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Investigating the Fretting Failure of Axial Thrust Steel Bearings in the Presence of Anti-Fretting Lubricating Paste

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Abstract: This paper investigated the fretting failure of axial thrust steel bearings as per ASTM 4170 in the presence of anti-fretting pastes used in process industries. The pastes were differentiated based on the content of additives in them. The results indicated that the paste containing the additive package of copper, molybdenum disulfide, and graphite exhibited excellent anti-fretting properties (75–80% less bearing race mass loss) as compared with other lubricating pastes that contained only graphite/molybdenum disulfide and nickel as primary additives. There was less surface damage to the bearing races in the lubricating paste containing copper, graphite, and molybdenum disulfide. The machine vision images of the false brinelling indicated that the average area of false brinelling on the bearing races with the paste containing copper, molybdenum disulfide, and graphite was 2.537 ± 0.623 mm^2, while that of the other pastes containing graphite/molybdenum disulfide and nickel as primary additives were 4.504 ± 0.566 mm^2 and 4.914 ± 0.621 mm^2, respectively, indicating 50% less false brinelling area in the paste containing copper, molybdenum disulfide, and graphite as compared with the paste containing graphite/molybdenum disulfide and nickel. An asymmetric wear pattern was also observed in the thrust bearings used during the tribo test. Surface characterizations indicated the formation of wear debris, plastic deformations, and surface cracks during the tribo tests. The physico-chemical properties of the lubricating pastes such as the viscosity and work penetration properties played an important role in controlling the failure of the bearings due to fretting.

Keywords: fretting wear; axial thrust bearing; lubricating paste; false brinelling

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1. Introduction

The presence of oscillatory motion or vibrations between two interfaces results in repeated micro-slips between surfaces, causing damages like fretting, flaking, scratching, preferential oxidation, cracking, seizing, and debris formation [1]. Fretting is a mechanical phenomenon that occurs at the contact interface between two surfaces under a small amplitude oscillatory motion or vibration. Efforts are being made to reduce fretting-related difficulties and improve the overall reliability and lifespan of components and systems. The usage of the right type of lubricant not only minimizes friction and wear between two contact surfaces but also prevents the entry of oxygen into the contact area [2]. These lubricants can be in the form of liquids, semisolids, pastes, solids, and gases. Apart from base oil and thickener, lubricants contain additives that prevent wear, control viscosity under intense pressure, produce films, and control sediment [3], etc. However, the content of the base oil, thickeners, and additives varies from one lubricant to another. Lubricating pastes are composed mostly of base oil and additives. The additive content in lubricating pastes is generally more than 40%, while in greases and oils, the additive content is 5–10%. Lubricating pastes prevents fretting, galling, seizing, and corrosion in bolts, flanges, fasteners, and stationary bearings of trolleys in heat treatment plants. These applications experience more oscillations and vibrations and less sliding motion. Additionally, the lubricating pastes are also used as assembly/disassembly lubricants as they aid in lubrication, making disassembly easier. The primary advantage of using a lubricant paste is the formation of a lubricating coating by the additives without affecting the threaded insert's mechanical properties or thermal conductivity; however, an outgassing process is to be used to avoid any contamination [4]. Fretting wear is also characterized by surface damages known as standstill marks and false brinelling. Several rolling element bearings exposed to oscillations fail due to fretting [5], and false brinelling marks can be seen on the raceways. As indicated earlier, several practices have indicated that the usage of the correct lubricant can prevent premature damage due to fretting. Considering the multifaceted nature of lubricant composition, particularly the presence of anti-wear and extreme pressure additives, several efforts are being undertaken to comprehend their mechanism of action. Since the beginning of the twentieth century, carbon-based solid lubricants, particularly graphite and diamond, have been used [6]. Other lamellar solids such as molybdenum disulfide (MoS_2), are known to be good solid lubricants that provide lubrication at high temperatures, in a vacuum, or in the presence of high radioactivity. Bas [7] investigated the tribological properties of MoS_2 particles as a lubricant additive on the performance of statically loaded radial journal bearings and reported that MoS_2 additives exhibited less friction behavior at high bearing loads and temperatures. Furthermore, it was reported that the effectiveness of MoS_2 additives increases with increasing bearing load and that they are more effective in the region of mixed friction than in the region of liquid film. Nehme [8] investigated the effect of anti-wear additives such as molybdenum disulfide (MoS_2) under severe pressure situations using a four-ball tribometer and reported that wear was mostly dependent on the speed condition under intense pressure loading. It was further reported that a low MoS_2 concentration is required to enhance the wear resistance of lithium-based greases. Though graphite and MoS_2 are well-known solid lubricants, they also have restricted usages. Graphite exhibits low friction in the air, while it exhibits high friction in dry nitrogen or vacuum, and MoS_2 exhibits low friction in vacuum or inert gas but exhibits a higher frictional coefficient in the air [9]. Nehme [10,11] was additionally able to emphasize the effect of zinc dialkyl-dithiophosphates (ZDDP) and FeF3 catalysts in tribological contact under extreme pressure conditions. Pavlo et al. [12] indicated that by adding talc powder to lubricating oil, with an optimal concentration of 0.15 wt%; the final friction coefficient decreased by more than 30% at 60–100 °C but raised at room temperature. Kimura et al. [13] reported hexagonal boron nitride (BN) to be a potential lubricating oil additive for certain applications. Apart from micro-size solid lubricants nano-solid lubricants also exhibited excellent tribological properties [14] with enhanced thermal properties [15].

