

Review of Doctoral Thesis

1. PhD candidate
Ing. Michal Okál / Michal.Okal@vut.cz
2. Name of PhD programme
Design and Process Engineering
3. Title of PhD thesis
The behaviour of grease in EHL contacts of ball bearings
4. Principal supervisor
prof. Ing. Ivan Křupka, Ph.D. / Ivan.Krupka@vut.cz
5. Co-supervisor
Ing. David Košťál, Ph.D. / David.Kostal@vut.cz
6. Reviewer
Dr. Vasilios Bakolas / bakolysi@schaeffler.com
Schaeffler Technologies AG & Co. KG
7. Overview of the scope of PhD thesis¹
Very good
The thesis deals with the problem of grease lubrication in ball bearings. It focuses on the behaviour of the different grease elements in and around the contact between ball and raceway. It also investigates the transferability of experimental results from elementary test rigs such as ball-on-disc to real ball bearing geometries. A major achievement was the methodology for dyeing grease components as well the development of a ball-on-ring optical tribometer. The latter allows for the investigations of grease-lubricated contacts with geometries that are much closer to those of ball bearings. Using these tribometers as well as an actual ball bearing test rig, the effect of raceway conformity on grease replenishment could be investigated. Furthermore, the influence this replenishment has on the behaviour of the thickener in the contact was studied. Finally, the correlation between the thickener type and the lubricating film was examined.
8. Significance of the topic and clarity of problem statement
Very good
Grease lubrication is a major topic of interest for the rolling element bearings industry, since approx. 80%-90% of REBs are lubricated with grease. Nevertheless, the mechanisms related with this type of

¹ Overview of the scope of PhD thesis is a short description of objectives of PhD thesis's research and summary of main findings and scientific achievements.



lubrication are still not fully understood. The contributions and behaviour of both the thickener as well as the base oil in and around a contact evolve over time and can vary significantly based on the type of thickener and the geometry of the contact. A deeper understanding of grease behaviour in highly loaded contacts could lead to more energy efficient REB designs as well as to better grease formulations. The replacement of lithium-based greases by urea-based greases only complicates the problem, since it appears that the experience that was accumulated regarding the behaviour of lithium-greases doesn't apply to urea grease. The thesis describes the problem in clear terms and suggests steps to answer some of the many questions associated with it.

9. Knowledge of existing literature

Excellent

The author has done an extensively literature research on the subject of grease lubrication. He covered the areas of grease lubrication fundamentals, such as replenishment, lubricant film starvation, grease film evolution, EHD modelling of grease lubricated contacts. He also reviewed all the experimental methods related to grease lubrication. His research covered all the major tribology journals and covered researchers from all around the world, from Europe to Japan and China. The publications considered in the literature review cover start in 1941 and end up in 2024, making sure that all the relevant developments in this area were taken into consideration.

10. Choice of methods and technical soundness

Excellent

The experimental methods used throughout the thesis is appropriate to investigate the phenomena outlined in the scope of the thesis. It is particularly important that the experimental methods provide a clear path to transfer data and knowledge from an elementary test rig such as the ball-on-disc (BoD) to an actual bearing mounted on a ball bearing test rig. Care was taken to make sure that the conditions across the experiments on the different test rigs would match as much as possible. A very interesting innovation was the use of a ball-on-ring (BoR) test rig to bridge the transferability gap between the other two test rigs. The use of fluorescent microscopy was correctly first checked for plausibility before actually being implemented. Its use was justified by the aim of observing the behaviour the different components of the grease separately.

11. Quality, originality and significance of the results

Excellent

The quality of the results is excellent. The test process is well thought and executed, ensuring reproducibility of the results by third researchers, should they have access to similar equipment. The use of fluorescence microscopy in this context has only been used in a limited manner from other researchers in the field, but its use in this work to differentiate between the different grease components is original. The fluorescence microscopy certainly gives new insights in the behaviour of the oil and the thickener in and around a grease lubricated contact. Furthermore, the use of a ball-on-ring- tribometer in the context of grease tribology is another original aspect of this work. This allows the study of grease at a contact whose geometry is much closer to a real rolling element bearing geometry. The results achieve present a major contribution in this field not only by themselves. The thesis proposes new experimental methods that can be used by researchers in the future to advance the understanding of grease lubrication.

