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Fault tree analysis of most common rolling bearing tribological failures

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Abstract. Wear as a tribological process has a major influence on the reliability and life of rolling bearings. Field examinations of bearing failures due to wear indicate possible causes and point to the necessary measurements for wear reduction or elimination. Wear itself is a very complex process initiated by the action of different mechanisms, and can be manifested by different wear types which are often related. However, the dominant type of wear can be approximately determined. The paper presents the classification of most common bearing damages according to the dominant wear type, i.e. abrasive wear, adhesive wear, surface fatigue wear, erosive wear, fretting wear and corrosive wear. The wear types are correlated with the terms used in ISO 15243 standard. Each wear type is illustrated with an appropriate photograph, and for each wear type, appropriate description of causes and manifestations is presented. Possible causes of rolling bearing failure are used for the fault tree analysis (FTA). It was performed to determine the root causes for bearing failures. The constructed fault tree diagram for rolling bearing failure can be useful tool for maintenance engineers.

1. Introduction

Rolling bearings are machine elements found in a wide field of applications, and they are typically very reliable. Nevertheless, any damage or failure of the rolling bearings results in a partial or complete functional failure of the machine and can cause significant economic losses. Although, generally, the price of the rolling bearing is relatively small, a bearing damage that reduces the function of the system or result in its failure can cause a lot of overhead costs. That is way it is very important to be able to identify and predict failure beforehand, if possible, so that preventive measures can be adopted. Under normal operating conditions, i.e. if rolling bearings are used correctly, they usually have a substantial service life. Method of calculating the basic rating life based on 90 % reliability, with commonly used high quality material, good manufacturing quality and with conventional operating conditions is specified in ISO 281 standard [1]. This standard also specifies method of calculating the modified rating life, in which various reliabilities, lubrication condition, contaminated lubricant and fatigue load of the bearing are taken into account. However, it does not take into account particular influence of wear and corrosion on bearing life.

Unfortunately, rolling bearings often fail prematurely due to avoidable mistakes, i.e. the effect of unanticipated wear may be to initiate damage that leads to premature failure. According to some studies [2,3], following common rolling bearing failure causes can be classified, with their percentage shares: (1) insufficient amount of lubricant: 15 %; (2) inadequate selection of lubricant: 20 %; (3) aged lubricant (wear products, additive depletion): 20 %; (4) solid particles contamination of lubricant: 20 %; (5) liquid contamination of lubricant: 5 %; (6) inadequate selection of bearing (design, size, load-carrying capacity): 10 %; (7) handling induced defects: 5 %; (8) mounting faults: 5 %; (9) bearing material and production faults: less than 1 %. As it can be seen, about 35 % of bearing failures are related to irregularities in the lubrication process (causes 1 and 2) and in total, about 80 % of bearing failures are associated with the tribological causes (causes 1 to 5).

According to the ISO 13372 standard failure is defined as "termination of the ability of an item to perform a required function" [4]. In practice, damage of a rolling bearing may often be the result of several mechanisms operating simultaneously. It is the complex combination of many influencing parameters which often causes difficulty in establishing the primary cause of damage. The relevant literature and practical experience show that the rolling bearing damages are mainly caused by wear, and that surface fatigue wear is the most common wear type. Also, very often, in mixed-to-boundary lubrication conditions, adhesive wear can occurs, as well as abrasive wear if lubricant is contaminated with foreign particles. Wear itself is a very complex process initiated by the action of different mechanisms, and can be manifested by different wear types which are often related. The paper presents the classification of most common bearing damages according to the dominant wear type, i.e. abrasive wear, adhesive wear, surface fatigue wear, erosive wear, fretting wear and corrosive wear. In addition, fault tree analysis (FTA) was performed to determine the root causes for bearing failures. Similar analysis was already performed for journal bearing failures [5].

2. Appearances and manifestations of the different wear types

2.1. Abrasive wear

Abrasive wear, according to ISO 15243, is classified as wear, i.e. abrasive wear. Terms: particle wear, three body wear, burnishing, and scoring are also used. Abrasive wear in rolling bearings occurs due to the presence of solid contaminants (three-body abrasion) or by rubbing of the bearing elements in direct contact (two-body abrasion) [6]. Rolling bearings are very sensitive to solid contaminants which can happen even during mounting of the bearing. Fine hard particle contamination can remove material from bearing contact surfaces by excessive polishing (burnishing) like a lapping compound, changing internal bearing geometry by abrasive wear [7]. Denting of contact surfaces (figure 1a) can occur when hard and ductile particles are entrained through heavily loaded bearing contacts and plastically deform the surfaces. Dents produced by large ductile particles may lead to pitting and spalling, while dents attributed to small ductile particles can lead to micro-pitting or peeling of bearing raceways [8]. Large hard particles can become embedded into softer cage material and create scratches and groove marks in rolling element body surfaces (figure 1b). Similar appearances show abrasive wear by rubbing of the bearing elements in direct contact. Intensive abrasive wear of rolling bearings will manifests as scoring (severe scratching).