Apart from the sliding wear under motion, researchers also focused on understanding the failure due to fretting [16]. The first standardized test and characterization procedure for oscillating rolling element bearings was ASTM D4170 [17,18], but the major disadvantage of this standard is the fixed load testing because, in industrial machinery, load conditions fluctuate. Yano et al. [19] designed a procedure for applying a variable vertical load to a thrust ball without causing the balls to oscillate. By comparing the data obtained with the two approaches, they discovered an ambiguous relationship between the fretting wear noticed on the tracks and the rheological characteristic of the basic oil of greases. Wang et al. [20] used a tribometer capable of performing an oscillating motion of an angular contact ball bearing in their research. They demonstrated that the mitigating effects of grease on fretting wear are closely related to the slip model observed in the contact region. Minh et. al. [21] investigated the tribological characteristics of greases with various chemical compositions according to ASTM D 4170 using a Fafnir wear rig. It was reported that the thrust ball bearing at the bottom of the column was worn more than the one at the top. Asymmetrical wear along the ball track was also reported after the test due to higher pressure zones emerging from the components of the force that were not evenly distributed by the connecting rod/crank configuration.

Though researchers have reported works in fretting, to the best knowledge of the authors, there has been no work reported in analyzing the fretting wear of steel bearings in the presence of lubricating anti-fretting paste. Steel bearings are used in several industrial and automotive applications such as trolley bearings in heat treatment plants. These bearings stay stationary when the trolleys are kept inside the furnace and the heat-treated components are replaced as required. Apart from the steel bearing applications such as high-strength steel, threaded connections are mostly under the boundary of the starved lubrication regime, and failure in such applications is primarily due to fretting. To avoid failure due to fretting, lubricating grease pastes are applied in these applications. Hence, it is important to investigate the tribological properties of the lubricating pastes and their wear phenomenon using steel bearings. Several well-known organizations such as the National Lubricating Grease Institute (NLGI) have also indicated the importance of fretting wear test results in their GC-LB specifications. A lubricant designated with "GC" means it is suitable for wheel bearings or chassis lubricant, while the designation "LB" means it is used for "chassis lubricant". Thus, the present work is the first of its kind where the study of fretting wear of axial steel thrust bearings using industrial lubricating pastes has been reported. Since there has been no work reported on the tribological properties of lubricating paste, this investigation of lubricating paste will be useful for understanding the fretting wear mechanisms in steel axial thrust bearings and developing next-generation highly effective lubricating pastes.

2. Experimental Procedure

2.1. Materials

Three commonly used industrial lubricating grease pastes (P1, P2, and P3) were chosen for this present work. These were procured from a local market in Chennai, India. Table 1 exhibits the properties of commercial industrial lubricating grease pastes. The commercially available pastes used in this work are shown in Figure 1.

Table 1. Properties of industrial lubricating pastes.

