lubricants

MDPI

Article

Evaluation of Lubricant Selection and Lubrication Intervals for Pin–Bushing Bearings Operating Under High-Temperature Conditions in Heavy-Duty Construction Machinery

Ilhan Celik [1], Abdullah Tahir Şensoy [2,3,*] and Sevki Burak Sezer [4]

1 Department of Mechanical Engineering, Faculty of Engineering and Natural Sciences, Samsun University, 55420 Samsun, Türkiye
2 Faculty of Mechanical Engineering, Delft University of Technology, Mekelweg 2, 2628 CD Delft, The Netherlands
3 Department of Biomedical Engineering, Faculty of Engineering and Natural Sciences, Samsun University, 55420 Samsun, Türkiye
4 Department of Mechanical Engineering, Institute of Graduate Programs, Samsun University, 55420 Samsun, Türkiye
* Correspondence: a.t.sensoy@tudelft.nl or tahirsensoy@hotmail.com

Abstract

Pin–bushing bearings in heavy-duty construction machinery operating in severe industrial environments are susceptible to accelerated wear, grease degradation, and lubrication failure, yet application-specific guidance for lubricant selection and re-greasing intervals under such conditions remains limited. This study evaluates the combined effects of bushing material (hardened steel, cast bronze, and Cu–Sn alloy), grease type (three commercially used greases with viscosities of 120, 460, and 150 mm^2/s at 40 °C), and lubrication interval (8, 12, and 24 h) on grease-condition indicators in a field-operating wheel loader used in slag handling, where surrounding slag temperatures may reach 700–800 °C. A Taguchi L9 orthogonal array was used to define nine experimental configurations, each applied for approximately one week under real operating conditions. Grease samples were characterised using the SKF grease analysis kit based on NLGI consistency grade, base oil release rate, and contamination particle count. All greases showed an increase in NLGI grade from 2 to 3–4 during service, indicating thickening and a possible risk of lubrication channel blockage. Oil release rates decreased by up to 60% in some configurations, indicating reduced base oil mobility during service. When the three grease-condition indicators were evaluated together by Grey Relational Analysis, the combination of steel bushing, type B grease (ISO VG 460, lithium complex with MoS_2), and a 12 h lubrication interval showed the most balanced overall response. These findings provide field-based guidance for grease selection and maintenance scheduling in pin–bushing systems operating under demanding service conditions.

Keywords: high-temperature greases; Taguchi method; pin–bushing lubrication; tribology

Check for updates

Received: 4 March 2026
Revised: 29 March 2026
Accepted: 11 April 2026
Published: 20 April 2026

1. Introduction

Throughout history, numerous research and development efforts have been undertaken to enhance the mechanical and physical properties of materials and improve their durability. These studies have primarily aimed to extend the service life of different material classes. Friction and wear issues encountered in many aspects of daily life lead not only to significant economic losses but also to increased labour costs. Consequently, the development of wear-resistant materials has become a key research focus in engineering, with many researchers investigating this topic across various materials and applications [1–3]. In recent years, rapid technological advancements in industrial machinery have made the development of different lubrication strategies essential for improving performance and ensuring the longevity of these machines. Machinery used in heavy industries such as automotive manufacturing, wind turbine production, construction, and steel production operates under harsh working conditions. Exposure to high temperatures causes problems such as wear and friction to occur more frequently, leading directly to performance losses [4]. There is a high demand for long-lasting greases in the grease market to help machines maintain their functionality under high-temperature conditions and offer a longer service life [5]. At high temperatures, grease performance is primarily determined by the decrease in base oil viscosity, oxidative degradation, and changes in the thickener structure, all of which directly affect film formation and wear behaviour. Previous studies have shown that thermal effects significantly alter the lubricant's rheology and load-carrying capacity, particularly under boundary and mixed lubrication regimes [4,6].

Machinery operating under high-temperature conditions requires lubrication systems with enhanced resistance to friction and wear. In particular, optimising lubrication conditions for such environments offers significant benefits in reducing maintenance costs and improving machine durability. However, the limited number of studies in this field means that a standardised guide for industrial applications has not yet been established. Despite this, the available research provides valuable insights for developing various lubrication strategies [7]. Pin–bushing systems operating under oscillating motion are particularly sensitive to dirt accumulation and lubrication deficiency due to repeated boundary contact conditions. In such systems, third-body abrasive particles and lubricant ageing mechanisms jointly determine the service life. Therefore, optimisation strategies should consider both contamination behaviour and lubricant stability rather than focusing solely on material hardness or nominal load capacity. In this context, some researchers have conducted studies on pin–bushing systems in the literature [8–10].

This study presents a series of experimental investigations aimed at optimising lubrication systems for industrial machinery, with particular emphasis on demanding field conditions. In this context, three grease types recommended for industrial use were evaluated in combination with different bushing materials and lubrication intervals. During the experimental stage, different optimization methods were used to structure the field trials and reduce the number of required configurations [11–16]. Among these, the Taguchi method was selected in the present study. To complement the separate single-response Taguchi evaluations, Grey Relational Analysis (GRA) was later used as a multi-criteria ranking tool for the three grease-condition indicators. Tests conducted with the SKF grease analysis kit evaluated oil release behaviour, NLGI grade, and contamination particle count. The resulting data provide practical guidance on how lubrication interval, grease formulation, and bushing material interact under harsh service conditions, and they offer useful recommendations for maintenance planning in heavily loaded industrial machinery.

2. Materials and Method

2.1. Industrial Work Machine Used in the Experiments and Its Technical Specifications

For this study, the Komatsu WA470-6 loader belonging to Yeşilyurt Iron and Steel Port Operations Inc. (Samsun, Türkiye), which is used in its steel mill factory, was selected as the work machine on which the trials would be conducted (Figure 1). With its 25-tonne weight, 6 m^3 bucket capacity, and 274-horsepower engine operating at 2000 rpm, this work machine performs tasks effectively in industrial environments, especially where heavy loads need to be transported and dumped. This widely used model in Türkiye plays a significant role in under-cast tapping operations in steel mills. Thanks to its high load capacity and powerful engine, it enables the rapid discharge of large volumes of material from under the cast.

Figure 1. The slag-handling loader during hot-slag loading (**a**,**b**); the studied pin–bushing assemblies are located in the bucket linkage mechanism.

During under-cast tapping operations, the loader is exposed to hot slag, and the surrounding slag temperature may reach approximately 700–800 °C. This value refers to the process environment rather than to a directly measured pin–bushing contact-interface temperature. The actual interface temperature was not instrumentally monitored in the present study.