12. Quality of attached papers

Excellent

The four papers that are attached to the thesis are of high quality and were published in journals with a rigorous peer-review process. They are consistent with one another building a meaningful series that contains the major points of the research carried out in the framework of the thesis. They are well written, substantiated and their reference list is complete.

13. Overall assessment, strengths and weaknesses (based upon the above evaluation categories 8–12)

Very good

This thesis represents a major improvement in the area of experimental work on grease lubrication. It presents two major innovations with a) the Ball-on-Ring test rig and b) the fluorescence microscopy. One of the major achievements is the connection that was built between the elementary Ball-on-Disk and the actual geometry of a ball bearing. Furthermore, the observation of the behaviour of the different grease components with the aid of fluorescence microscopy is also a major innovation in this field. Taking into account the amount of work that was needed to develop these two innovations, it is understandable that the amount and variety of the experiments was rather limited. Nevertheless, this doesn't affect negatively the very good impression that this thesis leaves to its reader. All its different elements, from its structure to the literature review and finally the presentation of the results and their discussion should please even the most demanding reader.

14. Questions and comments

The only request that this reviewer would have, is that the author should comment briefly on the temperature effects during the experiments and explain why they were neglected. The experiments were carried out with different greases and materials with different thermal properties. It should be expected that the temperature field that evolves would be different in every experiment. The author should briefly state his opinion on this topic.

15. Conclusion

PhD thesis is an independent scientific work that presents a novel solution to a significant problem in the research area and demonstrates the candidate's ability to conduct independent research.

YES

16. Date and signature

20/05/2025

Please note

- A. Evaluate categories 7 to 13 using the following scale: unacceptable, acceptable, satisfactory, good, very good, excellent. The qualification of 'excellent' should only be given for a PhD Thesis in the top 3% of the research in your field of expertise.

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6. Reviewer
Dr. Cesar Pastor / Cesar.Pastor@de.bosch.com
Robert Bosch GmbH
7. Overview of the scope of PhD thesis¹
Very good
The thesis clearly exposes its objectives on page 33, and the subsequent questions and hypotheses effectively address the research needs within the chosen topic. The structure of the thesis, with its well-defined stages, is highly suitable and has been successfully implemented across the included papers. The main findings of the thesis represent a significant advancement in the research area, yielding entirely novel results. While the behaviour of grease in elastohydrodynamic contacts remains a complex and incompletely understood phenomenon, the experiments conducted contribute substantially to a better understanding and modeling of this behaviour, raising important new questions and hypotheses for future investigation. A more in-depth analysis of the grease thickener structure, including a comparative study of different thickeners (an area explored only briefly in this work), would elevate the work to an "Excellent" rating.
8. Significance of the topic and clarity of problem statement
Very good

¹ Overview of the scope of PhD thesis is a short description of objectives of PhD thesis's research and summary of main findings and scientific achievements.

The behaviour of grease in tribological contacts, including but not limited to bearings, is a topic of critical importance. Its inherent complexity, arising from the numerous phenomena involved across different scales (from macro/system-level down to the molecular scale), has led to a degree of caution within the research community regarding in-depth investigation. Therefore, the selection of this topic was both ambitious and insightful, given its difficulty and significance. This PhD thesis aims, from the beginning, to understand the fundamental principles governing greased elastohydrodynamic contacts, formulating clear hypotheses and investigating them through a well-defined and comprehensible methodology. The development of a testing method capable of visualizing grease movement while simultaneously measuring minimum film thickness and meniscus formation represents a significant milestone in the research community. The inclusion of a wider range of rheological characteristics of greases and base oils, such as NLGI grades and thickener percentages, would further enhance the work for an "Excellent" rating.