Properties	Lubricating Grease Pastes		
	P1	**P2**	**P3**
Base oil type	Mineral oil	Mineral oil	Synthetic oil and inorganic thickener
Viscosity of base oil (cSt)	220	220	320
Primary additives	Copper, molybdenum disulfide and graphite	Graphite and molybdenum disulfide	Nickel
Worked penetration (mm)	280–330	310–340	250–300
Specific gravity	1.3	1.3	1.3
Color	Greyish brown to cupric red	Greyish black	Silvery grey

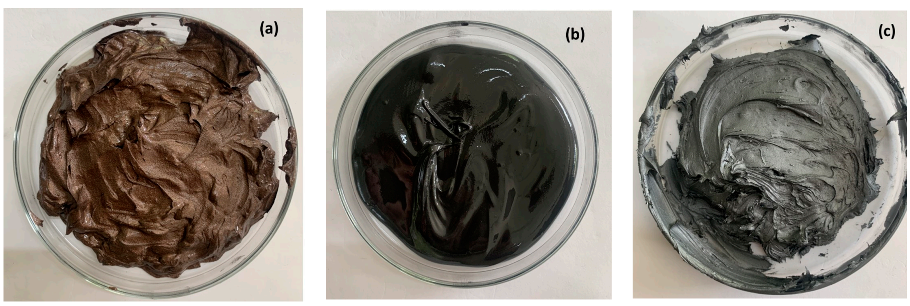

Figure 1. Photographic images of the commercial lubricating grease paste used in this study: (**a**) P1, (**b**) P2, and (**c**) P3.

2.2. Investigating Fretting Wear Properties Using the Fafnir Fretting Wear Test Rig (ASTM 4170)

The ASTM D4170 standard was followed to investigate the properties of industrial pastes to prevent fretting wear in oscillating bearings [21,22]. A Fafnir fretting test bench (Make: Magnum, Bangalore, India, Model: FTT01) as shown in Figure 2a,b, was used to address the fretting wear on the ball thrust bearings. Two ball thrust bearings (make: Nachi, Japan) were lubricated using the pastes. All the operating parameters were to the ASTM D4170 standard; however, to create a realistic industrial situation of interrupted lubrication supply or minimal lubrication supply, only the ball retainers were lubricated (Figure 2c). The excess paste from the bore and rim was carefully cleaned. The bearings were oscillated through 12° at a frequency of 30 Hz (540,000 cycles) at ambient temperature. A load of 2450 N was applied, and the test was conducted intermittently for 22 h. After the fretting test, the difference in the masses of the upper and lower pair of bearings was measured, and the mass difference is reported in this work. The composition of the bearing parts and their geometrical dimensions are shown in Tables 2 and 3.

Figure 2. (**a**) Fafnir fretting wear test rig; (**b**) arrangement of the test bearings in the Fafnir test rig; (**c**) paste applied on the bearing race; and (**d**) false brinelling indentation marks on the bearing raceway after the fretting test.

Table 2. Composition of thrust-bearing parts.

Equipment Used: OE-750, Hitachi	**Bearing Parts**		
	Race	**Balls**	**Ball Retainers**
Designated Alloy	**EN 31**		**CR3**
	Elements (%wt.)		
Carbon	1.001	0.990	0.078
Manganese	0.387	0.435	0.239
Silicon	0.219	0.281	-
Sulfur	0.012	0.024	0.014
Phosphorus	0.016	0.028	0.022
Chromium	1.518	1.468	-

Table 3. Dimensions of axial thrust bearings.

Parameters	Units	Values
External diameter	mm	35
Internal diameter	mm	16
Inner diameter of ball raceway	mm	3.5
Ball diameter	mm	7
No. of balls	mm	9
Roughness values (average)	microns	Ra: 0.1214 Rq:0.1558

2.3. Analyzing the Surface Damage to the Bearing Raceways after the Fretting Test

The mass loss of the upper and the lower pair of the bearings indicated the fretting resistance of the bearing. A machine vision system (make: Hexagon, Chennai, India; model: OLM 3020) was used to measure the areas of the false brinelling formed on the bearing race. An optical microscope (make: Olympus, Tokyo, Japan; model BX53M) was used to identify the surface damage on the raceways. After the tribo tests, all surfaces of the bearings, particularly, the bearing raceways, were thoroughly cleaned using an industrial degreaser (make: Mosil, Mumbai, India) to remove the lubricating pastes on the bearing races and any kind of lubricating films to avoid optical interference of bearing raceway.

3. Experimental Results

3.1. Investigating the Mass Loss of Bearing Races

Measuring the mass losses of the bearing races helped to differentiate the performances of the anti-fretting properties of the industrial pastes. The mass losses of the bearings were asymmetric. The upper bearings exhibited more mass loss than the lower bearings. The mass loss of the upper set of bearing races with P1 was (0.00485 ± 0.0057) g, while those for P2 and P3 were (0.0401 ± 0.0121) g and (0.0607 ± 0.0025) g, respectively. The mass loss of the lower set of bearings with P1 was (0.0148 ± 0.0038) g, while those for P2 and P3 were (0.05385 ± 0.0033) g and (0.1173 ± 0.0796) g, respectively. Figure 3 shows the average mass losses of the bearing races. It can be seen that the paste containing molybdenum disulfide and graphite (P1 and P2) exhibited less mass loss than the paste that did not contain molybdenum and graphite (P3). In addition to molybdenum disulfide and graphite, P1 also contains copper. The least resistance to mass loss was exhibited by P3, which is a nickel-based paste.

