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Research article

Bearing Degradation in a Pickling Line Gearbox

R. Pooja[a,*], N. Made Gowda[a], Dhanraj Patil[a], K. P. Mrunmaya[a]

[a]*JSW Steel Vijayanagar, Bellary, Karnataka, India.*

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* Corresponding author:

R. Pooja
E-mail: pooja.r@jsw.in

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A B S T R A C T

Lubricant integrity plays a critical role in maintaining the reliability and service life of industrial bearings. This study reports a bearing failure event in a pickling line gearbox and assesses the underlying mechanisms through lubricant condition assessment and wear debris analysis. Viscosity testing indicated a reduction from 320 cSt to 208 cSt at 40 °C, while moisture content measured 500 ppm, revealing thermal degradation and water ingress. Analytical ferrography identified severe sliding and oxidative wear, characterized by large ferrous plate-like particles with blue gold interference colors. Additional red oxide debris and external contaminants suggested inadequate sealing and abrasive ingress. SEM–EDS analysis confirmed that the debris originated from iron-based low-alloy steel and contained measurable oxygen, indicating oxidation-driven surface fatigue. Collectively, these findings point to boundary lubrication caused by viscosity loss, oxidation, and contamination as the primary contributors to premature bearing failure. The work underscores the need for proactive oil health monitoring and contamination control to enhance gearbox reliability in industrial environments.

1. INTRODUCTION

Bearings are essential components in rotating machinery, designed to support radial and axial loads while maintaining smooth motion and minimal friction. Their performance and reliability depend primarily on proper lubrication, which provides a continuous protective film between rolling and sliding surfaces. This film minimizes wear, dissipates heat, and prevents direct metal-to-metal contact. When the lubricant maintains correct viscosity, cleanliness, and oxidation stability, the bearing operates efficiently and achieves its designed service life.

However, improper lubrication arising from contamination, oxidation, or viscosity degradation causes premature bearing failure. Contaminants such as dust, moisture, and process residues disrupt the lubrication film and introduce abrasive particles into the contact zone. Meanwhile, oxidation of oil at elevated temperatures produces red oxides, varnish, and acidic by-products that corrode bearing surfaces. Viscosity reduction, whether due to thermal breakdown or dilution, further weakens the oil's film-forming ability, resulting in increased friction, heat, and wear. Over time, these mechanisms accelerate surface fatigue and generate abnormal wear debris, which can be detected through oil analysis and ferrography. Continuous monitoring of lubricant condition therefore plays a crucial role in identifying degradation trends and preventing unexpected bearing failures in industrial systems.

Offline wear debris analysis methods remain fundamental in machine condition monitoring due to their ability to provide detailed information on wear particle morphology, composition, and concentration. Common techniques include patch analysis, where lubricant samples are filtered and debris examined visually or microscopically to assess contamination levels and wear severity [1]. Ferrography, another widely employed offline method, uses magnetic separation to isolate ferrous particles on slides for morphological analysis, enabling the identification of wear mechanisms such as adhesive or abrasive wear [2] Particle counting combined with scanning electron microscopy (SEM) further refines wear diagnostics by quantifying particle size distribution and shape, although this requires expensive instrumentation and skilled operation [3]. Despite their richness in detail, offline methods inherently suffer from delays due to sampling, transport, and laboratory processing, limiting their ability to detect rapidly evolving wear conditions in real time [4].

The performance and reliability of bearings depend strongly on lubricant health. Studies have consistently shown that contamination, oxidation, and viscosity deterioration are leading causes of premature bearing failure. Cann et al. [5] demonstrated through R0F bearing tests that grease degradation under cyclic loading results in oxidation, oil bleed reduction, and viscosity changes that cause localized heating and boundary lubrication. This mechanism explains the generation of oxidized, reddish wear debris and accelerated surface wear under degraded lubrication conditions.

Similarly, Halmos et al. [6] investigated oil-lubricated bearings under small oscillating movements and reported that micro-motions promote boundary-film breakdown and surface fatigue, producing abnormal wear debris patterns comparable to those observed in contaminated oil systems. Fatigue-related degradation was also identified by the Journal of Failure Analysis & Prevention [7], which correlated grease oxidation and high-temperature exposure with pitting, fatigue spalling, and the formation of oxidized debris particles. Water contamination has a pronounced effect on lubricant rheology. Studies published in the ASME Journal of Tribology [8, 9] showed that even minor water ingress reduces hydrodynamic film thickness, induces micropitting, and increases frictional heat. Such deterioration promotes oxidation of both the lubricant and bearing surfaces, generating red-oxide deposits similar to those found in failed bearings using contaminated oil.