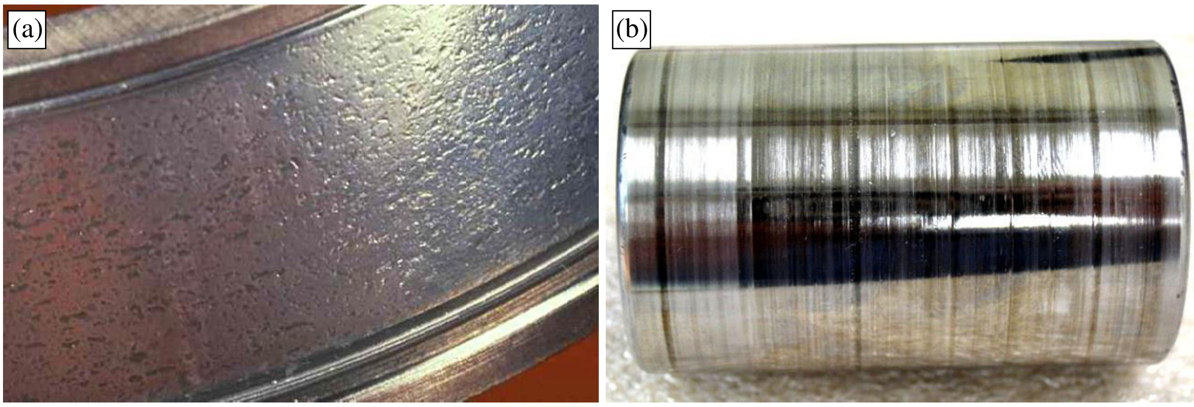

Figure 1. Bearing surfaces damaged by abrasive wear: (a) dull surface and visible dents (craters) on inner ring and (b) scratching and pronounced grooves on rollers.

2.2. *Adhesive wear*

Adhesive wear, according to ISO 15243, is classified as wear, i.e. adhesive wear. Terms: smearing, skidding, galling, and scuffing are also used. Adhesive wear in rolling bearings occurs when the conditions for formation of a lubricant film to separate bearing contacting surfaces are inadequate (boundary or mixed lubrication). In that conditions, and mainly in sliding contacts, contacting asperities bond in intimate contact (micro welds) and tear. Adhesive wear occurs at locations with high slide-to-roll ratio, i.e. contact of rolling elements with cage, shoulder or other rolling element (figures 2a and b). It also occurs when the rolling elements are subjected to sudden acceleration on their re-entry into the load zone (figure 2c). When the rolling elements are in the unloaded zone, without direct contact with the rings, their rotational speed is lower than when they are in the loaded zone. The rolling elements are therefore subjected to sudden acceleration when they enter the loaded zone, with high slide-to-roll ratio as a result.

Adhesive wear can occurs in the form of mild or "normal" wear or as severe adhesive wear. Mild adhesive wear typically manifests with wiping of the material from the contact surfaces, sometimes accompanied by change of colour of the bearing material (figures 2a and b). It is normal during the running-in of a rolling bearing, which is a natural short process after which the running behaviour stabilizes or even improves [9]. Severe adhesive wear (scuffing or galling) is usually accompanied by high temperatures, and occurs upon loss of lubrication at contacts with a large sliding component. It manifests with change of colour, significant plastic deformation of surfaces due to its softening, and material transfer (figures 2d, e and f). As a result, seizure may occur, when components are not easily separated due to significant welding of the worn surfaces. Smearing (skidding) is somewhat in between mild and severe adhesive wear. It is usually localized on specific areas (figure 2c). In smearing, bearing elements slip also produces plastic deformation, but at the asperity scale, that may be accompanied by material transfer from one surface to the other [8].