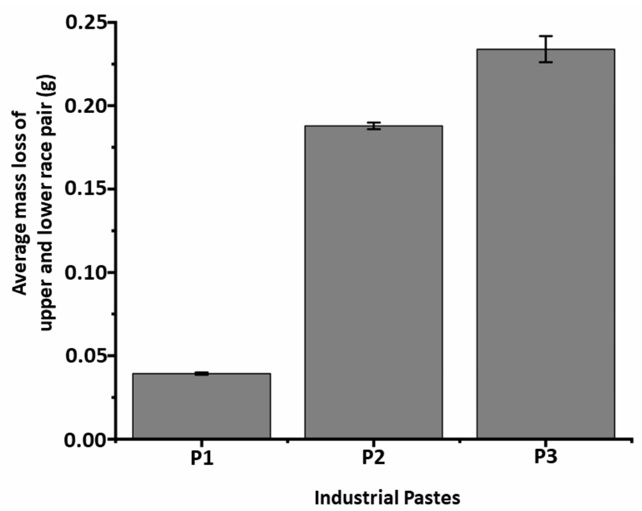

Figure 3. Average mass loss of the bearing races after 22 h of the fretting wear test.

The false brinelling on the upper bearings was less deep in P1, but excessive damage was seen in P2 and P3 even in the upper bearings, indicating lower fretting wear resistance of P2 and P3 as compared to P1 (Figure 4). Also, the other images of the wear scar indicated the asymmetric wear of the bearing. Similar asymmetric wear results using the Fafnir tribometer were also reported by Minh et. al. [21]. Hence, the presented results are in line with earlier reported results.