2.2. Grease Analysis Kit

The grease test kit is a set of test methods used to analyse grease samples. Lubricant analysis is an essential component of a predictive maintenance strategy, and oil analysis is already standard practice in many sectors. This kit can be used to test grease consistency, determine oil release properties, and assess grease contamination [17,18]. This test kit can perform three different analyses: grease oil consistency, oil release characteristics, and contamination assessment. These tests provide data on the performance and service life of the oil. Interpreting the results according to the included guidelines provides important information regarding lubrication intervals, contamination levels, and potential sources of pollution. The NLGI consistency grade of the grease samples was determined using a standardised testing method. A representative sample of grease was placed between two transparent plastic sheets and positioned on the NLGI grading template using an alignment plate. The assembly was then subjected to a constant load at room temperature for 15 s (Figure 2). This field consistency procedure follows the standard protocol of the SKF grease test kit (TKGT 1) and is consistent with ISO 2137 [19].

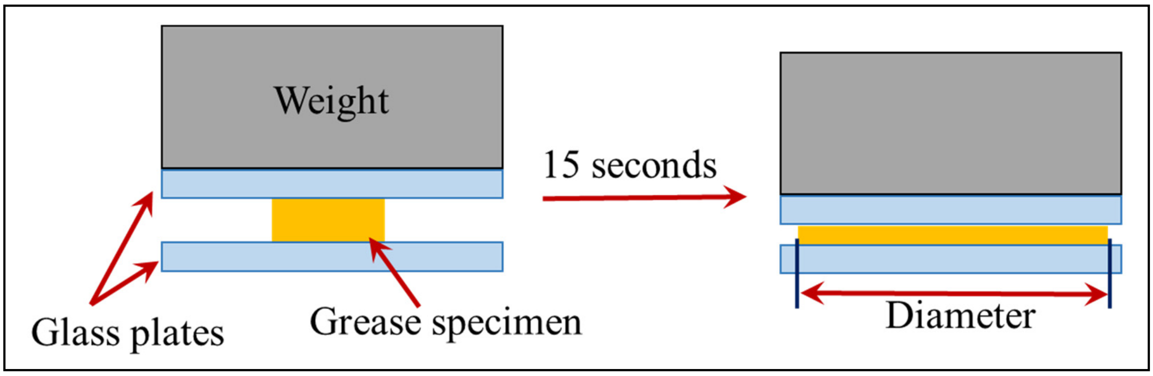

Figure 2. Schematic representation of the NLGI test method [20].

Once the weight had been removed, the grease sample distributed between the laminates was classified according to the outer ring diameter formed by the oil on the NLGI grading template, as well as the corresponding colour match. This was then evaluated as an increase or decrease in grade relative to the original NLGI grade of the unused grease. Base oil ratios within the internal structure of greases vary between 65% and 90%. Over time, working greases release the base oils they have penetrated internally, and this process stops after a certain period. The grease then begins to dry. This process, known as the ageing of the oil, is affected by various factors, including temperature, contamination, and pressure in the working environment. The amount and viscosity of the base oil contained within the grease should not change significantly within the recommended lubrication interval. In the test, a certain amount of oil is placed on absorbent paper and heated in a temperature-controlled environment of 15–60 °C for approximately two hours. During this time, the base oil is released from the grease. The diameter of the released oil on the absorbent paper is measured and compared using the same method with the release diameter of unused oil. This involves calculating the oil release areas for clean and contaminated oil samples and determining the rate of change in oil release according to the following formula: If the result is negative, the oil release is decreasing; if positive, it is increasing. In the present study, the oil release test was performed at 60 °C for 2 h (as defined by the kit procedure).

$$S = 0.785 \times ({D_{avg}}^2 - 100)$$

S: Oil Release Area
D_{avg}: Oil Release Diameter

$$\% = (S_{used} - S_{fresh})/S_{fresh}$$

The oil contamination test was used to assess the condition of grease samples and the likely severity of contamination in the pin–bushing system. Contamination may arise from poor sealing, harsh environmental exposure, dirty grease guns, improper assembly, and the ingress of water or dust. For comparative evaluation, the size, quantity, and morphology of visible particles were examined using the microscope included in the grease analysis kit (Figure 3). In the present study, contamination assessment was performed at 60–75× magnification, and particles ≥40 μm within an approximately 1–2 mm field of view were counted.

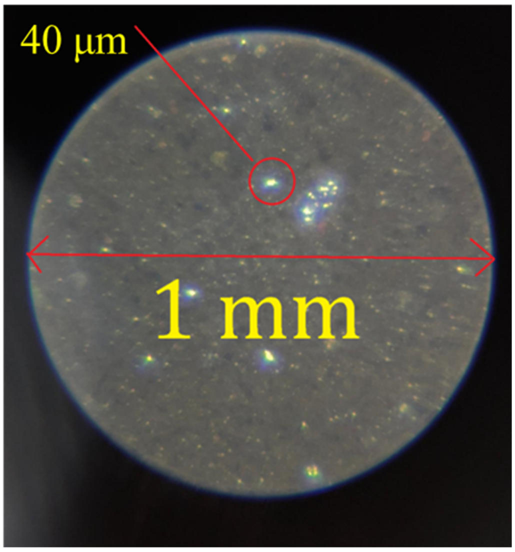

Figure 3. An example image taken from a contaminated pollution microscope.

2.3. Types of Bushing Materials

In this study, the pins in the bucket linkage mechanism of the work machine remained fixed, but performance comparisons were made using bushings with different material properties. Three bushing types that are readily available on the market and commonly used in field applications were selected for the experiment (Figure 4): (a) a hardened steel bushing, (b) a standard cast bronze bushing, and (c) a Cu–Sn alloy bushing. The three material groups were chosen because they represent common field solutions with distinct tribological characteristics. Hardened steel bushings are widely used because of their load-bearing capacity and availability, cast bronze bushings are often preferred for their conformability and grease retention behaviour, and Cu–Sn alloy bushings provide an additional comparison point because of their moderate hardness and corrosion resistance. To limit manufacturing-related variability, the bushings were obtained from the same production batch or serial line where possible. During the field campaign, three bushings were available for each material group, and the tested configurations were implemented across successive operating periods under routine field conditions. Each experimental configuration was maintained for approximately one week before the bushing was replaced and the next condition was started.