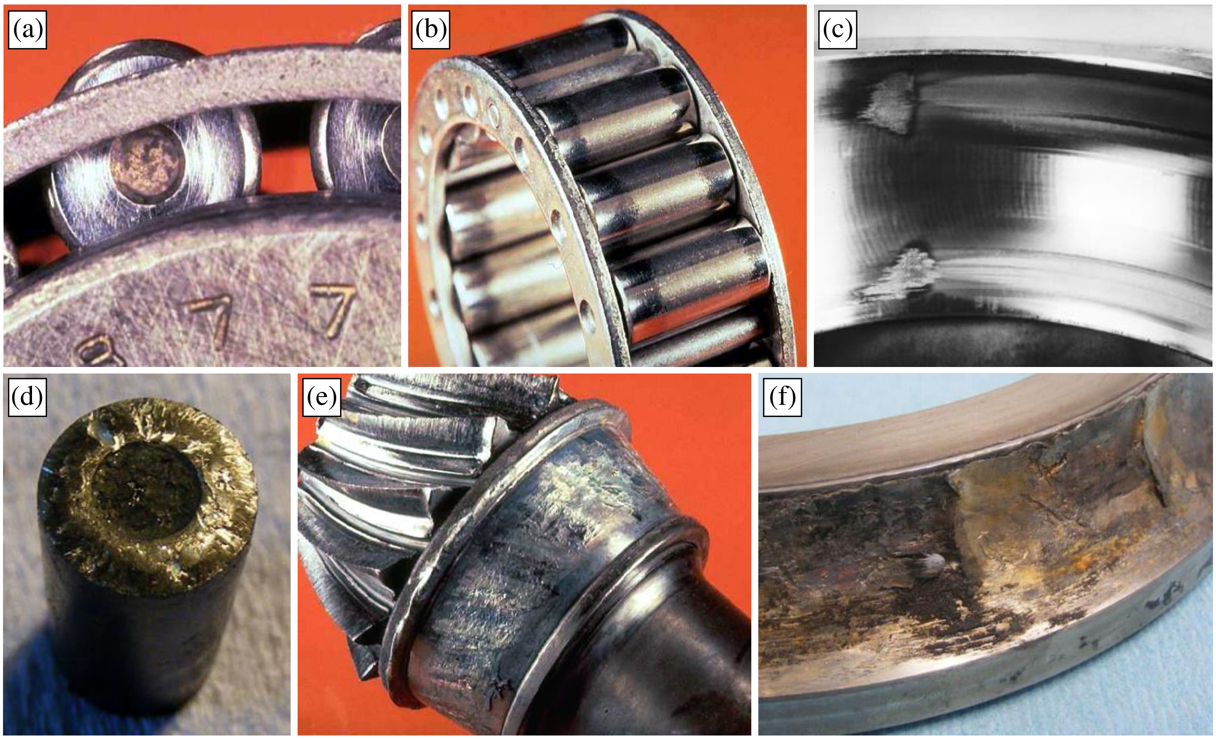

Figure 2. Bearing surfaces damaged by adhesive wear: (a) and (b) wiping of rollers (mild adhesive wear), (c) smearing of outer ring and (d), (e) and (f) change of colour and surface softening and flow of roller and inner rings material (severe adhesive wear).

2.3. Surface fatigue wear

Surface fatigue wear, according to ISO 15243, is classified as fatigue, i.e. subsurface initiated fatigue, and surface initiated fatigue. Terms: pitting, peeling, spalling, and flaking are also used. Surface fatigue wear in rolling bearings occurs due to the presence of dynamic load conditions. Continued cyclic contact stress may initiate cracks that can then propagate by fracture, leading to the removal of surface material. According to the location of initial cracks formation, two types of fatigue (rolling contact fatigue) can be distinguished, i.e. subsurface and surface initiated fatigue. Location of the initial crack is defined with the position of the highest shear stress, which is not the same for sliding/rolling (figure 3a). In pure rolling initial cracks will be initiated at a certain depth below the surface (figure 3b), usually 0.1 to 0.5 mm [10]. These near-surface cracks will propagate to the surface and ultimately lead to macroscopic surface material removal.

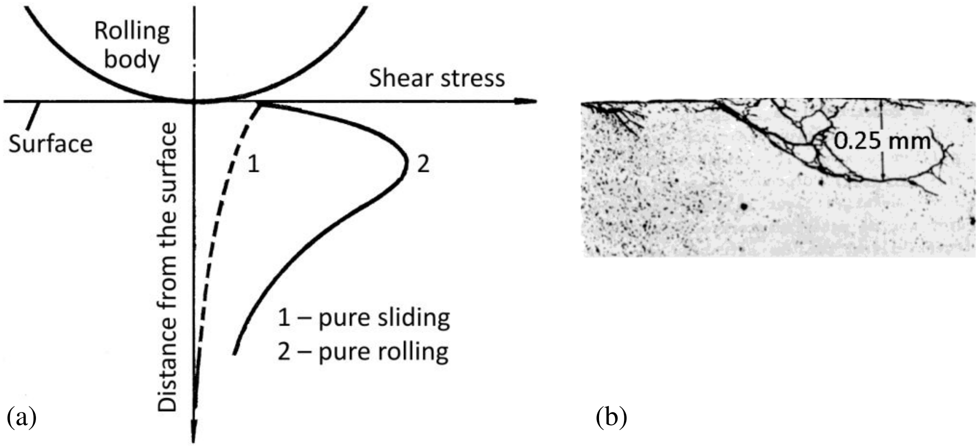

Figure 3. Surface fatigue wear: (a) position of the highest shear stress for pure sliding/rolling and (b) propagation of the initial crack to the surface.