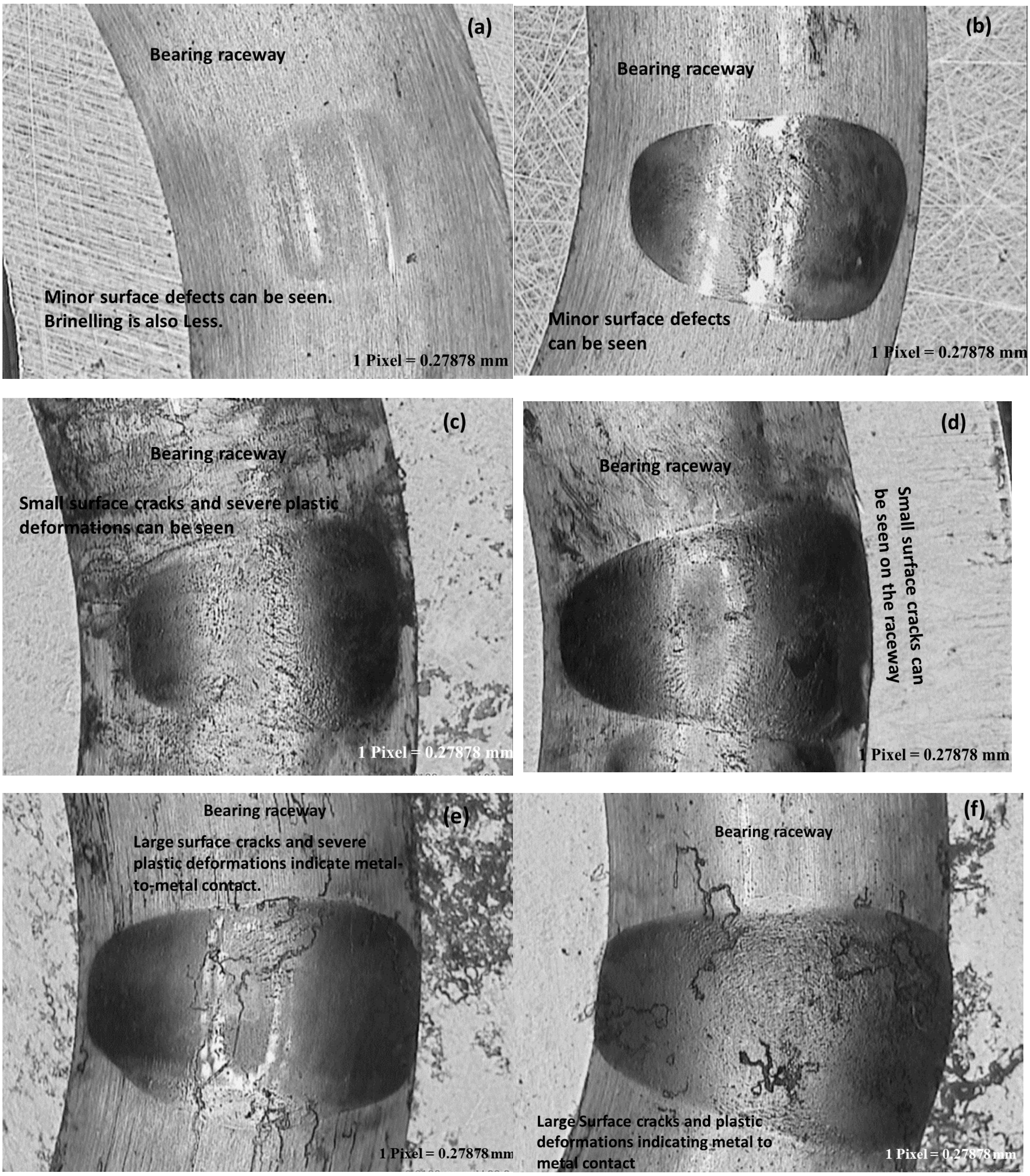

Figure 4. Machine vision images of P1, P2, and P3. Upper bearing (**a**,**c**,**e**) of P1, P2, and P3 and lower bearing (**b**,**d**,**f**) of P1, P2, and P3.

3.2. Measuring the Areas of the Indentations Formed during the Fretting Test Using a Machine Vision System

The areas of the indentations shown in Figure 2d on the races due to false brinelling were measured using a machine vision system (make: Hexagon, Chennai, India; model: OLM 3020) (Table 4). For each paste, 36 indentations were formed on the bearing race. The areas of the indentations caused due to fretting for Paste P1 were found to be between 1.656 and 3.86 mm^2 (average: 2.537 $\pm$ 0.623 mm^2), for Paste P2, it was between 2.92 and 5.706 mm^2 (average: 4.504 $\pm$ 0.566 mm^2), and for Paste P3, it was between 3.709 and 5.884 mm^2 (average: 4.914 $\pm$ 0.621 mm^2). The average area of the indentations is shown in Table 4, which shows that the average area of false brinelling with P1 was the least, at about 50% less than both P2 and P3. The optical microscope images captured using the machine vision system (Figure 4) indicate high surface damage (cracks and plastic deformations) in the cases of P2 and P3.

Table 4. Area of indentations measured after the fretting wear test.

Paste	Area of False Brinelling on the Bearing Raceways, mm^2								
P1	2.318	2.002	1.998	2.009	2.525	2.129	2.038	1.685	2.341
	2.343	2.132	2.843	3.372	3.724	3.385	3.111	2.853	2.454
	2.902	2.400	2.388	2.542	2.575	3.364	3.685	3.722	3.860
	2.051	2.083	1.656	2.065	1.713	1.924	2.223	2.317	2.605
	Average area of false brinelling with P1: 2.537 $\pm$ 0.623 mm^2								
P2	3.876	2.992	4.280	3.267	4.734	4.594	4.443	4.189	3.994
	4.418	3.977	3.736	3.975	3.890	4.471	5.035	4.797	4.799
	4.177	4.290	4.515	4.613	4.783	4.880	4.818	4.591	4.197
	4.886	4.511	4.936	5.288	5.706	5.170	5.124	5.014	5.203
	Average area of false brinelling with P2: 4.504 $\pm$ 0.566 mm^2								
P3	4.293	3.807	4.233	4.334	4.597	5.019	4.941	5.579	5.245
	4.971	4.752	5.342	3.959	3.709	5.025	5.780	5.470	5.355
	5.739	5.779	5.320	5.023	4.517	4.816	4.748	5.387	5.760
	5.844	5.551	5.195	4.891	4.227	3.975	3.874	4.738	5.117
	Average area of false brinelling with P3: 4.914 $\pm$ 0.621 mm^2								