Akchurin et al. [10] conducted detailed SEM/EDS analyses of wear particles in boundary-lubricated contacts, classifying them as sliding, cutting, or oxidative debris. Their morphology correlated directly with lubrication condition and contamination level, confirming that the presence of oxidized ferrous flakes or dark oxide films is a reliable indicator of boundary lubrication failure. In complementary research, Marco de Lucas et al. [11] examined oxidation of debris during fretting wear and observed reddish oxide layers forming on metallic debris surfaces confirming that oxidation is a dominant mechanism during lubricant breakdown and metal-to-metal interaction.

Thermal effects on lubricant stability were quantified by Schneidhofer et al. and Silva et al. [12, 13], who showed that short-term high-temperature exposure accelerates grease oxidation, viscosity loss, and vibration response. These findings align with practical industrial observations where high-temperature, contaminated oil leads to film rupture and abnormal wear debris formation. Zhao et al. [14] advanced the diagnostic perspective by integrating oil debris monitoring and vibration analysis to detect abnormal bearing wear in early stages. Their results reinforce the utility of offline wear-debris analysis in identifying contamination-induced wear mechanisms.

Complementary research by Yang et al. [15] emphasized modern debris-measurement techniques to quantify particle concentration and morphology, which are essential tools for root-cause investigation in failed systems. Peng et al. [16] provided a comprehensive review of tribological failure analysis, highlighting that lubrication degradation through contamination, oxidation, and viscosity changes leads to abnormal wear, surface fatigue, and debris oxidation.

2. METHODOLOGY

Oil samples were collected from the operating bearing for detailed condition monitoring and failure diagnosis. Initially, viscosity testing was conducted to assess any deviation from the specified grade, as both viscosity reduction and thickening can impair lubricant film formation. Moisture content was evaluated to determine the presence of water, which can accelerate corrosion and promote red-oxide formation. To characterize the nature of particulate contamination, offline wear-debris analysis was carried out, enabling observation of particle size, shape, and wear mechanisms. Subsequently, selected particles were examined using Scanning Electron Microscopy coupled with Energy Dispersive Spectroscopy (SEM-EDS) to determine surface morphology and elemental composition. The procedure for the analysis was stated below.

2.1 Viscosity and Moisture Analysis

Kinematic viscosity of the lubricant was measured using a Cannon Mini-AV automatic viscometer as shown in figure1, in accordance with ASTM D445. The sample was conditioned to the required test temperature (40 °C), after which the instrument automatically drew the oil into a calibrated capillary tube. The viscometer recorded the flow time between two optical markers, and viscosity was calculated using the tube constant. Moisture content in the used lubricating oil was measured using the Kittiwake Oil Test Centre, model AS 3412. Moisture content indicates possible issues such as condensation, coolant ingress, or improper sealing, all of which accelerate oxidation, reduce lubricant film strength, and contribute to bearing wear and premature failure. This test provided essential supporting evidence in the overall failure analysis.

Fig. 1. Kinematic viscometer.

2.2 Ferrography Analysis

Ferrography analysis was carried out to understand the condition of the machine by examining the wear particles present in the lubricating oil. This method helps identify how much wear is occurring and what type of wear mechanism is active by studying the size, shape, and behavior of the particles under a magnetic field. In this ferrography analysis there are two methods; Direct Reading (DR) ferrography and Analytical ferrography. In direct reading ferrography, the used oil sample was first heated to 60 °C to disperse the particles evenly, then diluted with an equal amount of heptane to reduce viscosity for smooth flow through the precipitation tube. A strong magnet beneath the tube attracts metal particles, causing larger particles to settle first and smaller ones later. After deposition, the instrument measures the light transmitted through the tube and calculates the percentage of large and small particles. The ratio between these particles typically stays consistent unless the wear rate increases. The DR ferrography results provide the large particle value (DL) and small particle value (DS), which together form the Wear Particle Concentration (WPC) value used to assess wear severity. To measure the WPC, a Predict Direct Reading (DR) Ferrography instrument, model 720700, was used (figure (2) a).

In analytical ferrography, the wear source was evaluated using a Predict Ferrogram Maker (FM), model 72060E (figure (2) b). A mixture of 3 ml oil sample and 2 ml solvent was allowed to flow over an inclined glass slide positioned above a strong magnet, causing the particles to separate based on their size and magnetic response. Magnetic particles settled near the magnet, while larger but less magnetic particles deposited farther along the slide. After deposition, the slide was rinsed to remove excess oil, and the resulting ferrogram was heated to 330 °C for 90 seconds as per ASTM procedure. Microscopic examination of the wear particles was then carried out using a bi-chromatic microscope (Olympus BX-41).