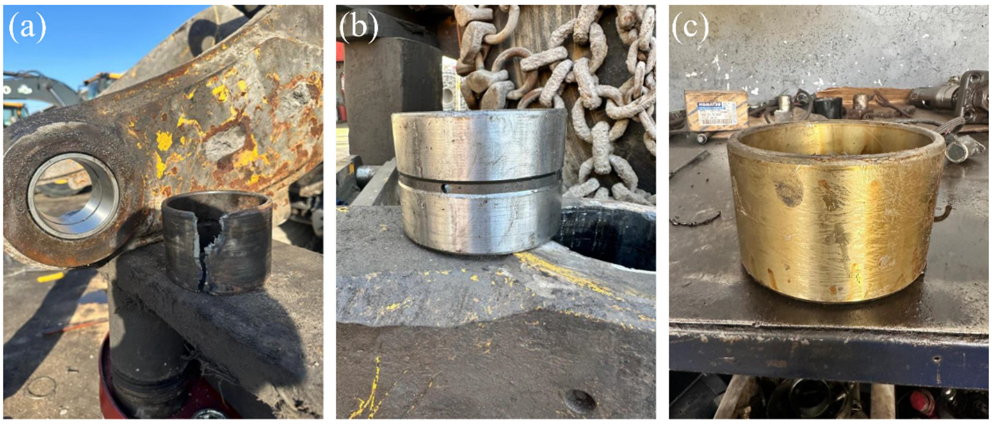

Figure 4. Bushings used in the study: (**a**) a damaged bushing that was replaced with a new one; (**b**) a hardened steel bushing; and (**c**) a Cu-Sn alloy bushing.

2.4. Lubricants Used in the Study

This study compared the lubrication performance of the connecting elements of a work machine using three different grease oils (coded A, B, and C). These greases have different formulations and viscosity properties. Grease A is a multipurpose extreme pressure (EP) grease made with a mineral base oil and a lithium-molybdenum thickener system. It has a viscosity of around 120 mm^2/s at 40 °C and can remain stable up to a dropping point of 190 °C. Grease B contains a mineral base oil of ISO VG 460 viscosity grade and has a lithium complex thickener structure. It is formulated for heavy-duty service conditions and exhibits a viscosity of approximately 460 mm^2/s at 40 °C. Thanks to its high dropping point (approximately 300 °C) and 3% molybdenum disulfide (MoS_2) additive, it is durable under high pressure and vibration conditions. Grease C, on the other hand, is a lithium soap grease containing a highly refined mineral base oil. It has a viscosity of 150 mm^2/s and a dropping point of 200 °C. Fortified with EP additives and oxidation-corrosion inhibitors, this grease provides superior protection against rust and water, especially in humid environments. It also offers continuous lubrication by maintaining film strength under medium-to-heavy-load conditions. All greases were tested under the same experimental protocol to evaluate the performance of the materials depending on temperature, load, and environmental effects under application conditions.

There are many methods used for lubricating machinery and equipment. Programmable automatic lubrication systems and manual lubrication methods are the most common lubrication methods. Traditional manual lubrication methods are used more often for machines operating in harsh environments. Traditional methods require more attention and monitoring than automatic methods because they are operated manually. In this study, the lubrication process was carried out by the maintenance personnel of the construction machinery used in slag removal after the general cleaning and washing–lubrication of the machine, in accordance with the test parameters. Lubrication was performed by the site maintenance team following the same work instruction and the predefined test schedule; nevertheless, minor operator-related variability in lubricant application quantity cannot be fully excluded and is therefore acknowledged as a limitation.

2.5. Determination of Experimental Design (Taguchi Method)

This study applied the Taguchi experimental design method to organise the field campaign and compare the effects of the selected factors with a limited number of trials. An L9 (3^3) orthogonal array was used for three factors at three levels (Table 1). In this study, the "Smaller-the-Better" criterion was adopted for the response calculations. The S/N ratio was calculated using the expression $\eta = -10 \log_{10} [(1/n) \times \Sigma(y_i^2)]$. In the general Taguchi formulation, η denotes the S/N ratio, y_i denotes the observed response value, and n denotes the number of values used in the calculation. In the present study, the S/N analysis was used to compare the L9 configurations under field conditions [21,22].

Table 1. Taguchi experimental design: control factors and levels.

Factor	Level 1	Level 2	Level 3
1	Steel	Bronze	Cu-Sn Alloy
2	Grease A	Grease B	Grease C
3	Once every 8 h	Once every 12 h	Once every 24 h

The levels of each factor were determined by considering accessibility under field conditions and the range within which material–lubricant interactions could directly affect performance (Table 2). These levels were selected to create combinations that are both theoretically significant and practically applicable. A total of nine experimental configurations were created using Taguchi's L9 (3^3) orthogonal design. Each configuration was tested for one week. For example, in the first experiment, we used a steel bushing and Type A grease, and performed oil changes every eight hours over a one-week period. Used oil samples were analysed at the end of each period. At the end of each week, any necessary changes were made to the relevant equipment and the next configuration was initiated. This approach aimed to determine the optimal lubrication conditions and develop data-driven recommendations for field applications. In the Taguchi method, the output was to determine the NLGI grade of the samples, their base oil release rate, and the particle count they contained.

Table 2. Taguchi L9 design used in the experimental study.

Experiment No	Bushing Type	Grease Type	Lubrication Interval
1	Steel	Grease A	Once every 8 h
2	Steel	Grease B	Once every 12 h
3	Steel	Grease C	Once every 24 h
4	Bronze	Grease A	Once every 12 h
5	Bronze	Grease B	Once every 24 h
6	Bronze	Grease C	Once every 8 h
7	Cu-Sn Alloy	Grease A	Once every 24 h
8	Cu-Sn Alloy	Grease B	Once every 8 h
9	Cu-Sn Alloy	Grease C	Once every 12 h

3. Results and Discussion

3.1. Experimental Analysis

The NLGI grade results obtained for different bushing materials, grease types, and lubrication intervals are summarised in Table 3. For the grease samples taken from the bucket connection bearings operating with the steel bushing, the NLGI grade was determined as 3 for Experiment No: 1, where lubrication was performed every 8 h with Grease A. In Experiment No: 2, where lubrication was performed every 12 h with Grease B, the NLGI grade was 2, while in Experiment No: 3, where lubrication was performed every 24 h with Grease C, the NLGI grade was found to be approximately 4. According to the results obtained in systems using the bronze bushing, the NLGI grade was determined as 3 for Experiment No: 4, where lubrication was performed every 12 h with Grease A, and for Experiment No: 5, where lubrication was performed every 24 h with Grease B. In Experiment No: 6, where lubrication was performed every 8 h with Grease C, the NLGI grade was observed to be 2. For the bucket connection bearings operating with the alloy bushing, the NLGI grade was determined as 4 for Experiment No: 7, where lubrication was performed every 24 h with Grease A. For Experiment No: 8, where lubrication was performed every 8 h with Grease B, and for Experiment No: 9, where lubrication was performed every 12 h with Grease C, the NLGI grade was found to be 3. The obtained results show that the bushing material and lubrication interval have a significant effect on the consistency properties of the grease. It was observed, especially in longer lubrication intervals, that the NLGI grade increased for some grease types, while in conditions with more frequent lubrication, it remained at lower or medium levels.