4. Discussion

4.1. Role of Lubricating Composition in Controlling the Fretting Wear of the Bearings

False brinelling occurs in the presence of small oscillations between the bearing ring and rolling elements. Indentations of false bearing can be seen on the raceways in each case of the lubricants in this work. It is known that lubricants separate the mating pairs in the bearings due to the formation of elastohydrodynamic (EHD) regimes. However, ensuring an efficient EHD regime requires certain conditions such as the inlet of the lubricant flow and the retainment of the lubricant between the mating pairs [22]. The retainment of the lubricant in a unidirectional motion is quite possible as compared with an oscillating motion. It has been reported that due to less amplitude of oscillation than the contact region, lubricants do not reach many of these contact areas [22], leading to greatly starved lubrication conditions and resulting in surface-to-surface contact. The absence of lubricating film leads to the formation of iron oxides, which accelerates the wear between the mating pairs. Therefore, under false brinelling conditions, both the bearing balls and the races are not protected by an adequate quantity of lubricant. Hence, the wear mechanism is a complex phenomenon including several wear mechanisms such as the formation of three body wear, adhesion, wear, and even corrosion. The failures observed in the present study are similar to false brinelling; however, the presence of lubricant can be notified as a distinctive fretting wear [22].

Highly additivated pastes are efficient in controlling the wear between the mating pairs. As reported earlier [22], the high wear in fretting is due to the chances that lubricants are not available between the mating pairs, indicating a more severe situation than the boundary lubrication regime. Thus, the absence of favorable conditions for generating EHL conditions indicated the limitation of lubrication by the oils. Therefore, industrial pastes containing a hybrid solid lubricant would be a better choice for applications subjected to oscillatory and vibratory motion; however, the type of additives present in the lubricating pastes also play an important role. Kontou et al. [23] used ZDDP as additives along with dispersants and reported the positive effect of the lubricating nature of ZDDP in reducing fretting wear. Zhan et al. [24] also reported that the frictional coefficient was more stable with less wear when graphite was introduced along with copper in a composite. Xiao et. al. [25] also indicated that the presence of copper and molybdenum in a system significantly reduced friction between the mating pairs. Thus, it is known that graphite, molybdenum disulfide, and copper exhibit excellent anti-wear and extreme pressure properties. Hence, the presence of a combined package of copper, graphite, and molybdenum disulfide in P1 and graphite and molybdenum disulfide in P2 helped to exhibit more excellent tribological properties than P3, which primarily contains nickel. Thus, the present results are in line with those of earlier reported work.

Apart from the additive content and their types, the properties of the lubricants such as viscosity and work penetration also play an important role. Maruyama et al. [26] reported that lubricants' viscosity and work penetration, particularly, the grease-type lubricants, played an important role in controlling the fretting wear. Low viscosity and high work penetration favor a reduction in fretting wear. Higher viscosity under intense velocity increases the chances of starved lubrication. In the present work, the base oil viscosity of P3 was more than P1 and P2. Additionally, the work penetration of P1 and P2 was more than P3. Thus, the low viscosity and more work penetration of P1 and P2 resulted in easy oil separation in P1 and P2 as compared with P3. Due to easy oil separation in P1 and P2, the solid lubricants formed a stable layer between the mating pair. Figure 5 shows a schematic diagram of the easy separation of the oil leaving behind the solid lubricants to form a layer between the mating pair (Figure 5a), while due to high viscosity and low work penetration, the additives remain entrapped without forming a lubricating film on the mating surfaces, which are in boundary regime lubrication (Figure 5b). Thus, the lubrication mechanisms exhibited by the pastes in the present work are like grease-type lubricants already reported earlier [26].

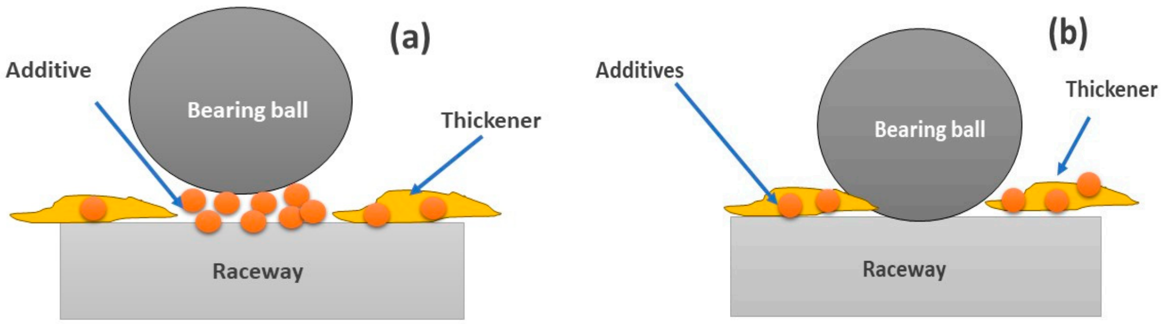

Figure 5. Schematic diagram of the plausible mechanism of lubricating grease paste (**a**) film formation in the presence of optimal viscosity and work penetration (**b**) absence of film in high viscosity and low work penetration lubricants.

