INSTITUTE OF MACHINE AND INDUSTRIAL DESIGN

FME

Faculty of Mechanical Engineering
Brno University of Technology

Review of Doctoral Thesis

1. PhD candidate
Ing. Jiří Křupka / Jiri.Krupka@vut.cz
2. Name of PhD programme
Design and Process Engineering (Mechanical Engineering Design)
3. Title of PhD thesis
Development of film thickness in elastohydrodynamically lubricated compliant contacts

4. Principal supervisor
prof. Ing. Ivan Křupka, Ph.D. / Ivan.Krupka@vut.cz
5. Co-supervisor
Ing. Petr Šperka, Ph.D./ Petr.Sperka@vut.cz

6. Reviewer
Prof. Romeo Glovnea / R.P.Glovnea@sussex.ac.uk
University of Sussex

7. Overview of the scope of PhD thesis[1]
Very good
The thesis by Mr Jiri Krupka approaches a relatively little researched topic of lubrication of polymeric materials. The objectives of the research are clearly identified and stated in the scientific questions: 1) Will a coherent lubricant film always be formed in compliant contacts, fully separating the rubbing surfaces? 2) What is the effect of the load and entrainment speed on the fluid-film thickness and the contact shape in the compliant contact operated in the TR region of EHL? 3) How the rheological response of the lubricant contributes to the formation of the fluid-film thickness in the TR region of the EHL, considering a different effect in the I-E and P-E modes of the EHL? 4) What is the contribution of the constitutive viscoelastic response of the material in the compliant contacts to the formation of fluid-film thickness and contact shape changes in the TR region of EHL? These are pertinent objectives, and the author pursues them systematically in four research outputs which form the core of the results chapter of the thesis.

8. Significance of the topic and clarity of problem statement
Excellent
The quest for improving efficiency of machinery and other engineering systems and consequently reduce the carbon footprint of industrial activities led to the use of lighter materials in applications which

[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.

traditionally metals (especially steel) have been used. Polymers appear as good candidates due to their low density, decent mechanical properties and adequate tribological properties. Traditionally these materials have been regarded as suitable for very low speeds and loads applications, where lubrication was not deemed necessary. Increasing the demands of the applications, with other words increasing the load and sliding speed however have shifted this approach and the attention of researchers has started to focus on lubrication of these machine components. The thesis by Mr Krupka comes at the right time to set benchmarks on the most important aspects of the lubrication of polymeric machine components. The problem is clearly identified and followed through.

9. Knowledge of existing literature

Excellent

The literature review forms a consistent part of the thesis. It shows the breadth and depth of author's knowledge in the field of lubrication elastohydrodynamic contacts in general and the soft EHL in particular. The literature review clearly identifies the state of the art in soft elastohydrodynamic lubrication of compliant, (relatively) soft contacts. The references are ample and relevant, encompassing areas of both experimental and theoretical lubrication research, rheology of materials, contact mechanics and characterisation of materials properties. The literature review is superbly arranged and presented, easing the reader into the subject and offering them the platform to understand the new research problem tackled in the thesis.

10. Choice of methods and technical soundness

Excellent

The huge breakthrough in the research of elastohydrodynamic lubrication was no doubt the application of the optical interferometry method at the Tribology Laboratory, Imperial College London, in 1960s. This method confirmed the earlier theoretical approached and open the doors for tremendous research into the understanding of the details of the mechanisms of the lubricant film formation in high-pressure contacts. If for hard EHL, other methods can be used, e.g. electrical capacitance or resistance, it is obvious that these methods are inadequate when one of the contacting bodies are made of a polymer, that is an insulating material. It follows that optical interferometry really is the only method of choice in this case and the author benefited by the wealth of experience and expertise present in the host laboratory. Going through the literature review I eagerly anticipated the chapters describing the experimental methods and I was not disappointed; the author's approach is elegant and comprehensive, as it considers both anticipated arrangements: soft disk/hard ball and the opposite, hard disk and soft ball. This is in my view a sound approach which gives robustness to the experimental results.

