

CONFERENCE PROGRAMME AND PROCEEDINGS

3rd & 4th June 2026
Euskalduna Conference Center
Bilbao

LUBRICANTS, TRIBOLOGY AND CONDITION MONITORING

CONFERENCE & EXHIBITIONS

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ORGANIZERS



Tekniker is a research centre specialized in advanced manufacturing, surface engineering, product engineering, and TICs for manufacturing.

Our mission is to deliver growth and wellbeing to society at large via R&D&I and to further the competitiveness of the business fabric in a sustainable manner. The strategy in surface engineering has two main vectors: tribology and industrial fluids. The tribology lab in Tekniker is focused in solving problems related with friction and wear, selecting the proper materials for each mechanism in to achieve the best performance during service. The knowledge of fluids is not only related to their properties, but also to the interaction with the environment and the surfaces in contact, being our main goal, the understanding of the fluid in operation providing analytical techniques for its control in use. Regarding Asset Management and Condition Monitoring, Tekniker is focusing on the incorporation of novel AI technologies, in particular Generative AI and Quantum, that will lead to more robust, accurate and faster algorithms regarding tasks such as anomaly identification and prediction, workload optimization, or trustworthy interaction with operators.



Atten2 is specialist in the design, development and manufacture of solutions for fluid monitoring, using their [innovative optical technology] enhanced by cutting-edge software, computer vision and data analysis in high criticality industrial environments. They measure lubricant quality and condition from [a deeper perspective] that revolutionizes the concept of predictive maintenance: [See more], [See better], [See before anyone else].



Bureau Veritas-Lubrication Management is dedicated to bringing a superior added-value service to our clients by providing proactive fluid condition monitoring. Lubrication Management is committed to maintaining a leading position in oil analysis. We use the latest lubrication testing equipment in our laboratories and the latest technologies to provide a vast improvement in the speed of interactive information flow between the laboratory and customers.

Lubrication Management encourages dialogue with customers and suppliers to continually improve our systems.

We run more than 150,000 samples per year according to ISO 17025 accreditation.



The Jost Institute for Tribotechnology is in the Northwest region of the UK and was established to provide a centre of excellence of international standing for industrially relevant research, teaching and knowledge transfer within the area of tribotechnology. It provides training / teaching, research and consultancy in a wide range of applications, including space, automotive, aero and power generation, aiming to bring economic, environmental and social benefits to society.

SPONSORS

Silver



EXHIBITORS



MEDIA PARTNERS



With the support of the Basque Government



PREFACE

LUBMAT was a joint initiative between TEKNIKER and JOST Institute for Lubrication and Tribology. Both realized that, even though there were numerous international congresses dealing with the scientific approach for lubrication and wear, there were not any specific industrially focused. So LUBMAT intends to address the industrial public without losing sight of the academic and scientific vision and has celebrated in 2026 its 10th edition.

The 2026 edition took place at the take place at the **Euskalduna Conference Centre in Bilbao** on 3–4 June which offered ideal conditions in terms of location, size, equipment and facilities to fully meet our needs relating to technical exchange and personal contacts between colleagues from different fields and cultures.

The conference program consisted of 2 plenary lectures, 12 invited presentations and 69 oral presentations, organized into 3 parallel sessions. Simultaneously, 12 companies exhibited the most relevant products, equipment and techniques for industrial applications and academic research.

The organizing committee warmly thanks all participants for their attendance to this conference. As a memento of the LUBMAT experience, photographs are available at: Lubmat Congress 2026 [while the video link is https://youtu.be/FojtV_EjlWI](https://youtu.be/FojtV_EjlWI).

This volume contains the proceedings of the contributions presented at the LUBMAT 26 conference. We hope that they will serve as a valuable reference and that this meeting has been an excellent platform for scientific discussion and enjoyment. We look forward to meeting you again in the next edition.