Both, subsurface and surface initiated fatigue manifest like pitting, i.e. formation of the surface craters or voids (pits) by loss of material. If the pitting is caused by overload due to the fault assembly of the bearing (misalignment or small clearance) failures occur at intervals corresponding to rolling element pitch (figure 4a). Overload due to the large clearance during mounting of the bearing will also cause localised failure, but the rolling elements and raceways wear unevenly (figure 4b). On the other hand, inadequate lubrication will cause pitting on the whole contact area (figure 4c). Surface fatigue wear starts as initial pitting (peeling), but over the time pits grow and join together causing progressive pitting (spalling or flaking). Peeling or micro-pitting occurs when thin flakes of material are removed from contact surfaces. The damage area is usually shallow on a microscopic scale, giving the gray stained appearance [10].

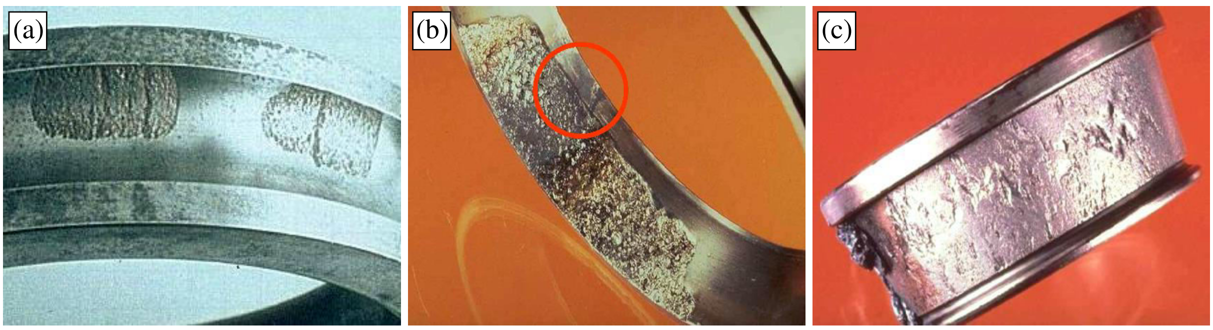

Figure 4. Bearing surfaces damaged by surface fatigue wear: (a) and (b) localised pitting of the inner and outer ring due to overload and (c) progressive pitting of the inner ring due to the inadequate lubrication.

2.4. Erosive wear

Erosive wear, according to ISO 15243, is classified as electrical erosion, i.e. excessive voltage, and current leakage. Terms: electrical pitting, electrical fluting, and washboarding are also used. Erosive wear (electrical erosion) in rolling bearings occurs due to the passage of an electric current in the area of minimum lubricant film thickness between the rolling elements and raceway. This type of wear most often occurs in bearings of the electric motors. Two electrical erosion damages can be distinguished, depending on the voltage, i.e. high-voltage electrical erosion (excessive voltage) and low-voltage electrical erosion (current leakage). In high-voltage electrical erosion (electrical pitting) the flow lines of the current are condensed, resulting in localized and rapid heating, so that the contact areas melt and weld together. It manifests as a series of small craters (pits) on both contact surfaces (figure 5a). Craters diameters are usually up to 100 μm [9]. In low-voltage electrical erosion (electrical fluting or washboarding), the intensity of the current is relatively low but acts during the long period of time. The damage manifests as corrugation marks on the contact surfaces (figure 5b). Formed groves are shallow, close to each other and equally spaced.