4.2. Wear Mechanisms Experienced by the Bearings during Fretting

As reported earlier, fretting involves the generation of wear debris that comes out of the fretting contact area into the system [22]. The debris that formed are oxides; however, due to an insufficient supply of oxygen, the surface damage is adhesion, resulting in micro-welding of the debris on the surface. Figure 6 indicates the adhesion of debris on the surface during fretting wear. Oxygen supply to the contact areas is an important parameter in fretting. There are chances that the surfaces in contact are deprived of an adequate supply of oxygen because of:

i. The increase in the fretting wear surface are.
ii. The presence of lubricants provided by the lubricating pastes.

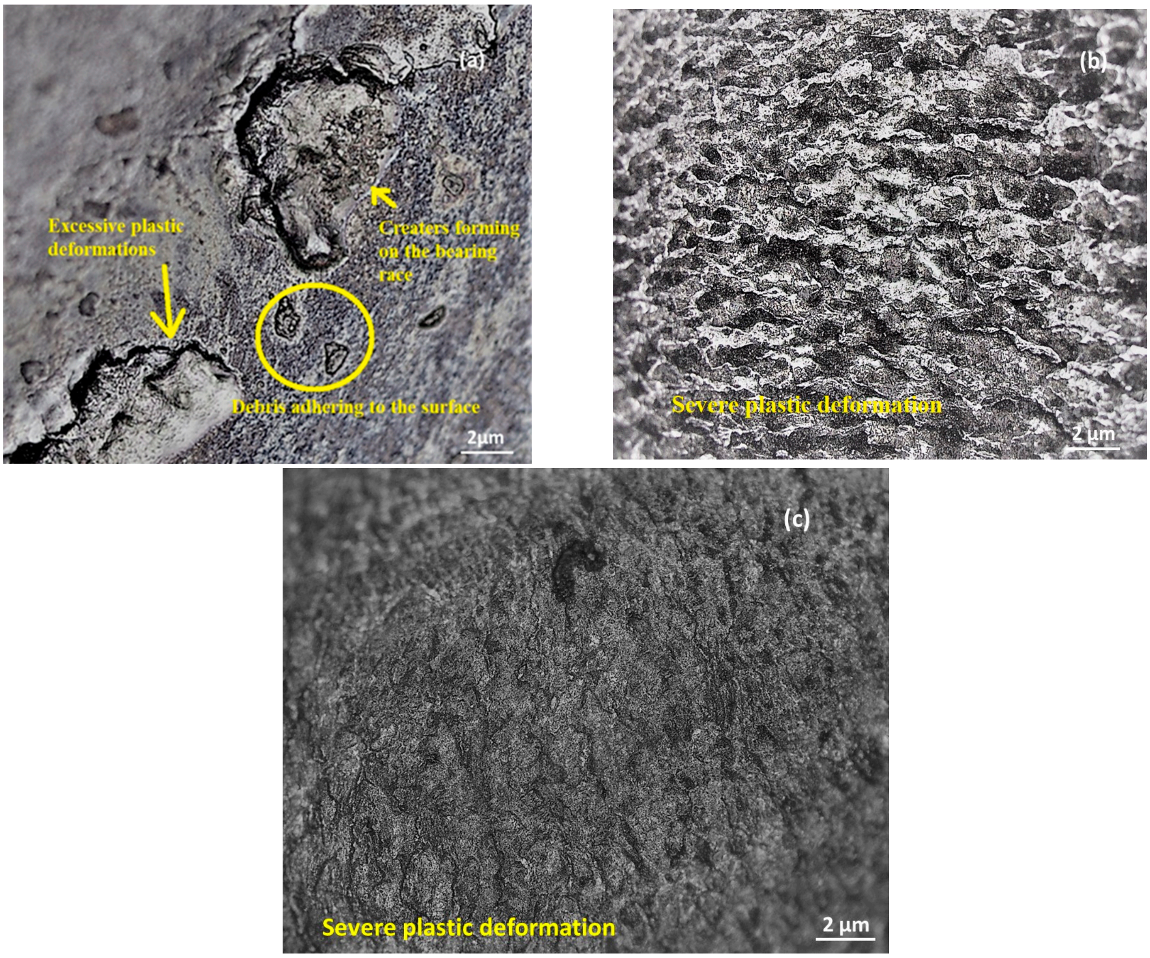

Figure 6. Optical microscope images of the brinelling surfaces of the bearing races while using (**a**) P1, (**b**) P2, and (**c**) P3.