9. Knowledge of existing literature

Satisfactory

In my opinion, the literature review is missing several key contributions from prominent research groups. While the work of Piet Lugt's group is well-documented, the research of R. S. Dwyer-Joyce's group at the University of Sheffield is equally important for the testing part and should have been included. Furthermore, the group from the Institute for Machine Elements and Systems Engineering (IMSE) at the University of Aachen has been actively publishing papers and presenting at conferences in the last 3-5 years, and their work deserves consideration. I would have expected to see at least some of their papers cited and discussed, particularly those published up to mid-2024. These are just a few examples of relevant papers from important research groups that are absent from the review:

Gray WA and Dwyer-Joyce RS (2022) In-situ measurement of the meniscus at the entry and exit of grease and oil lubricated rolling bearing contacts. Front. Mech. Eng 8:1056950. doi: 10.3389/fmech.2022.1056950

Zhang, Shuo & Jacobs, Georg & Vafaei, Seyedmohammad & von Goedel, Stephan & König, Florian. (2023). CFD investigation of starvation behaviors in a grease lubricated EHL rolling contact. Forschung im Ingenieurwesen. 87. 1-10. 10.1007/s10010-023-00633-2.

Fischer, Dennis & von Goedel, Stephan & Jacobs, Georg & Stratmann, Andreas. (2021). Numerical Investigation of Effects on Replenishment in Rolling Point Contacts using CFD Simulations. Tribology International. 157. 106858. 10.1016/j.triboint.2021.106858.

10. Choice of methods and technical soundness

Excellent

The methodology developed within this PhD thesis is, in my opinion, among the best, if not the best, currently available in the field. The accuracy of the methods used to analyze film thickness, the thoughtful selection of dyes, the appropriate scale of measurements, and the thorough explanation of the methodology and calibration procedures in the published papers have been highly regarded within the research community in recent years. The widespread interest from various universities and research institutes is evidenced by the collaborations that have emerged over the past several years, resulting in publications. Furthermore, the significant interest from industry is demonstrated by the numerous consulting engagements and contracted experimental testing services. I firmly believe that the methodology and technical soundness of this work merit an "Excellent" rating.

11. Quality, originality and significance of the results

Very good

As previously stated, the quality of the results is excellent. Considering the state of the art prior to this work, the findings are not only novel but also remarkably accurate. While a deeper understanding of grease as a dual-phase material (thickener and oil) is desirable for a more complete understanding of the mechanisms underlying channelling, bleeding, starvation, replenishment, and other related phenomena, the current work makes significant progress. The use of diverse dyes and fluorescence microscopy demonstrates a high degree of originality, and the results are highly significant for the study of bearings. Although extending the investigation to other tribological contacts is beyond the scope of this thesis, a brief comment on the potential applicability of the findings to other systems would have been a valuable addition.

12. Quality of attached papers

Very good

The papers included in the thesis meet the necessary quality standards for doctoral publication. All papers were published in internationally recognized journals. Of the four papers, the candidate's contribution to three of them was approximately 60-70%. In the first paper, which detailed the development and documentation of the testing methodology, the candidate's contribution was 35%. The papers logically progress along a pre-defined path, starting with the development of a novel testing and analysis method, moving to an in-depth investigation of various factors that contribute to channelling and starvation (such as contact conformity and thickener behavior in tribological sample tests), and culminating in an application/system-level analysis. The structure and logical flow of the papers are appropriate and well-suited for this case study.