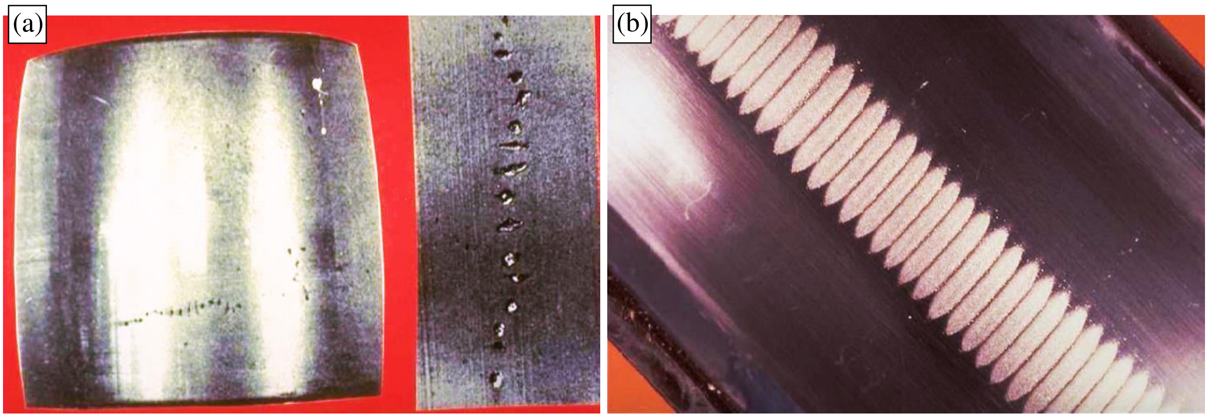

Figure 5. Bearing surfaces damaged by erosive wear (electrical erosion): (a) small craters (pits) on roller and inner ring due to the excessive voltage (electrical pitting) and (b) shallow and equally spaced groves (flutes) due to the current leakage (electrical fluting or washboarding).

2.5. Fretting wear

Fretting wear, according to ISO 15243, is classified as corrosion (frictional corrosion), i.e. fretting corrosion, and false brinelling. Terms: fretting rust, tribocorrosion, tribo-oxidation, and vibration corrosion are also used. Fretting (vibration) wear in rolling bearings occurs due to the relative micromovements between mating surfaces caused by vibrations. These micromovements can induce the oxidation of material surface. In presence of corrosive environment, corroded layer can be formed as well. Subsequent micromovements remove or disrupt this oxide/corroded surface layer, and the cycle repeats. This type of wear is very common in rolling bearings. According to the location of damage, two types of fretting (vibration) wear can be distinguished, i.e. fretting corrosion/oxidation (fretting rust, tribocorrosion or tribo-oxidation) and false brinelling (vibration corrosion). Fretting corrosion/oxidation occurs between inner ring and shaft or outer ring and housings as a result of vibrations and insufficient press fit (too light interference fit). It manifests with visible wear products in powder form, and very often changes of colour (figure 6a). False brinelling occurs between rolling elements and raceways as a result of vibrations and insufficient clearance. It manifests as shallow depressions in the raceways at rolling element pitch and usually accompanied by loss of surface finish marks in the worn areas (shiny colour) and the presence of reddish or black wear debris (figure 6b).

2.6. Corrosive wear

Corrosive wear, according to ISO 15243, is classified as corrosion, i.e. moisture corrosion. Terms: oxidation and rust are also used. Corrosive wear in rolling bearings occurs due to the chemical

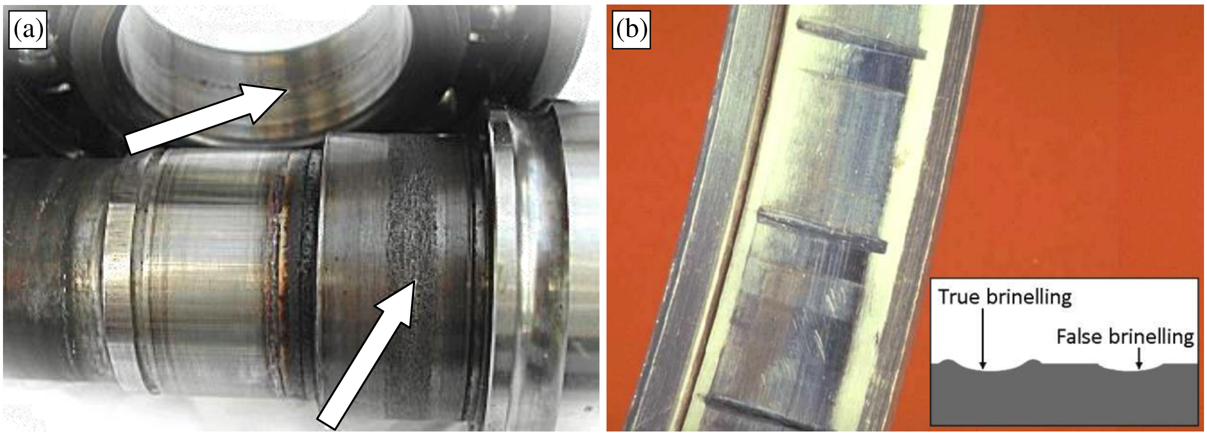

Figure 6. Bearing surfaces damaged by fretting (vibration) wear: (a) powder wear debris and change of colour on inner ring and shaft, due to the insufficient clearance and (b) equally spaced depressions and shiny worn areas (false brinelling) on inner ring due to the insufficient press fit.

reaction (oxidation/corrosion) of steel surfaces with the environment, and subsequent removing or disrupting of oxide/corroded surface layer, due to the relative movements of the bearing elements. The origin chemically aggressive medias (water or moisture, acids and products from lubricant degradation) is either outside the bearing (contaminants) or they are generated within the bearing itself. This type of wear most often occurs in bearings used in papermaking machines. Corrosion wear manifests with corrosion pits or rust on critical surfaces which change colour and chemical composition (figure 7a). A specific form of corrosion wear in the contact areas between rolling elements and raceways manifests with equally spaced discoloured areas on both contact surfaces (figures 7b and c).