11. Quality, originality and significance of the results

Very good

The results are presented in an original format, as a summary of three research papers. This is a proof of the originality of the results, as those papers have passed through the scrutiny and rigour of the journal reviewing process. The results are very clearly presented covering all the scientific questions set by the author. They bring new knowledge to the field proving originality and the same time they are detailed and significant to the chosen field they are applied to. Presenting the results as a summary of the published papers gives the author the opportunity to bring the various topics in one place and offer coherent and comprehensive discussion.

12. Quality of attached papers

Very good

As mentioned in the above section the papers have already went through the scrutiny and rigour of the review process. This is in itself a guarantee of their quality. Each paper addresses a slice of the research programme set in this thesis. They are well-written and arranged, with detailed discussion and pertinent conclusions. The figures are relevant and explanatory and the references appropriate. Each of those papers form one of the pieces of the puzzle which is the whole research programme. They fall well into place, complementing each other to offer an overall response to the research questions asked by the author.

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

Very good

This is a very good thesis, built on the foundation of three/four research output published in relevant journals/conferences. The thesis is concise and very well written and structured. The description of the method is adequate, with the only negative aspect the lack of details of the calibration method, as I will explain below. The English is excellent, with only very minor corrections needed, which really can be ignored. In my opinion the author followed a superb research programme and set directions of future research in the field. In my opinion the thesis I of high quality and it is a firm foundation of the PhD degree, assuming successful defending during the oral viva.

14. Questions and comments

The research questions are complemented by a number of hypotheses; In my view these are too many. It also looks like some of these hypotheses end with a phrase which is rather a conclusion not a hypothesis (e.g. H1c, H2 and H3a). Hypothesis H3c states: "An increase in the loading frequency of the solid material, referred to as the entrainment speed in the EHL..". This is new to me and I cannot see how loading frequency can be defined and entrainment speed; it is needs clarifications.
-The author presents relevant material properties of the lubricants, underlining the thermal degradation of 5P4E oil up to 450 C; In my view this is not relevant as polymeric gears and other machine components are not meant to work at this temperature.
-Personally I would have liked to see details of the calibration procedure. As this is a PhD thesis it needs to include these details, even if they were presented in the research papers attached to the thesis. In fact the thesis sends the reader to the research papers, where they are send to other, previous research papers.
-I also wanted to see more explanations on the difference between the soft disk/hard ball and hard disk/soft balls experiments. Was the roughness of the balls the only reason why the hard disc/soft balls were not used? Regarding the film thickness of the glass disk/polymer ball: what was the phase change upon reflection at the ball surface? Was this considered? Is it the same for all ball materials?

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		
20/03/2024		

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.Javorcekova@vut.cz

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6. Reviewer
Prof. Nicolas Fillot/ nicolas.fillot@insa-lyon.fr
INSA Lyon

7. Overview of the scope of PhD thesis[1]
Very good
The presented manuscript deals with lubrication of gears made of soft materials such as polymers, as it is nowadays a common situation, though lubrication literature mainly considers hard rubbing surfaces. The experimental campaign involves a ball-on-disc tribometer and a dedicated optical interferometry technique. The main findings are an experimental evidence of the formation of a lubricant film in all tested situation (involving a non-zero entrainment speed). In total 3 published papers and 1 conference proceeding are discussed. Above the glass transition temperature, as the entrainment speed increases, the circular shape of the contact is lost, becoming wide elliptical. But contrary to literature on soft EHL, the minimum film thickness stays at the side lobes (not the exit) of the contact. As the temperature increases, the film thickness surprisingly increases (compared to hard-EHL), presumable because of the influence of temperature on constitutive polymer material behaviour. Below the glass transition temperature, isoviscous-elastic EHL models from literature suit best the shown experiments (40°C), while at higher temperature, piezoviscous-elastic models are better. This is a conter-intuitive result that is explained by the fact that temperature influence both the lubricant rheology and the viscoelastic response of the polymer.

[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.

8. Significance of the topic and clarity of problem statement

Excellent

The significance of the proposed thesis is excellent since few works in the literature address the soft-EHL problem. However, it is nowadays a very common challenge. More than that: the literature results are not consistent and conclusions often differ. Most of the literature results are based on numerical modelling and until now very few experimental evidences where shown. This work is then a perfect piece of work to fill the gap. The manuscript exposes very clearly the objectives and the scientific questions to be answered in the conclusion, as well as the hypotheses related to this work.