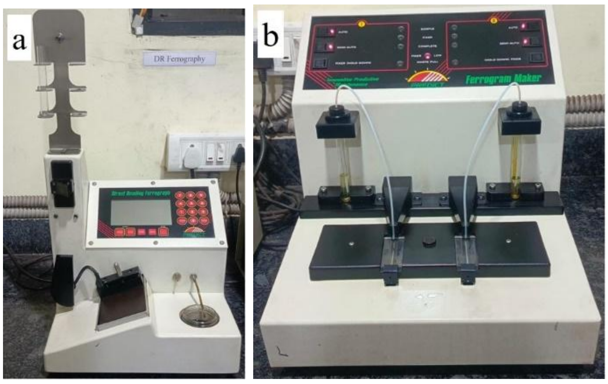

Fig. 2. Ferrography Instruments (a) Predict Direct Reading Ferrography, and (b) Predict Ferrogram maker.

2.3 SEM and EDS Analysis

Detailed observation of wear particle size, shape, surface texture, and damage features was carried out using Scanning Electron Microscopy (SEM) with a Hitachi S-3400N model. These morphological characteristics help identify wear mechanisms such as abrasive wear, adhesive wear, fatigue wear, and oxidative wear. Energy Dispersive Spectroscopy (EDS), used together with SEM, determines the elemental composition of each particle. By combining SEM morphology with EDS elemental analysis, wear particles was accurately classified, enabling precise identification of the wear mechanism and the component from which the debris originated.

3. RESULT AND DISCUSSION

3.1 Viscosity and Moisture Analysis

The results of this study clearly show that improper lubrication specifically viscosity degradation and moisture contamination played a decisive role in the bearing failure within the pickling line gearbox. The viscosity drop from 320 cSt to 208 cSt at 40 °C reduced the lubricant's film-forming ability, shifting the system toward boundary lubrication and increasing friction, metal-to-metal contact, and surface fatigue, consistent with reported mechanisms in literature [5, 12]. Moisture contamination (500 ppm) further weakened lubrication performance by promoting film collapse, corrosion, and micropitting, aligning with studies showing that even low water levels (≤1000 ppm) accelerate rheological deterioration and fatigue [8, 9]. Together, these factors created synergistic degradation pathways that intensified wear and ultimately led to bearing failure.

3.2 Ferrography result

The Direct Reading Ferrography results presented in Table 1 show a Large Particle Index (DL) of 1157.0, a Small Particle Index (DS) of 448.0, and a Wear Particle Concentration (WPC) of 1605.0, indicating a significantly elevated concentration of wear debris in the lubricant.

Table 1. Concentration of wear particles in oil sample.

Sl. No.	Large Particle Index (DL)	Small Particle Index (DS)	Wear Particle Concentration (WPC)
1	1157	448	1605

In analytical ferrography, the prepared ferrogram slide was examined under an optical microscope at 100X–500X magnification, using both transmitted and reflected light to assess metallic luster. Microscopic examination of the extracted wear particles revealed the presence of large, flat, plate-like particles exhibiting vivid interference colors ranging from blue to golden-yellow, as shown in figures 3(a) (Low alloy steel, several sliding wear particles) and 3(b) (Low alloy steel, fatigue wear particles). According to analytical ferrography color interpretation guidelines [17], blue and purple oxide films are typically associated with severe sliding wear occurring under high-temperature conditions. The interference colors indicate that these particles have undergone thermal oxidation, suggesting localized surface overheating and breakdown of the lubricant film. The morphology of the particles thin, laminated, and oxidized indicates adhesive wear transitioning to oxidative wear, which is commonly observed when a lubricant loses its protective viscosity or becomes contaminated. These findings correlate with literature reports [5, 10, 12] describing oxidation and discoloration of wear debris resulting from improper lubrication and boundary lubrication conditions. Hence, the observed blue-purple oxide layers confirm that the bearing operated under inadequate lubrication and thermal stress, leading to surface fatigue and accelerated material removal.

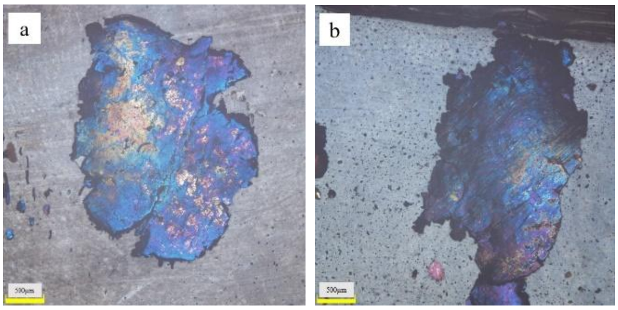

Fig. 3. Types of wear particles (a) Low alloy steel several sliding wear particle, and (b) Low alloy steel Fatigue wear particles were found on the ferrogram slide.

External contaminants (mill scales and sand dirt) and red oxides also observed in the ferrogram, as shown in figures 4. These contaminants showed no change in appearance after heat treatment and appeared as white crystalline particles under transmitted light. Red oxides were identified using polarized light microscopy.

Fig. 4. Red oxide particles and contaminates identified under polarized light on the ferrogram slide.

