Costly and a source of contamination due to wear on some combinations of bearings and axle boxes.

- Better insulation and grounding on locomotives and EMUs: May require redesigns of affected units.
- Switch to insulated ceramic roller bearings where applicable: Expensive and untested.
- Conductive grease: Expensive and may worsen other more important properties of the grease.

6

Further research

6.1 Further evaluation of causes

- Further research on how electrical corrosion spreads in bearings and under which circumstances (voltage, amperage, speed, load, quality and composition of grease etc).
- More research on how different high-frequency waveforms in the return currents at different stages of operation (standing still, moving slowly, moving fast) affect voltages over the bearing. This could foreseeably be performed in a lab environment.
- More research on real-world current paths in different types of trains and how they affect the voltage potential over and current through the bearings.
- A structured case study on the prominence of electrical damage of bearings on different train types and tracks.

6.2 More thorough evaluation of potential solutions

- Further technical and economical evaluations of the more reasonable proposed solutions such as conductive greases, insulated locomotive couplings, and light-duty grounding brushes for freight cars using double-sealed bearing boxes.
- Test vehicles equipped with proposed solutions subjected to regular checkups over a long period of time.

6.3 Other research within the topic

- Further research on how different stages of electrical erosion affect mechanical wear and grease compositions.
- Comprehensive lifetime-cost analysis of maintenance due to electrical damage to bearings.
- Establishment of a standard for acceptable damages in axle bearings caused by electrical erosion.
- Development of a system capable of objectively determining the extent of electrical erosion on bearings.

7
Conclusion

The investigation's overall goal was to comprehend electrical damage in roller bearings in train axles and how it may affect the bearing function. Whilst the cause of electrical erosion in bearings is self-evident (unwanted currents flowing through the bearings), knowing exactly why and when it occurs on specific axle bearings is not. It is therefore still very hard to efficiently plan for preventative maintenance. Amongst the different plausible causes are: high coupling currents in freight trains along with improper grounding routes, failed insulation, and EDM currents induced by high rate of change return currents. The precise effect of this damage on bearing dependability is still being researched, though.

Potential solutions were brought up along with some difficulties suggested by industry professionals. One of the major obstacles to implementing different solutions is cost. Conductive grease, electrically insulated bearings, and electrically insulated couplings generated questions regarding their high cost and technical complexity.

There exists a need for a standardized way to measure and evaluate the extent of electrical damage in bearings. It would be easier to perform maintenance and troubleshooting if there was a system in place to recognize and classify electrical damage. Procedures to decrease what type and extent of electrical damage that is deemed acceptable need to be established. The development of a model to forecast the spread of electrical damage will help with bearing usage decisions in the future. Additional tests with insulated connections and different current flows can shed light on how to avoid electrical damage and its effects on bearing longevity. Overall, the railway industry may enhance its comprehension of electrical damage in roller bearings and guarantee safer and more dependable train operations along with better preventative maintenance by resolving these issues and performing recommended additional studies.

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