9. Knowledge of existing literature

Excellent

The state-of-the art section of the manuscript is a very substantial section, covering especially elastohydrodynamic lubrication (EHL) regime and subregimes such as isoviscous-elastic, piezoviscous-elastic (etc.) and transition regions, since such soft contact often operates in-between distinct regimes. A focus is made on soft elastohydrodynamic lubrication regime (i.e. using soft materials), and the (few works relating the) main characteristics of lubricant film thickness in this situation, including semi-analytical film thickness prediction models. Though the very disparate knowledge in the literature concerning soft -EHL (often not consistent), the author succeeded perfectly in giving a clear and exhaustive view of the litterature.

10. Choice of methods and technical soundness

Very good

The author proposes a well-established optical interferometry technique to measure film thickness in EHL ball-on-disc contacts. The novelty of the approach, which also explains why few experimental works have been done yet, is the difficulty to find transparent (and optically ideal) polymer materials through which film thickness can be measured. Different ball-on-disc configurations were tested included BK-7 or sapphire disc on polymer ball (either polyamide, PEEK, polyacethal) or (the other way around) PMMA disc on steel ball. Unfortunately, the polishing of polymer balls was not efficient enough to guaranty a small enough roughness, and only the PMMA disc on steel ball configuration was studied. With this choice, the author was able to conduct a very sound and high-quality experimental campaign, discussed in the three published papers.

11. Quality, originality and significance of the results

Very good

The results shown in the manuscript and through the published papers are significant, as exposed earlier, since few works of that kind exist in the literature. The measured film thickness, with high precision, was compared with existing models of the literature. Interesting discussions arised concerning the influence of temperature, load and entrainment velocity on film thickness and a deep understanding was proposed concerning the involved mechanisms, concerning either the piezoviscous response of the lubricant or the viscoelastic constitutive polymer material behaviour. Unexpected results were sometimes found, compared to existing litterature and the author always proposed a temptative explanation based on sound physical basis.

12. Quality of attached papers

Very good

Linked to the manuscript are three published papers in international, high-quality, peer-reviewed journals. They are the basis on which the results section of the manuscript is made of. They are very well written, very clear and original. The findings are very sound. The author explores a new lubrication framework and discussed the relevance of the existing models from the literature. He even proposes to integrate the viscoelastic response of PMMA into existing (H&D) EHL film thickness models, and achieve with this attempt a very good agreement at high temperature. However, the lubrication regime by itself is not well predicted yet, showing that this topic would probably give scientific challenges for several decades to come.

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

Very good

This manuscript represents a very good piece of work. The experimental strategy is very relevant, and the author managed to find acceptable enough surface conditions with new (polymer) materials to be able to measure film thickness with optical interferometry technique. The principal strengths of this work are a very deep understanding of the state-of-the-art and very good experimental skills. The new results represent a very useful basis to be able to challenge mostly numerical results from the literature on this (relatively little explored) soft-EHL topic. Main weaknesses are linked to the limitations of the available experimental possibilities. Other polymers than PMMA should be consider in the future to be able to take some height on these results.

14. Questions and comments

While reading the manuscript, some questions arise. In some configurations, film thickness results are in good agreement with hard-EHL usual prediction formulae. This is surprising since polymer surfaces are considered above glass transition temperature where the viscoelastic behaviour should be dominant. Also, the fact that no absolute minimal film thickness was found at the exit part of the contact (but always at the side lobes) contradicts the literature. With two different fluids (TOTM and SQL), the central film thickness is either greater or smaller than the prediction from semi-analytical models from the litterature. But the range of entrainment velocities is also very different, meaning that the loading cycle of the polymer surface is different and so is the viscoelastic response. It is mentioned that the slide-to-roll ratio (SRR) has almost no effect on film thickness, except at pure sliding, where the film thickness expectedly decreases. But the thermal effects that may be the cause of this result could be investigated deeper. For example, do we expect a difference between PMMA disc at rest or steel ball at rest (i.e. SRR = +2 or -2) ? Heat transfers in the solid at rest would be probably very different between these two situations.

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.