Javier Barriga
LUBMAT Chairperson
Head of Tribology Unit
TEKNIKER

COMMITTEES

 Chair Adolfo Málaga Bureau Veritas	 Co-Chair Javier Barriga Fundación Tekniker	 Co-Chair Ian Sherrington Jost Institute for Tribotechnology
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ORGANIZING COMMITTEE

NAME	INSTITUTION
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Jose Ignacio Bayón	Bureau Veritas
Adolfo Málaga	Bureau Veritas
Jorge Alarcon	Bureau Veritas
Ana Aranzabe	Tekniker
Amaya Igartua	Tekniker
Javier Barriga	Tekniker
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Itziar Alonso	Tekniker

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Stefan Mitterer	OELCHECK
Mathew Mathew	UIC
Josefa Fernandez Perez	Universidad de Santiago
Rafael Rodriguez Trias	Universidad Pública de Navarra

LUBMAT 2026 PROGRAMME - Schematic time schedule

TIME	WEDNESDAY, 03 JUNE 2026		
08:30 – 09:00	ATTENDEES REGISTRATION		
09:00 – 09:30	ROOM 0B: OPEN CEREMONY Javier Barriga (Tekniker), Adolfo Málaga (Bureau Veritas), Eneko Gorriategi (Atten2), Ian Sherrington (JOST Jost Institute for Tribotechnology) ALBERTO FERNÁNDEZ (BASQUE GOVERNMENT - DIRECTOR OF TECHNOLOGY AND INNOVATION)		
09:30 – 10:00	ROOM 0B: PLENARY SPEAKER: MAR COMBARROS IQL Where sustainability meets performance: gear oil case study.		
	ROOM 0B	ROOM 0C	ROOM 0D
10:05 – 10:30	KEYNOTE	KEYNOTE	KEYNOTE
10:30 – 11:30	Lubricants 1	Tribology 1	Conditioning 1
11:30 – 12:00	COFFEE BREAK - POSTERS PRESENTATION		
12:00 – 13:00	Lubricants 2	Tribology 2	Conditioning 2
13:00 – 13:30	STAND VISIT		
13:30 – 14:30	LUNCH		
14:30 – 15:00	KEYNOTE	KEYNOTE	KEYNOTE
15:00 – 16:00	Lubricants 3	Tribology 3	Conditioning 3
16:00 – 16:20	COFFEE BREAK		
16:20 – 17:20	Lubricants 4	Tribology 4	Conditioning 4
20:30 – 23:30	GALA DINNER: THE ARTIST GRAND HOTEL OF ART		

TIME	THURSDAY, 04 JUNE 2026		
09:00 – 09:30	ATTENDEES REGISTRATION		
09:30 – 10:00	ROOM 0B: PLENARY SPEAKER: ESTEBAN BROITMAN SENTYS Tribological Coatings for Wind Turbine Bearings: An Overview		
	ROOM 0B	ROOM 0C	ROOM 0D
10:05 – 10:30	KEYNOTE	KEYNOTE	KEYNOTE
10:30 – 11:30	Lubricants 5	Tribology 5	Conditioning 5
11:30 – 12:00	COFFEE BREAK - POSTERS PRESENTATION		
12:00 – 13:00	Lubricants 6	Tribology 6	Conditioning 6
13:00 – 13:30	STAND VISIT		
13:30 – 14:30	LUNCH		
14:30 – 15:00	KEYNOTE	KEYNOTE	KEYNOTE
15:00 – 16:00	Lubricants 7	Tribology 7	Conditioning 7
16:00 – 16:20	COFFEE BREAK		
16:20 – 17:00	Lubricants 8	Tribology 8	Conditioning 8
17:00 – 18:30	CLOSING CEREMONY AND 10TH EDITION COCKTAIL Javier Barriga (Tekniker), Ian Sherrington (JOST Jost Institute for Tribotechnology) LUIS URIARTE (TEKNIKER)		

PLENARY AND KEYNOTE SPEAKERS



Mar Combarros

IQL

June 3, 2026

9:00-9:30 Room OB

PS1 Where sustainability meets performance: a gear oil case study

She is a chemical engineer with a PhD in Mechanical and Process Engineering from the Technical University of Braunschweig. She has more than 10 years of experience in the lubricant industry working on the research, design and development of new products across a broad range of applications.

Mar currently works as project manager at IQL, coordinating research and innovation projects related to lubrication and tribology. Her main professional focus is sustainability in lubrication. She approaches sustainability not only from the perspective of lubricant formulation, but also by considering performance, efficiency, durability and overall system impact; with the aim of contributing to a more sustainable future for industrial applications.