In such cases where oxidation might not occur, fretting results in severe plastic deformation and material transfer between the contact pairs (as seen in Figure 6), which can be seen significantly in P3. The surface area of the damage was greater in P3 as compared with P1 and P2. The debris formation in fretting contacts of steel was also reported by Kirk et al. [27]. However, the presence of such debris can be advantageous or disadvantageous. These debris are mostly oxides of iron, primarily hematite. Additionally, the debris remains attached to the bed intermittently at different locations. Thus, tribo-sintering of the debris on the debris bed is also a phenomenon in fretting reported by researchers [28,29]. Other authors also described similar adhered debris as “oxide compact layers” or “glazed layers” [30], and these are formed due to hot pressing between the mating pairs. The presence of such “glazed layers” forms a protective layer that reduces the wear between the surfaces [31,32]. This calls for an important observation that in the present situation, the adherence of the debris on the raceways helped to reduce the wear in P1 as compared with P2 and P3. Apart from adhering to the surfaces, the particles dislodged from the surfaces of metals are highly reactive and hence, become oxidized. These oxidized particles can either act as abrasive particles or can act as oxide films separating the two mating pairs [33,34]. In the present situation, the debris was seen to have mostly been adhered to the surfaces, and the results indicated the least mass losses of the bearing races. Hence, the presence of debris in the present situation is an advantageous factor. Additionally, the presence of the lubricating paste between the mating pair might not have allowed for the free flow of the loose debris and thus, the third body wear caused by the particles with the lubricant as the carrier might not have happened in this case. This can be supported by the data shown in the work penetration values of the lubricating paste. The work penetration of P1 was 280–330, while the work penetration of P2 was 310–340, indicating the easy flow of the debris-inclusive paste in P2, which might have formed as abrasive particles. However, since the additive package was not very effective in P3, even though the work penetration was less than in P1 and P2, it exhibited more wear. Therefore, the properties and the composition of the lubricants play a major role in controlling fretting wear. Furthermore, a severe amount of plastic deformation was observed on the surfaces of the bearing, which is a characteristic feature of fretting wear. Warmuth et al. [35] and Bouydon et al. [36] indicated that an increase in contact area hinders the oxygen supply to the contact areas, resulting in oxygen-derived areas that favor severe plastic deformations, as seen in all the lubricating pastes. Paste P3 exhibited high wear scar areas; thus, the plastic deformation was severe, and the mass loss of the bearing races was also the highest among the three, which is in line with the findings of other researchers. Thus, debris formation and plastic deformation are important factors in understanding the wear mechanisms of fretting wear.

5. Conclusions

The present work exhibited a systematic study of the fretting wear of axial thrust steel bearings following ASTM D 4170 standards. To create a realistic situation of intermittent or scarce lubricant supply, the tests were conducted on a starved lubrication regime with very minimal lubricant paste applied only on the ball retainers. Additionally, to the best knowledge of the authors, there has been no systematic work reported on investigating the fretting wear of axial thrust bearings in the presence of industrial lubricating pastes.

From the results, it was observed that the debris formation in fretting plays an important role in controlling the damage that occurs during fretting wear. The adhesion of the debris and the severe plastic deformation indicated a deficiency in the oxygen supply to the mating contact. Additionally, the mating pair (bearing race and balls) witnessed mechanical deformations and adherence of the debris on the raceways. Further wear was facilitated with the removal of the debris from the contact surfaces. The wear patterns indicated that each paste exhibited a different wear mechanism. The supply of oxygen between the mating pairs determines the type of wear mechanism. Thus, to protect the steel surfaces of the bearings from fretting wear, the usage of the correct type of paste is important. The present work indicated that the lubricating paste containing a mixture of graphite, molybdenum disulfide, and copper is a better choice than nickel-based paste; however, the type of applications where this paste is to be applied would also be a deciding factor. The mass loss of the bearing races in the case of P1 was about 75–80% less than P2 and P3. Additionally, the area of the indentations formed on the bearings in the case of P1 was almost 50% less than P2 and P3. These results further indicated that the type of base oil and the solid lubricants present in a lubricating paste play a major role. This work will be highly beneficial in understanding the fretting wear behavior of industrial fretting pastes.

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