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Principal supervisor's final report on the PhD study

1. PhD candidate
Jiří Křupka / jiri.krupka@vut.cz
2. Name of PhD programme
Design and Process Engineering
3. Title of PhD thesis
Development of film thickness in elastohydrodynamically lubricated compliant contacts

4. Principal supervisor
Prof. Ing. Ivan Křupka, Ph.D. / krupka@fme.vutbr.cz
5. Co-supervisor
Ing. Petr Šperka, Ph.D. / petr.sperka@vut.cz

6. Stays at other institutions (min. 7 days)
Institution / Country / From / To

7. Teaching activities
Course name / Total number of hours 1K (2017) / 26 hours 2K (2018) / 26 hours 3CD (2017 - 2022) / 416 hours 4KC (2017 - 2021) / 286 hours

8. List of main publications
Bibliography references cited according to the norm ISO 690. If appropriate, impact factor must be specified. KRUPKA, Jiri, DOCKAL, Krystof, KRUPKA, Ivan and HARTL, Martin. Elastohydrodynamic Lubrication of Compliant Circular Contacts near Glass-Transition Temperature. *Lubricants* [online]. 13 July 2022. Vol. 10, no. 7, p. 155. DOI: 10.3390/lubricants10070155 **IF=3.5, Q2** KRUPKA, Jiri, DOCKAL, Krystof, KRUPKA, Ivan and HARTL, Martin. Polymer Lubrication: Pressure–Viscosity–Temperature Dependence of Film Thickness for Highly Loaded Compliant Contacts in Elastohydrodynamic Lubrication Regime. Journal of Tribology [online]. 1 February 2023. Vol. 145, no. 2. DOI: 10.1115/1.4055558 **IF=2.5, Q3**

KRUPKA, Jiri, DOCKAL, Krystof, SEDLACEK, Tomas, REBENDA, David, KRUPKA, Ivan and HARTL, Martin. Viscoelastic Response of Elastohydrodynamically Lubricated Compliant Contacts below Glass-Transition Temperature. *Polymers* [online]. 30 May 2023. Vol. 15, no. 11, p. 2528. DOI: 10.3390/polym15112528
IF=5.0, Q1

9. Assessment of the supervision process

Very good

Justification for evaluation: The student started solving the problem without any previous experience in the given field. During his studies, he mastered the experimental methods needed to solve the given problem. Despite the initial problems, he managed to implement the necessary experiments and publish their results in journals with an impact factor. The longer period of study was mainly due to insufficient previous experience in the field of tribology and to the search for a suitable approach. In the end, he was able to successfully overcome these problems. He passed all required exams and fulfilled other requirements for PhD study. He has demonstrated the skills needed to successfully complete a PhD study.

10. Assessment of the candidate's ability to work independently

Very good

Justification for evaluation: The solution of the dissertation took place in two phases, which differed in the degree of independence of the student. The beginning of the solution was somewhat gradual, which was caused by the search for a suitable approach to the problem being solved. This was also due to less experience of the student in the given field. In the second phase, there was a significant improvement in the student's independence and his active approach to finding a suitable solution procedure and evaluating the obtained results. He was able to both implement his own experiments and plan collaboration with other colleagues. This was also reflected in the successful publication of the obtained results.

11. Assessment of the contribution that the research makes to knowledge in the field

Very good

Justification for evaluation: The topic of the PhD thesis was focused on the transition between hard and soft EHL regimes. The main task was to observe the film shape changes due to the different conditions. Soft EHL conditions represented significant problems with experiments due to the materials of contacting bodies. Finally, most experimental work was done with soft disk and steel ball. Due to the experimental technique used, the chromium layer was applied on the disk surface. However, there were problems with the durability of this layer especially under sliding conditions. Despite those complications the significant contributions were obtained. There are three main contributions. The first is identification of fluid-film thickness and contact shape changes in compliant contacts operating in the transition region of EHL. The second is implementation of experimentally obtained viscoelastic response of the solid material and rheological response of the lubricant into the EHL models. The last one is the experimental investigation of the film thickness in compliant contacts operated near the glass-transition temperature by the optical interferometry method.

12. Other comments

13. 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

14. Date and signature	
16/11/2023	

Please note

A. *Evaluate categories 9 to 11 using the following scale: unacceptable, acceptable, satisfactory, good, very good, excellent.*
B. *In each category 9 to 11 explain reasons for evaluation using between 100–200 words.*
C. *E-mail the completed form to: Klara.Javorcekova@vut.cz*