The differences in particle size and particle count observed in the grease samples indicate that bushing material, grease type, and lubrication interval influenced grease condition during service (Figure 5). Experiments 1, 3, 4, and 5 showed four particles of approximately 50 μm within the observed field, whereas Experiment 2 showed only one particle of comparable size. This lower particle count suggests that the grease–material–interval combination used in Experiment 2 was more favourable in limiting solid contamination and/or wear debris in the sampled grease. Experiments 6, 7, 8, and 9, in which three particles were observed, may be interpreted as showing an intermediate response. These observations should be read as comparative lubricant-condition evidence rather than as a direct measurement of wear rate or a definitive identification of a specific lubrication regime. Nevertheless, the results support the practical conclusion that grease selection and lubrication interval materially affect the tribological behaviour of the system under field conditions, consistent with previous studies highlighting the importance of lubrication conditions and surface interactions in wear-related damage evolution [23–25].

Table 3. Grease analysis results obtained under different bushing materials and lubrication conditions.

Exp. No	NLGI Grade	Particle Count	Oil Release Rate
1	3	4	−32.49
2	2	1	−29.35
3	4	4	−57.37
4	3	4	−31.84
5	3	4	−37.26
6	2	3	−34.37
7	4	3	−55.68
8	3	3	−44.76
9	3	3	−59.96

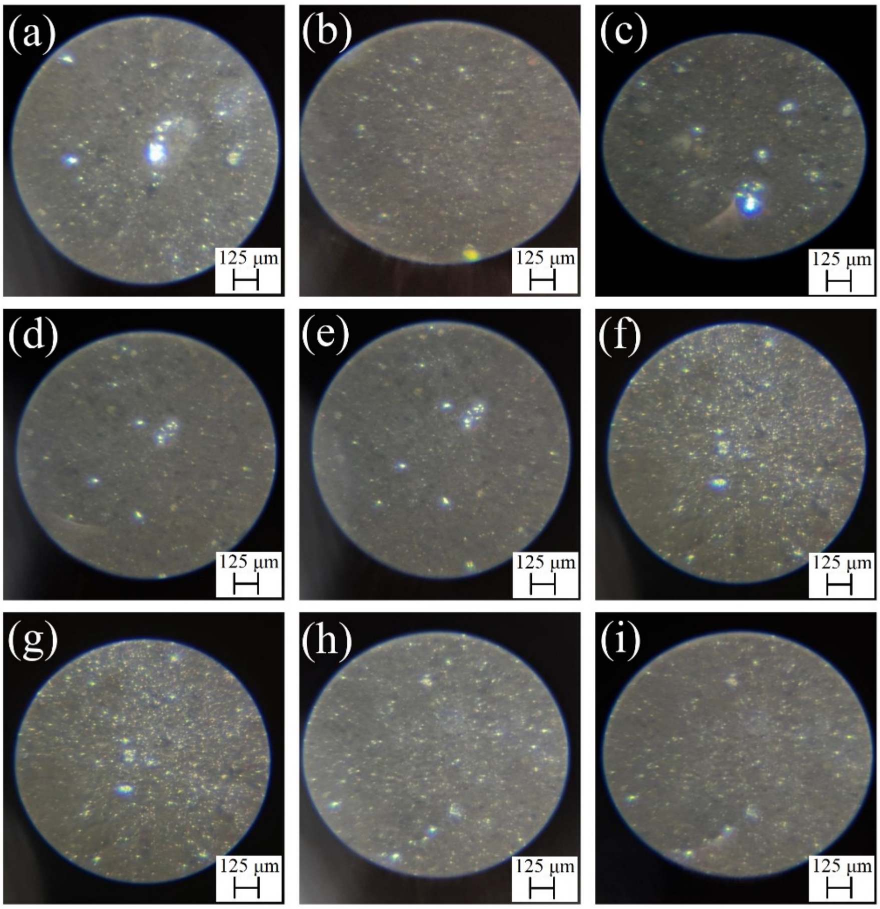

Figure 5. Image-based comparison of particle distribution and particle count in grease samples under different experimental conditions (Experiment No. 1–9); panels (**a**–**i**) correspond to Experiments 1–9, respectively.

Oil release rate analyses show that different bushing materials, grease types, and lubrication intervals have significant effects on the base oil retention capacity. While the measured oil release diameters within the scope of Experiments No. 1–9 varied in the range of 20.5–29.5 mm, the calculated oil release rate changes took negative values in all experiments, revealing that the base oil release capability of the greases used decreased during their operating time (Figure 6). Particularly in Experiments No. 3, 7, and 9, the reduction in oil release, reaching levels of −55% to −60% alongside lower D_{avg} values, indicates that the base oil became more entrapped within the thickener matrix of the grease structure and oil ageing progressed. This mechanism can be associated with the partial evaporation, oxidation, or retention by wear particles of the base oil under the influence of temperature, pressure, and environmental contamination applied during operation. In contrast, the relatively limited oil release reduction in Experiments No. 2 and 5, where higher oil release diameters were measured, suggests that the grease formulation and lubrication interval were effective in preserving base oil mobility. From an engineering perspective, a significant decrease in the oil release rate indicates an increased tendency of the grease to dry out and a heightened risk of transitioning to boundary lubrication conditions in the long term. Therefore, when selecting grease for bushing–bearing systems operating under high load and temperature, not only the initial NLGI grade but also the base oil release stability and ageing behaviour should be considered; the system's tribological continuity should be ensured through an appropriate grease–lubrication interval combination. This increase in the consistency grade of grease can be explained by the irreversible deformation of the thickener fibre structure contained in lubricants under high temperatures. Particularly over 24 h periods, the evaporation and oxidation of the base oil result in an increase in the oil content trapped within the soap matrix, causing the oil to lose its fluidity and leading to an increase in the NLGI grade. This situation may pose a risk of oil supply interruption, especially in pin–bushing systems with narrow channels [5,26].