Figure 7. Bearing surfaces damaged by corrosive wear: (a) corrosion pits and rust all over the bearing and (b) and (c) discolouration of contact areas on rollers and outer ring.

3. Fault tree analysis

Rolling element bearings are typically operated under elastohydrodynamic lubrication (EHL) regime. Elastohydrodynamic lubrication can be defined as a form of hydrodynamic lubrication where the elastic deformation of the contacting bodies and the changes of viscosity with pressure play fundamental roles [11]. A thin layer of EHL lubricant film separates bearing elements, preventing their direct contact (boundary or mixed lubrication), and thus minimizes friction and wear. Lubricants also act as a medium to remove and/or distribute heat, protect the surface from corrosion, and remove wear products from contact zone [2]. There are many parameters that affect lubricant film thickness and obtained lubrication regime, and most important are presented in figure 8.

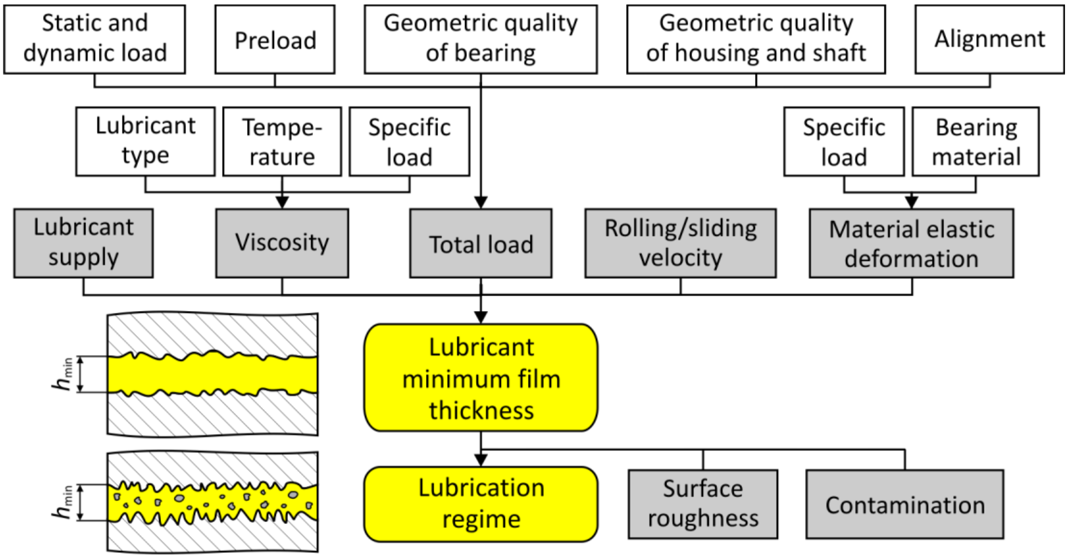

Figure 8. Parameters related to the lubricant film thickness and lubrication regime in a rolling bearing.

Possible causes of rolling bearing failure, used for the fault tree analysis (FTA), were taken from the literature data and personal experience. The different types of bearing damages were correlated with the ISO standard 15243 [9], which can be used for the further explanation/description of the constructed fault tree root causes. FTA is a useful tool that can be applied on different mechanical engineering problems [12-14]. A fault tree diagram is a logic diagram which traces the possible events leading to a major event, almost like a family tree. The desired or, in most cases, undesired main event is placed at the top of the tree and called the ''top event'' [15]. In our case, the top event will be entitled ''rolling bearing failure''. In general terms, we can categorize two basic types of failure: (1) tribological and (2) mechanical, but as more dominant, only tribological failures were discussed further. Tribological failures include six broad wear types: (1) abrasive, (2) adhesive, (3) surface fatigue, (4) erosive (electrical erosion), (5) fretting (vibration), and (6) corrosive wear. The discussion of different wear type failures must be more general, since they are intermediate events on fault tree of tribological bearing failure (figure 9).

Abrasive wear in rolling bearings is mainly caused by the (1) contamination of lubricant with foreign particles. Lubricant contamination with foreign particles is basically caused by poor sealing of the bearing or poor filtration of the lubricant. Scratches also occur during sliding of the bearing elements in direct contact. Direct contact of the bearing elements can occur due to the (2) insufficient clearance (caused by poor design of the bearing, or its fault assembly, or high surface roughness) or (3) inadequate lubrication (caused by insufficient amount of the lubricant, low viscosity of the lubricant or inadequate quality of the lubricant).