3.3 SEM and EDS Analysis

The particles shown in Figure 3(a) (Low alloy steel, several sliding wear particles) and Figure 3(b) (Low alloy steel, fatigue wear particles) were the same particles used for SEM and EDS analysis. Table 2 summarizes the elemental composition of two wear particles extracted from the ferrogram slide. Energy Dispersive Spectroscopy (EDS) detected Fe, Cr, Si, and O in both samples. Wear Particle-a primarily consists of Fe (94.09–95.98%), with minor amounts of O (1.37–2.07%), Cr (2.56–2.91%), and Si (0.20%). Wear Particle-b contains Fe (93.98–94.09%) along with slightly lower levels of O (2.28–2.30%), Cr (1.60–1.66%), and higher Si content (2.00–2.47%). The analyzed regions are indicated in figures 5. The elemental composition confirms that both particles originated from iron-based low-alloy steel. The presence of oxygen in both samples indicates oxidation. This oxidation may be influenced by the component's exposure to chemical cleaning during the pickling stage of the cold rolling process, which promotes oxide layer formation. Therefore, the oxygen detected may be attributed to a combination of oxidative wear during service and chemical reactions associated with the pickling environment or airborne dust contamination.

Table 2. Chemical composition of Wear Particles.

Wear Particles	Chemical composition [%]			
	Fe	Cr	O	Si
Wear Particle-a Area 1-2	94.62-95.90	2.91-2.56	2.07-1.34	0.2-0.2
Wear Particle-b Area 1-2	94.09-93.98	1.60-1.66	2.30-2.28	2-2.47

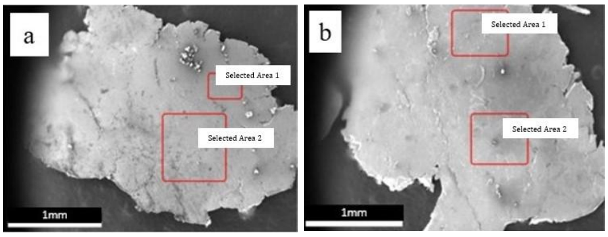

Fig. 5. Elemental mapping of wear particles (a) and (b), collected from the ferrogram slide, was performed using SEM–EDS

Variations in the minor element concentrations between individual wear particles are well documented in tribology literature and often arise from localized differences in wear mechanisms, micro-contact conditions, and surface chemical reactions. Studies on wear debris morphology and composition show that particles formed under different stress levels or contact regimes naturally exhibit distinct elemental signatures due to selective material removal, tribo-film rupture, or micro-scale alloy transfer [1-3]. Differences in oxygen content are commonly attributed to oxidative wear, surface corrosion, and environmental chemical attack, processes observed in both metallic and polymer-metal contact systems where debris undergoes partial oxidation or reacts with contaminants during sliding or rolling contact [10, 11]. Additionally, literature on bearing failures indicates that operational stresses combined with lubricant degradation and contamination significantly influence the chemical composition of debris, promoting oxidation, increased oxygen uptake, and altered surface chemistry conditions that accelerate micropitting, surface fatigue, and overall bearing deterioration [5, 6].

4. CONCLUSION

This investigation confirms that the premature bearing failure in the pickling line gearbox primarily resulted from lubricant deterioration driven by viscosity loss, water contamination, and oxidative stress. The significant reduction in viscosity from 320 cSt to 208 cSt, coupled with a moisture content of 500 ppm, directly weakened the lubricant film strength and promoted boundary lubrication. Under these conditions, metal-to-metal interaction occurred, accelerating frictional heating and promoting surface oxidation.

Wear debris analysis revealed large ferrous flakes and red oxide clusters, strongly indicative of severe sliding, thermal distress, and oxidative wear. Color interference patterns blue, purple, and golden hues validated thermal oxidation, while external contaminants such as mill scale and dust suggested sealing deficiencies and abrasive ingress. SEM–EDS characterization further verified that the particles originated from iron-based low-alloy steel and contained measurable oxygen, confirming oxidative transformation during service. The combination of abrasive, oxidative, and fatigue wear mechanisms demonstrates a compounding degradation process that progressively weakened the bearing surfaces.

These findings emphasize that lubricant health particularly viscosity stability and cleanliness is essential for reliable bearing operation in harsh industrial environments. Proactive oil-condition monitoring, including viscosity measurement, moisture detection, and ferrography, is therefore critical to detect early degradation. Additionally, strengthening shaft sealing, minimizing exposure to pickling chemicals, and ensuring timely oil replacement can significantly reduce contamination-induced wear.

Overall, implementing contamination control practices, routine offline wear-debris analysis, and early fault diagnostics will enhance bearing life and prevent unplanned downtime. This study reinforces the importance of integrating lubricant health assessment into predictive maintenance strategies to improve gearbox reliability in steel-processing applications.

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