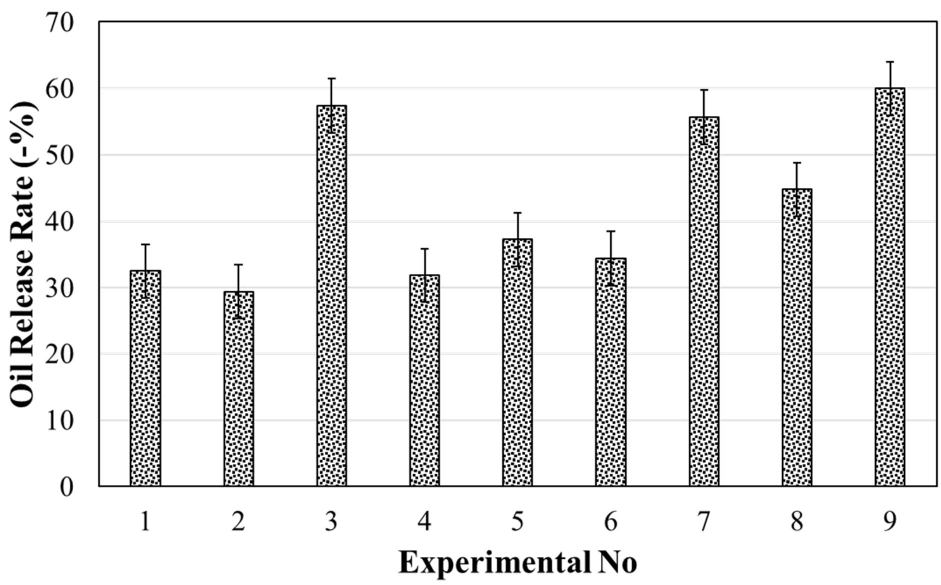

Figure 6. Oil release rates for different experimental conditions.

3.2. Optimisation Analysis

Within the scope of the Taguchi method, Figure 7 presents the main effects plot for the S/N ratios calculated using the "smaller is better" approach for the NLGI grade. Based on the average S/N ratio values, the optimum parameter combination for keeping the NLGI grade at the lowest level is revealed to be the bronze bushing, type B grease, and a 12 h lubrication interval. This can be explained by the fact that bronze bushings create a more stable contact surface than steel and alloy bushings, thereby preserving the structural integrity of the grease for longer and limiting mechanical breakdown. Similarly, the change in NLGI grade is found to be more limited during operation due to the balanced consistency and base oil–thickener compatibility of type B grease. Setting the lubrication interval to 12 h provides optimal operating conditions by balancing the effects of over-lubrication and drying that may occur at longer intervals. From an engineering perspective, selecting this combination enables the grease to maintain the target consistency grade throughout its service life, optimises maintenance intervals, and facilitates more predictable and sustainable lubrication performance, particularly in pin–bushing systems operating under heavy-duty conditions.

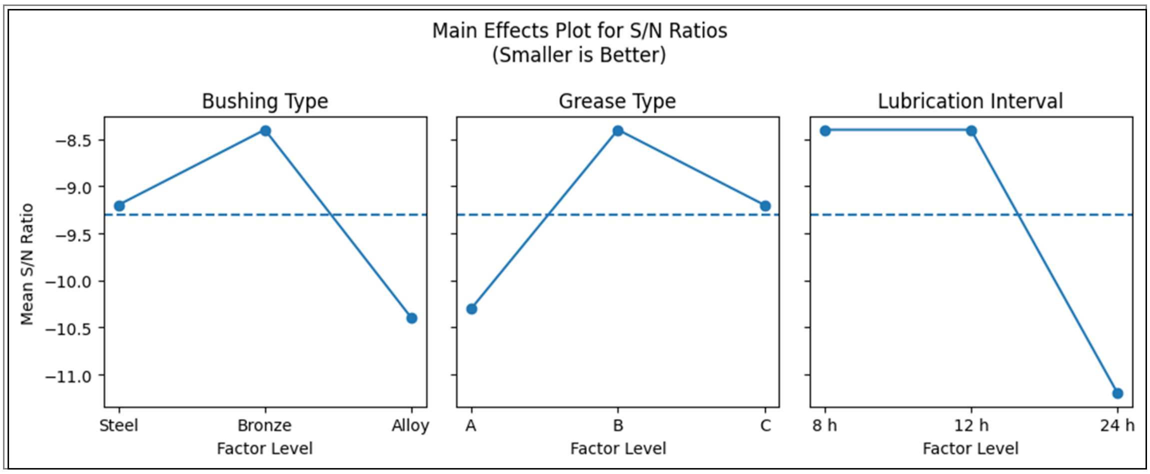

Figure 7. Main effect graph of S/N ratios for the NLGI grade.

In evaluating particle count, the "smaller is better" S/N ratio criterion was adopted within the Taguchi optimisation approach to minimise the adverse effects of wear-related solid contaminants on grease performance. Figure 8 shows the main effects plot created using the S/N ratios obtained with this approach, clearly demonstrating the relative effect of each factor level on particle count. Examining Figure 8 shows that the highest S/N ratios for the bushing material, grease type, and lubrication interval factors are obtained with the steel bushing, type B grease, and 12 h lubrication interval combination, respectively. As a higher S/N ratio indicates lower variation and more stable system behaviour, it can be concluded that this combination most effectively limits particle formation. From a mechanistic perspective, the steel bushing's more homogeneous surface properties and stable contact behaviour under load reduce wear-related particle formation. Type B grease, on the other hand, is thought to suppress micro-wear mechanisms by forming a more effective oil film on the contact surfaces due to its suitable base oil viscosity and additive system. Additionally, the 12 h lubrication interval provides a balanced operating regime for the system, preventing boundary lubrication conditions due to insufficient lubrication or contamination, as well as grease degradation due to over-lubrication. From an engineering viewpoint, the results in Figure 8 clearly demonstrate that the lubrication frequency, bushing material, and grease must all be optimised together for pin–bushing systems operating under heavy-duty conditions. In this context, the optimum combination identified provides significant operational benefits in terms of minimising wear particles and ensuring a longer service life and predictable maintenance intervals. Particle count reflects solid contaminants and potential wear debris suspended in the grease and is used here as a lubricant-condition indicator; it should not be interpreted as a direct measurement of bushing wear.