13. Overall assessment, strengths and weaknesses (based upon the above evaluation categories 8–12)

Very good

Mr. Okál's PhD thesis addresses an actual and relevant topic in the development, research, and design of tribological contacts. The decision to focus the thesis on grease lubrication represents a significant advancement over previous works that considered starvation phenomena solely in the context of oil lubrication or the base oil component of greases. In this regard, the thesis expands our understanding of grease-lubricated contacts, which exhibit considerably greater complexity than their oil-lubricated counterparts. Furthermore, the selection of rolling bearings as a use case was sensible, given the well-established and standardized nature of this tribological system. The knowledge presented in this thesis should be further developed and extended to other types of contacts. Given the particular emphasis on the effect of the thickener on the lubrication process, a more in-depth study of its chemical composition, filament structure, bleeding models, molecular forces, adhesion, and cohesion forces is necessary to better understand the fundamental behaviour of thickeners and to explain the differences between various thickener types. For example, in P.5 of the third paper (Tribology Letters, 2024), SEM images of three different greases were presented but received limited commentary. A clear distinction between the thickeners was not made, nor was it adequately explained. Another area lacking sufficient detail is the deposition mechanism of the thickener in the contact zone, leading to the formation of a tribofilm. Overall, this thesis exhibits more strengths than weaknesses and deserves a grade of "Very Good."

14. Questions and comments



In the version provided for the review there were several literature sources missing. Specially figures taken from published papers need to be referenced prior to the publishing of the thesis

15. Conclusion

PhD thesis is an independent scientific work that presents a novel solution to a significant problem in the research area and demonstrates the candidate's ability to conduct independent research.

YES

16. Date and signature

Date:

Please note

- A. Evaluate categories 7 to 13 using the following scale: unacceptable, acceptable, satisfactory, good, very good, excellent. The qualification of 'excellent' should only be given for a PhD Thesis in the top 3% of the research in your field of expertise.
- B. E-mail the completed form to: Klara.Javorceкова@vut.cz

Posudek vedoucího dizertační práce

Akademický rok:	2024/25
Ústav:	Ústav konstruování
Student(ka):	Ing. Michal Okál
Doktorský studijní program:	Konstrukční a procesní inženýrství
Studijní obor:	bez specializace
Vedoucí dizertační práce:	prof. Ing. Ivan Křupka, Ph.D.
Oponent dizertační práce:	
Datum poslední úpravy:	-999

Název dizertační práce:

Chování plastického maziva v EHL kontaktech kuličkových ložisek

Hodnocení dizertační práce:

Kritérium:

Hodnocení A-F dle ECTS

Celkové hodnocení dizertační práce:

Předloženou dizertační práci doporučuji k obhajobě.
Celkové hodnocení: velmi dobře / B.

Celkové slovní hodnocení:

The dissertation explores the crucial role of grease components in the elastohydrodynamic contact of ball bearings, particularly focusing on their ability to form an effective lubricating film. Ball bearings are integral to numerous engineering applications, yet significant gaps remain in our understanding of how greases perform in these critical systems. While commonly used methods, such as tribometers in ball-on-disc configurations and testing on actual ball bearings, offer insights, they fall short in providing comprehensive data. The ball-on-disc configuration oversimplifies bearing geometry, while real bearing tests lack direct analysis of the contact area. The student successfully identified key problems that needed to be addressed. Throughout his studies, he acquired proficiency in the experimental methods necessary to tackle the challenges at hand. He effectively carried out the required experiments and published the results in journals with an impact factor. In addition, he collaborated with other researchers worldwide to conduct essential experiments for validating the findings.

The student demonstrated the ability to work independently on the assigned topic. He analyzed the issue based on a critical review of available publications and prepared an overview of the current state of knowledge, from which he identified key problems to address. He proposed a solution approach, conducted the experiment, and drew conclusions from the analysis of obtained results, which contributed to advancing the understanding of the topic. He completed all required exams and met the other criteria for the PhD program. His performance clearly reflects the skills needed to successfully complete a PhD.

A novel approach is introduced, combining existing methods with experiments using a ball-on-ring configuration device that accurately simulates the realistic contact conditions of a ball bearing. The results offer valuable insights that will directly impact the development of more precise lubrication solutions and improved bearing performance, making this research essential for advancing both industrial applications and theoretical models in lubrication science.