Esteban Broitman

Sentys

June 4, 2026

8:30-9:00 Room 1

PS2-Tribological Coatings for Wind Turbine Bearings: An Overview

Prof. Dr. Esteban Broitman is a materials scientist and translational research leader. He holds a PhD in Physics and a Docent (Habilitation) in Tribology, with more than 20 years of academic and industrial experience in surface engineering. His career includes professorships and senior scientist roles at the University of Buenos Aires (Argentina), Carnegie Mellon University (USA), and Linköping University (Sweden), as well as R&D leadership at SKF (Netherlands) and Sentys (USA).

He has integrated fundamental research on PVD/PACVD coatings, pilot-scale development, coatings nanomechanics and tribology, and commercialization to deliver measurable societal and economic impact. He has published more than 200 peer-reviewed articles, holds over 10 patents, and is included on Stanford's World's Top 2% Scientists list. His work focuses on using advanced surface engineering to control friction and wear at the macro, micro, and nano scales.



Dr. Balasubramaniam Vengudusamy

Klüber Lubrication München GmbH & Co. KG

June 3, 2026

10:05- 10:30 Room 0B

***KN1 From Tribology Challenges to Lifetime Extension –
Advanced Lubrication Strategies for Modern Wind
Turbines.***

Dr. Balasubramaniam Vengudusamy (Bala) is a Senior Expert in Tribology at Klüber Lubrication, based in Munich, Germany, with over 20 years of experience in lubrication science and tribology. He holds a degree in Mechanical Engineering and earned his Ph.D. in Tribology from Imperial College London. He has extensive experience in tribology, lubrication science, and failure analysis, and has played a key role in developing lubrication strategies for wind turbine applications. His work focuses particularly on rolling bearings, gears, WEC, electrically induced damage mechanisms, and their mitigation. By bridging fundamental tribological research with industrial practice, he supports the reliable and sustainable operation of critical machinery.

He has authored and co-authored numerous technical papers in leading journals and regularly contributes to international conferences and industry forums. He serves as an Associate Editor of the ASME Journal of Tribology and as a Technical Editor for Tribology & Lubrication Technology (TLT) and is actively involved in collaborative research with academia and industry worldwide.



Tim Hosenfeldt

Schaeffler AG

June 3, 2026

10:05- 10:30 Room 0C

KN 2 Holistic Tribology for Sustainable and Efficient Motion.

Prof. Dr.-Ing. Tim Hosenfeldt is Senior Vice President Central Technologies at Schaeffler AG. He studied production engineering at the University of Bremen and worked as a research engineer at the Leibniz Institute for Materials Engineering. After receiving his doctorate from the University of Bremen in 2000, he joined the Schaeffler Group, where he established the coating and surface technology division.

From 2015 to 2022 he served as Head of Central Innovation, and since 2022 he has led Central Technologies. Since 2016 he has been honorary professor for Engineering Design at Friedrich-Alexander University Erlangen-Nuremberg (FAU) and is board member of the EU initiative Innovative and Advanced Materials (IAM-I).



Marc Vila

Petronor Repsol

June 3, 2026

10:05- 10:30 Room 0D

***KN 3 A Proportional Hazards Models
perspective on MTBF estimation for centrifugal
pumps***

Marc Vila Forteza holds a Master of Science in Industrial Engineering (Mechanics) and a Bachelor of Science in Marine Engineering from the Polytechnic University of Catalonia (Spain). With more than 25 years of professional experience, his career has been dedicated to the reliability and diagnostics of rotating machinery.

He currently works as a Technical Advisor in Rotating Equipment Reliability at the Petronor refinery (Muskiz, Spain), part of the Repsol Group. He is also pursuing a PhD at the Division of Operation and Maintenance Engineering at Luleå University of Technology (LTU), Sweden, focused on remaining useful life prediction of centrifugal pumps through advanced monitoring and predictive maintenance strategies.

Borja Armendariz

TEKNIKER



June 3, 2026

14:30- 15:00 Room 0B

KN 4 Copper oleate–EP synergy in low-viscosity lubricants: antiwear comparison with commercial oils

He is a researcher in the Tribology and Materials Department at Tekniker, where his work focuses on the tribological characterization of gear lubricants and high-temperature tribology, with particular focus on nickel-based materials. His research contributes to the understanding of lubrication mechanisms and material behavior under severe operating conditions, providing improved performance and durability of mechanical components.