Figure 8. Main effect graph of S/N ratios for the particle count.

Since all experimental results obtained in the evaluation of the oil release rate were negative values, as required by the Taguchi analysis, these values were entered into the Minitab 22.0 (Minitab, LLC, State College, PA, USA) software as positive magnitudes, and the analysis was performed using the "smaller-is-better" S/N approach. Examining the main effects plot given in Figure 9, it is clearly seen that each of the factors—bushing type, grease type, and lubrication interval—has distinct effects on the S/N ratios. Particularly from the bushing type perspective, it was determined that using a bronze bushing raised the average S/N ratio to the highest level, thereby most effectively reducing the oil release rate. This situation can be explained by bronze bushings, in terms of surface energy, microstructure, and grease–surface interaction, allowing the base oil to be better retained within the structure. When evaluating the grease type parameter, it is seen that type B grease offers a higher S/N ratio compared to types A and C; this result shows that the thickener structure and base oil–thickener balance of grease B creates a more stable structure that limits oil release under operating conditions. From the perspective of the lubrication interval, it is observed that lubrication performed every 8 h is more advantageous compared to 12 and 24 h intervals and exhibits behaviour that minimises the oil release rate. It is thought that shorter lubrication intervals contribute to preserving the structural integrity of the grease by preventing excessive ageing and base oil loss in the operating environment. When all these findings are evaluated together, it is concluded that the combination of bronze bushing—type B grease—8 h lubrication interval is the optimal parameter set that minimises oil release. This result has the potential to directly contribute to grease selection and the determination of lubrication strategy for pin–bushing systems operating under heavy-duty conditions, offering valuable contributions to the industry in terms of optimising maintenance intervals and the sustainability of grease performance.

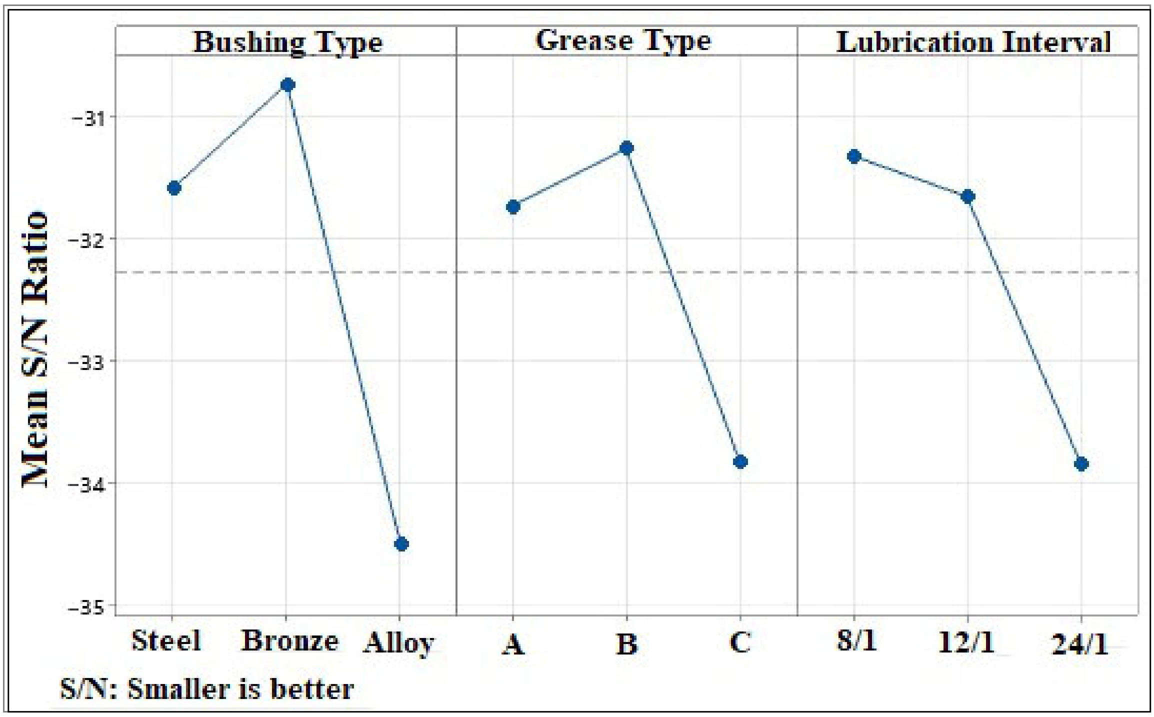

Figure 9. Main effect graph of oil release rate and S/N ratios.

When Figures 8 and 9 are evaluated together, it can be seen that the system performance is analysed through two different but interrelated tribological indicators. Figure 8 presents the S/N ratio analysis aimed at minimising the particle count, while Figure 9 provides the S/N analysis aimed at minimising the oil release rate. In both analyses, the grease type parameter consistently favours grease type B. This indicates that grease type B both limits the formation of solid particles caused by wear and maintains structural stability, thereby controlling oil release. When evaluated in terms of bearing material, steel bearings provide an advantage in reducing particle formation, while bronze bearings yield more favourable results in controlling oil release. This difference stems from the material characteristics related to wear resistance and grease retention capacity. Similarly, in the lubrication interval parameter, it is observed that the optimum level between the two performance criteria can differ. This situation indicates that particle formation and oil leakage are controlled by different tribological mechanisms. Direct quantification of bushing wear (e.g., mass loss or dimensional change) and in situ measurements of the bearing interface temperature were not included in the present study; these measurements are recommended for future instrumented field investigations.

3.3. Grey Relational Analysis (GRA)

To complement the separate single-response Taguchi evaluations, Grey Relational Analysis (GRA) was applied as a multi-criteria ranking tool. GRA converts the normalised responses into a single Grey Relational Grade (GRG), allowing NLGI consistency grade, particle count, and oil release rate to be considered together. Since lower values were preferred for all three responses, smaller-the-better normalisation was used. The distinguishing coefficient was taken as $\zeta = 0.5$, and equal weights (1/3 each) were assigned to the three indicators.