Adhesive wear in rolling bearings is mainly caused by the (1) lubricant film breakdown due to excessive load or speed or presence of vibrations (poor balancing) or (2) inadequate lubrication due to the insufficient or excessive amount of the lubricant, low viscosity of the lubricant or inadequate quality of the lubricant. In both cases, lubricant film thickness is insufficient to prevent direct contact between the bearing elements (boundary or mixed lubrication). Adhesive wear can be also caused by (3) improper material selection, i.e. combination of compatible materials (usually connected with seizure) or (4) insufficient clearance due to the poor design of the bearing or its fault assembly).

Surface fatigue wear in rolling bearings is mainly caused by the low fatigue strength of the bearing elements material, i.e. when (1) load exceeds fatigue strength. Subsurface initiated fatigue could be also caused by the (2) improper material production, i.e. presence of structural defects and/or inclusions in bearing elements material. Surface initiated fatigue is mostly attributable to surface distress and occurs when a certain percentage of sliding motion is present. Surface distress could be

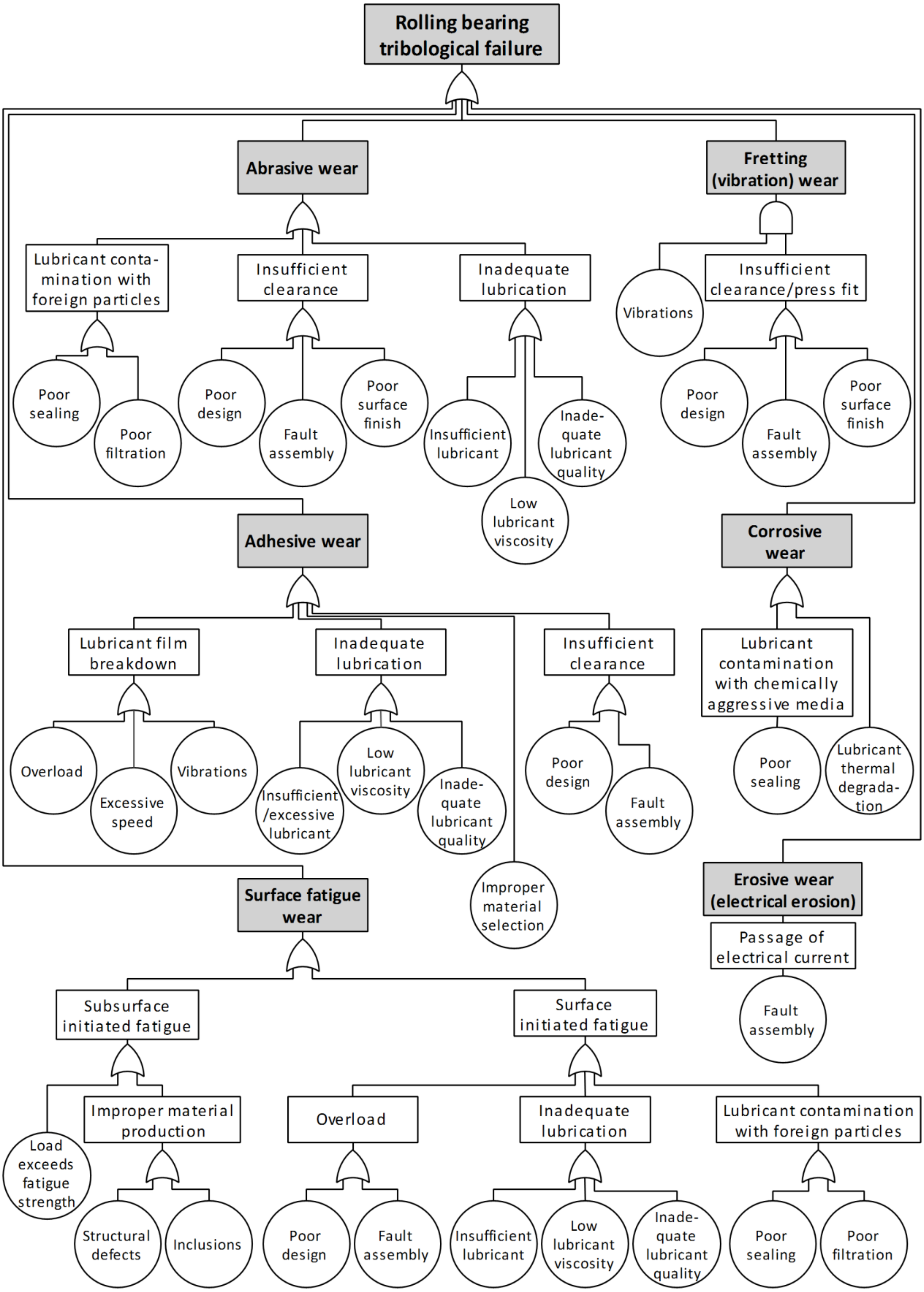

Figure 9. Fault tree of tribological rolling bearing failure.

caused by (3) overload due to the poor design of the bearing or its fault assembly, or (4) inadequate lubrication due to the insufficient amount of the lubricant, its low viscosity or inadequate quality of the lubricant, or (5) lubricant contamination with foreign particles due to the poor sealing of the bearing or poor filtration of the lubricant (contamination of the bearing and subsequent indentation of the foreign particles will crate places with high stress concentrations). Surface initiated fatigue could be also caused by the surface defect that might be caused by some other type of wear.