He holds a bachelor's degree in physics from the University of the Basque Country (UPV/EHU) and a Master's degree in Advanced Materials Engineering from the UPV/EHU. He is currently a PhD student at UPV/EHU, where his doctoral research is focused on the development of low-viscosity gear lubricants based on the synergistic effect between copper oleate and extreme-pressure (EP) additives.

Anna Andersson

ABB Corporate Research Centre June 19, 2024



June 3, 2026

14:30- 15:00 Room 0C

KN 5 Towards grease-free lubrication in electrical switching

Anna Andersson is an experienced materials scientist and senior researcher at the ABB Corporate Research Centre in Västerås, Sweden. She received her PhD in Inorganic Chemistry from Uppsala University in 2000, with a research focus on surface phenomena in lithium-ion batteries. After working in the United States and in the Swedish steel industry, she joined ABB in 2007. Her research interests span energy storage materials and the tribological performance of electrical contacts, with graphene serving as a unifying theme across both domains. She has acted as principal coordinator for several national and European collaborative research projects and has served as an assistant PhD supervisor in the areas of lithium-ion battery materials and materials for tribo-electrical applications.

Since 2017, she has investigated innovative graphene-metal composites aimed at multifunctional, low-friction components in electrical switching devices. From 2020 to 2023, she coordinated the EU-funded Graphene Flagship Spearhead project CircuitBreakers, which successfully demonstrated a first-of-its-kind, maintenance-free low-voltage circuit breaker based on solid graphene-based coating technology operating without conventional grease lubrication. She serves on the executive board of Batteries Sweden (BASE) and is a board member of IAM-I, the Innovative Advanced Materials Initiative, which leads the co-programmed EU partnership on advanced materials (IAM4EU).



Sophia Bastidas

Virtual Vehicle

June 3, 2026

14:30-15:00 Room 0D

KN 6 Investigating combustion engine wear during running-in and an overview of journal bearing performance prediction using a hybrid model approach.

Dr. Sophia Bastidas is a senior researcher at Virtual Vehicle Research GmbH, specializing in automotive data science, machine learning, and tribology. Her research combines experimental methods, physics-based modelling, and data-driven approaches, with a particular emphasis on predictive maintenance, anomaly detection, and federated learning with applications to bearings and lubrication systems.

She obtained a PhD in Propulsive Systems in Transportation from the Universitat Politècnica de València and was awarded the highly competitive Margarita Salas postdoctoral fellowship, funded by the European Union's NextGenerationEU program. She is project leader of the EU-funded SoliDAIR project and is involved in multiple national and EU-funded projects.



Peter Dufresne

EPT Clean Oil

June 4, 2026

10:05-10:30 Room 0B

KN 7

Peter Dufresne is the Chief Executive Officer of EPT Clean Oil, where he has dedicated more than 30 years to advancing lubricant reliability and contamination control technologies. He is widely recognized as a specialist in lubricant maintenance, condition monitoring, and testing for turbine lubrication systems, control fluids, and other critical industrial applications.

A pioneer in the application of ion exchange resin technology for lubricant purification, Peter has played a leading role in developing innovative treatment solutions and holds multiple patents in this field. He is the author of more than 20 published technical papers and is a sought-after speaker, having presented at numerous industry conferences, professional associations, and regulatory forums worldwide.



Cristian Schmid

Grupo Sichelub Lubritech

June 4, 2026

10:05-10:30 Room 0C

KN 8 Tribology for Industry: Closing the Gap Between Knowledge, Application and Measurable Benefits

Cristián Schmid is an Electromechanical Engineer (UTN, Argentina) and holds an MBA from Euncet Business School (Spain), with more than 25 years of experience in industrial maintenance, tribology, and rotating equipment reliability. He currently serves as General Manager of Grupo Sichelub Lubritech, overseeing operations across Latin America and Europe. His professional work focuses on the development and implementation of advanced lubrication engineering solutions aimed at improving reliability, availability, and operational efficiency in sectors such as power generation, Oil & Gas, mining, and steel. He holds international certifications from the International Council for Machinery Lubrication (ICML), including MLT I (Machine Lubrication Technician), MLA II (Machine Lubricant Analyst), and VPR (Varnish Prevention & Removal), with specialization in varnish control in lubrication and hydraulic systems.