The normalised performance values x^*_{ij} were calculated using the smaller-the-better formula: $x^*_{ij} = (\max x_j - x_{ij})/(\max x_j - \min x_j)$. The Grey Relational Coefficient (GRC) for each response was then computed as $GRC = (\Delta\min + \zeta\Delta\max)/(\Delta_{ij} + \zeta\Delta\max)$, where $\Delta_{ij} = |x^*_{ij} - 1|$, $\Delta\min = 0.000$, and $\Delta\max = 1.000$. Finally, the GRG for each experiment was obtained as the weighted average of the three GRC values. The resulting normalised values, GRC coefficients, and GRG rankings are summarised in Table 4.

Table 4. Grey Relational Analysis results.

Exp.	Norm. NLGI	Norm. Part.	Norm. Oil	GRC (NLGI)	GRC (Part.)	GRC (Oil)	GRG	Rank
1	0.5000	0.0000	0.8974	0.5000	0.3333	0.8298	0.5544	4
2	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1
3	0.0000	0.0000	0.0846	0.3333	0.3333	0.3533	0.3400	9
4	0.5000	0.0000	0.9187	0.5000	0.3333	0.8601	0.5645	3
5	0.5000	0.0000	0.7416	0.5000	0.3333	0.6593	0.4975	5
6	1.0000	0.3333	0.8360	1.0000	0.4286	0.7530	0.7272	2
7	0.0000	0.3333	0.1398	0.3333	0.4286	0.3676	0.3765	8
8	0.5000	0.3333	0.4966	0.5000	0.4286	0.4983	0.4756	6
9	0.5000	0.3333	0.0000	0.5000	0.4286	0.3333	0.4206	7

The GRA results ranked Experiment No. 2 (steel bushing, type B grease, 12 h lubrication interval) first, with the highest GRG, followed by Experiment No. 6 (bronze bushing, type C grease, 8 h interval). The factor-level averages of GRG are summarised in Table 5. Based on the GRG level averages, the highest-ranked factor combination was steel bushing (GRG avg. = 0.631), type B grease (GRG avg. = 0.658), and a 12 h lubrication interval (GRG avg. = 0.662). The delta values indicate that lubrication interval had the greatest influence on the combined response ($\Delta = 0.257$), followed by bushing material ($\Delta = 0.207$) and grease type ($\Delta = 0.161$). This multi-response ranking is consistent with the strong performance of Experiment No. 2 in the single-response analyses and provides a transparent way to compare the three grease-condition indicators together.

Table 5. Factor-level averages of GRG and delta values.

Factor	Level 1	Level 2	Level 3	Delta	Rank
Bushing Material	Steel: 0.6314	Bronze: 0.5964	Cu-Sn: 0.4243	0.207	2
Grease Type	A: 0.4984	B: 0.6577	C: 0.4959	0.161	3
Lubrication Interval	8 h: 0.5857	12 h: 0.6617	24 h: 0.4047	0.257	1

4. Conclusions

This study systematically evaluated the effects of grease selection and bushing material on the grease-condition response of pin–bushing systems operating in demanding field conditions. Greases with different properties, together with steel, bronze, and Cu–Sn alloy bushings, were examined over approximately nine weeks according to the selected orthogonal array. Grease samples from each experimental condition were evaluated using the SKF grease analysis kit and microscopic observation. The results showed that unused greases that were initially at NLGI grade 2 generally shifted to grades 3 and 4 after service, indicating thickening and a potential risk of restricted grease flow in the pin–bushing lubrication channels. Microscopic observation revealed wear-related and contamination-derived particles of approximately 50 μm within the observed field, while oil release tests at 60 °C showed substantial reductions in base oil release capacity after service. When NLGI grade, particle count, and oil release behaviour were considered together through Grey Relational Analysis, experimental condition No. 2 (steel bushing, type B grease, 12 h interval) showed the most balanced overall response. Under this condition, the grease maintained comparatively favourable consistency, particle count, and oil release behaviour relative to the other tested configurations. These findings highlight the importance of selecting lubricants and bushing materials on the basis of application-specific field evidence in addition to supplier recommendations. Based on the present results, the following practical recommendations can be made for pin–bushing systems operating under heavy-duty conditions:

✓ When selecting grease, supplier recommendations alone are not sufficient. Grease choice should also be checked against oil release behaviour after use and the tendency to form solid particles in used samples.

✓ During operation, consistency increases (NLGI grade drift) should be monitored. A noticeable increase can be taken as a practical sign of grease ageing/thickening and can trigger re-greasing or grease replacement depending on the trend.

✓ Very long re-greasing intervals should be avoided under harsh conditions. The interval should be confirmed for the specific system by periodic sampling.

✓ Field-applicable analysis methods, such as particle counting and oil release tests, should be integrated into maintenance planning to support a predictive maintenance approach. These recommendations are proposed to reduce wear in pin–bushing systems, ensure sustainable grease performance, and optimise maintenance costs.

The tests were conducted under real field conditions, and load, contamination level, and contact-interface temperature were not instrumentally controlled as separate variables. The evaluation therefore relies on grease-condition indicators rather than direct measurements of friction coefficient, mass loss, or dimensional wear. Future instrumented field studies could strengthen the findings by adding direct tribological measurements and controlled thermal monitoring.

Author Contributions: I.C.: project administration, supervision, validation, visualisation, writing—original draft, writing—review and editing. A.T.Ş.: validation, visualisation, writing—original draft, writing—review and editing. S.B.S.: investigation, resources, writing—original draft, data curation. All authors have read and agreed to the published version of the manuscript.

Funding: The APC was funded by TU Delft.

Data Availability Statement: The data are available upon request.

Acknowledgments: The authors gratefully acknowledge the support of Yeşilyurt Iron and Steel Port Operations Inc. for providing the necessary resources for this research.