Erosive wear (electrical erosion) in rolling bearings is caused by the (1) passage of an electric current in the area of minimum lubricant film thickness between the rolling elements and raceway. Main reason for this is the fault assembly of the bearing (improper grounding of equipment, insufficient or defective insulation of bearing, or static discharge issues).

Fretting wear in rolling bearings is caused by the (1) vibrations and (2) insufficient clearance or insufficient press fit due to the poor design of the bearing, or its fault assembly, or high surface roughness.

Corrosive wear in rolling bearings is caused by the (1) lubricant contamination with chemically aggressive media due to the poor sealing or (2) thermal degradation of lubricant during service.

4. Conclusions

The presented examples of damages represent the main types of wear that occur in rolling bearings. Based on the literature, the most prominent (and thus the most important) types of wear in rolling bearings are surface fatigue wear, adhesive wear and abrasive wear. Other types of wear, i.e. erosive (electrical erosion), fretting (vibration) and corrosive wear are less pronounced, although for certain conditions and applications they can cause significant damage of bearing.

Described visual manifestations of the most common bearing damages assist in determining the dominant wear type in damaged rolling bearing. Establishment of dominant type of wear facilitate the determination of the measures for its reduction or elimination and thus extending the service life and reliability of the rolling bearings. In addition, sometimes confusing terms for rolling bearing damages used in ISO 15243 standard are correlated with the generally accepted and well known terms for wear types.

Further help in determining the root causes for roller bearing failures is provided by the fault tree analysis (FTA) which was performed, and appropriate descriptions of causes are presented. Constructed fault tree diagram for rolling bearing failure should give better perceive to the engineers in practice and help them in maintenance of machines with belonging rolling bearings.

Acknowledgments

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References

[1] ISO 281 2007 Rolling bearings – Dynamic load ratings and rating life
[2] Hannon W M and Ai X 2013 Rolling bearing lubricants, in: Wang Q J and Chung Y - W (Eds.) *Encyclopedia of Tribology* (New York: Springer) pp 2848–56
[3] -- 2015 Selecting the right grease for rolling bearings, *World Pumps* **2015** 31–33
[4] ISO 13372 2004 Condition monitoring and diagnostics of machines – Vocabulary
[5] Vencl A and Rac A 2014 Diesel engine crankshaft journal bearings failures: Case study, *Eng. Fail. Anal.* **44** 217-228
[6] Kandeva M, Karastoyanov D and Vencl A 2016 *Advanced Tribological Coatings for Heavy-Duty Applications: Case Studies* (Sofia: Marin Drinov Academic Publishing House)
[7] Widner R L 1986 Failures of rolling-element bearings, in: *ASM Handbook Volume 11, Failure Analysis and Prevention* (Metals Park: ASM International) pp 490–513
[8] Evans R D 2013 Wear of bearings, in: Wang Q J and Chung Y - W (Eds.) *Encyclopedia of Tribology* (New York: Springer) pp 4061–68
[9] ISO 15243 2004 Rolling bearings – Damage and failures – Terms, characteristics and causes

IOP Conf. Series: Materials Science and Engineering **174** (2017) 012048 doi:10.1088/1757-899X/174/1/012048

[10] van Beek A 2009 *Advanced Engineering Design* (Delft: TU Delft)
[11] Stachowiak G W and Batchelor A W 2014 *Engineering Tribology* (Amsterdam: Elsevier)
[12] Moraru R-I and Băbuţ G-B 2013 The use of fault tree in industrial risk analysis: A case study, in: *Proc. 1st Int. Conf. on Industrial and Manufacturing Technologies (Vouliagmeni)* (WSEAS Press) 70–75
[13] Olmi G 2015 Statistical tools applied for the reduction of the defect rate of coffee degassing valves, *Case Stud. Eng. Fail. Anal.* **3** 17–24
[14] Nouri.Gharahasanlou A, Mokhtarei A, Khodayarei A and Ataei M 2014 Fault tree analysis of failure cause of crushing plant and mixing bed hall at Khoy cement factory in Iran, *Case Stud. Eng. Fail. Anal.* **2** 33–38
[15] Strauss B M 1984 Fault tree analysis of bearing failures, *Lubr. Eng.* **40** 674–680