Conflicts of Interest: Author Sevki Burak Sezer was employed by the company Yeşilyurt Iron and Steel Port Operations Inc. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Yilmaz, E.C. Investigation of Bruxism Wear Behavior of Titanium Alloy Biomaterials; Experimental and 3D Finite Element Simulation. *Comput. Methods Biomech. Biomed. Engin.* **2025**, *28*, 1771–1782. [CrossRef]
2. Celik, I.; Yuksel, O. Investigation of Structural, Electrical and Tribological Properties of Duplex Surface Treated and Aged Cu−Cr−Zr Alloy. *Materwiss. Werksttech.* **2023**, *54*, 761–771. [CrossRef]
3. Celik, I.; Karakan, M. Effect of Plasma Nitriding Treatment on Structural, Tribological and Electrochemical Properties of Commercially Pure Titanium. *Proc. Inst. Mech. Eng. Part H J. Eng. Med.* **2016**, *230*, 145–152. [CrossRef]
4. Lugt, P.M. Modern Advancements in Lubricating Grease Technology. *Tribol. Int.* **2016**, *97*, 467–477. [CrossRef]
5. Watanabe, K.; Tanaka, K. Study into Structural Impact of Novel Calcium Complex Grease Delivering High Temperature Performance. *Tribol. Online* **2016**, *11*, 639–645. [CrossRef]
6. Cann, P.; Lubrecht, A.A. An Analysis of the Mechanisms of Grease Lubrication in Rolling Element Bearings. *Lubr. Sci.* **1999**, *11*, 227–245. [CrossRef]
7. Shah, R.; Tung, S.; Chen, R.; Miller, R. Grease Performance Requirements and Future Perspectives for Electric and Hybrid Vehicle Applications. *Lubricants* **2021**, *9*, 40. [CrossRef]
8. Noguchi, S.; Yoshiba, H.; Nakayama, S.; Kanada, T. Evaluation of Wear between Pin and Bush in Roller Chain. *J. Adv. Mech. Des. Manuf.* **2009**, *3*, 355–365. [CrossRef]

9. Zhang, A.; Zhang, M.; Wang, J.; Zhang, J.; Shang, Z.; Liu, Y.; Dai, L. Experimental Study of Pin Surface Precision on Lubrication Behavior of Pin-Bush Pairs in Industrial Roller Chains. *Ind. Lubr. Tribol.* **2021**, *73*, 765–774. [CrossRef]
10. Zou, Y.; Cheng, B.; Luo, Q.; Zheng, Y.; Shao, T. High-Temperature Reciprocating Torsional Tribometer for Pin-Bushing Friction Pairs. *Tribol. Int.* **2026**, *214*, 111372. [CrossRef]
11. Hazım, U.J.; Mohammed, M.N.; Muhsin, J.J.; Mahdi, E.; Aljibori, H.S.S.; Abdullah, O.I.; Ruggiero, A.; Alfiras, M.; Josef, S. On the Use of Taguchi Method in the Analysis of the Dynamic Response of Variable Bearing Design under Impact Load. *Adv. Tribol.* **2024**, *2024*, 7260336. [CrossRef]
12. Celik, I.; Şensoy, A.T.; Seven, G.; Cicek, D. Improving Deep Drawing Quality of DD13 Sheet Metal: Optimization of Process Parameters Using Box–Behnken Design. *Materials* **2025**, *18*, 1424. [CrossRef]
13. Antony, J.; Bhat, S.; Mittal, A.; Jayaraman, R.; Gijo, E.V.; Cudney, E.A. Application of Taguchi Design of Experiments in the Food Industry: A Systematic Literature Review. *Total Qual. Manag. Bus. Excell.* **2024**, *35*, 687–712. [CrossRef]
14. Kallesh, S.S.; Marigoudar, R.N. Taguchi Method for Tribological Excellence: Insights into Copper-Based Metal Matrix Composites. *Tribol. Ind.* **2025**, *47*, 279–293. [CrossRef]
15. Raghavulu, K.V.; Mahidhar Reddy, V.; Govindha Rasu, N.; Jani, S.P.; Sudhakar, U.; Godara, S.S.; Kumar, A.; Bhadauria, A.; Kaur, K.; Revathi, V. Optimization and Tribological Behavior of Carbon Nano Tubes Blended with POE Oil. *Eng. Res. Express* **2024**, *6*, 035430. [CrossRef]
16. Kazeem, R.A.; Jen, T.-C. Performance Assessment of Jatropha Seed Oil as Lubricant during Turning of AISI 1525 Steel Using Taguchi-Grey Relational Analysis Methodology. *Int. J. Interact. Des. Manuf.* **2024**, *19*, 5023–5037. [CrossRef]
17. Rahman, N.A.; Japar, N.S.A.; Aziz, N.J.M.; Razik, A.; Yunus, M. Sodium Grease Formulation from Waste Engine Oil. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *257*, 012018. [CrossRef]
18. Bashari, N.A.F.; Aziz, M.A.A.; Hairunnaja, M.A.; Mu'Tasim, T.M.A.B.N. Eco-grease from Upcycling of Waste Oils: A Formulation Study for High-performance Lubricants. *Int. J. Environ. Sci. Technol.* **2025**, *22*, 16095–16110. [CrossRef]
19. *ISO 2137:2020*; Petroleum Products and Lubricants—Determination of Cone Penetration of Lubricating Greases and Petrolatum. International Organization for Standardization (ISO): Geneva, Switzerland, 2020.
20. Hairunnaja, M.A.; Aziz, M.A.A.; Arifin, M.A.; Bashari, N.A.F.; Nedumaran, N.; Ali, M.F.; Mu'tasim, M.A.N.; Abdullah, F.F.; Houd, M.A. The ingenious study on the formulation of thermal stability bio-based grease. *J. Teknol. Sci. Eng.* **2025**, *87*, 529–537. [CrossRef]
21. Taguchi, G. *Introduction to Quality Engineering: Designing Quality into Products and Processes*; Asian Productivity Organization: Tokyo, Japan, 1986.
22. Khorramshahgol, R. Applying Taguchi Method to Determine the Target Values in Goal Programming. *J. Inf. Optim. Sci.* **2009**, *30*, 691–705. [CrossRef]
23. Li, X.; Tang, J.; Shao, W.; Zhang, D.; Chen, J.; Zhao, J.; You, S.; Wen, Y. Gear Contact Fatigue Prediction under Mixed Elastohydrodynamic Lubrication with Ellipsoidal Asperity Rough Surface: Experimental and Numerical Investigation. *Eng. Fract. Mech.* **2024**, *307*, 110334. [CrossRef]
24. Hamrock, B.; Dowson, D. Elastohydrodynamic Lubrication of Elliptical Contacts for Materials of Low Elastic Modulus I—Fully Flooded Conjunction. *J. Lubr. Technol.* **1978**, *100*, 236–245. [CrossRef]
25. AL-Mayali, M.F.; Hutt, S.; Sharif, K.J.; Clarke, A.; Evans, H.P. Experimental and Numerical Study of Micropitting Initiation in Real Rough Surfaces in a Micro-Elastohydrodynamic Lubrication Regime. *Tribol. Lett.* **2018**, *66*, 150. [CrossRef]
26. Cann, P.; Doner, J.; Webster, M.; Wikstrom, V. Grease Degradation in Rolling Element Bearings. *Tribol. Trans.* **2001**, *44*, 399–404. [CrossRef]