He has led applied engineering projects involving technologies such as oil mist lubrication, oil purification, high-velocity flushing, and varnish mitigation in turbomachinery, contributing to improvements in reliability indicators (MTBF) and reduction of operational failures. Since 2025, he has served as President of the Argentine Association of Tribology, promoting technical knowledge dissemination and strengthening the link between industry and academia through conferences, training programs, and technical events. He is a frequent speaker at regional and international technical conferences, with a focus on tribology, predictive maintenance, and asset management.



Carlos Mota

GALP

June 4, 2026

10:05-10:30 Room 0D

***KN 9 From Lubrication Practice to Data Driven Asset
Insight: A Digital Approach to Lubrication Excellence and
Condition Monitoring***

Unit Manager @ Galp | Executive MBA – Porto Business School Carlos Mota is a Unit Manager at Galp, with a multidisciplinary career in the energy sector, strongly focused on industrial lubrication, reliability engineering, and predictive maintenance.

He holds a background in Chemistry, Quality Engineering and Mechanical Engineering. Throughout his professional path, he has led technical teams and projects related to lubricant analysis, contamination control, process optimization, asset management, and quality system implementation, supporting industrial clients operating in highly critical environments. He is a strong advocate of condition-based and predictive maintenance, applied tribology, and the use of technical data to support decision-making, promoting practices that improve equipment reliability, reduce operational costs, and extend asset life.



Gema del Olmo

FUCHS

June 4, 2026

14:30-15:00 Room 0B

KN 10 Sustainability in lubricants development

With a degree in Chemical Sciences, Gema began her career at FUCHS in 1997 as a cutting fluids specialist. Later, she became the development supervisor of product categories related to the metal processing: cutting, forming, and rolling, ensuring that the developed products were in line with market needs and the latest technologies, always respecting legislative developments.

Since 2017, she has been the director of the laboratory of the Spanish subsidiary and has been part of the steering committee for 5 years. Gema is currently focused in developing the R+D team in Spain in coordination with FUCHS LUBRICANTS Germany and the EMEA region, where the Spanish team has an important role in metal process products development.



Jorge Seabra

INEGI

June 4, 2026

14:30-15:00 Room 0C

KN11 Torque loss in an angular contact ball bearing

Jorge is a Professor of Mechanical Engineering who joined Porto University Engineering Faculty (FEUP) in 1981. He holds a BSc in Mechanical Engineering, MSc in Structural Engineering, PhD in Mechanics – Tribology (INSA de Lyon, France, 1988), and "Agregação" in Mechanical Engineering (FEUP, 2005). Research topics include Contact Mechanics, EHD Lubrication, Gears, Rolling Bearings, Lubricants, and Surface Failures.

He has coordinated more than 60 R&D projects financed by the EU, the Portuguese Agency for R&D (FCT), and several industrial companies worldwide. He has supervised 10 Post-Doctoral Fellowships, 17 PhD Theses, and more than 50 MSc Dissertations, and authored more than 120 papers in peer-reviewed scientific journals. He served as Director of the Department of Mechanical Engineering at Porto University (2015–2023) and Director of the Tribology Research Unit (CETRIB) at INEGI (1992–2022).



Jorge Alarcón

Bureau Veritas

June 4, 2026

14:30-15:00 Room 0D

KN12 AI Agents in Condition Monitoring and Predictive Maintenance: Reshaping the Future of Asset Reliability

Reliability Manager, Condition Monitoring Engineer, Researcher and consultant in Condition Monitoring and Predictive Maintenance in the power generation, manufacturing and wind energy industries, among others.

Extensive knowledge of the Predictive Maintenance markets of Europe and the Americas, full customer technical support, focused on improving plant reliability through oil condition monitoring, lubrication best practices and digital transformation strategies.

PROGRAMME

DAY 1- 3 JUNE 2026

LUBRICANTS Room 0B

09:00 – 09:30 OPEN CEREMONY

Javier Barriga (Tekniker), Adolfo Málaga (Bureau Veritas), Eneko Gorritxategi (Atten2), Ian Sherrington (JOST Jost Institute for Tribotechnology) Alberto Fernández (Basque Government - Director of Technology and Innovation)

09:30 – 10:00 PLENARY SPEAKER: MAR COMBARROS IQL Where sustainability meets performance: gear oil case study.

10:05 – 10:30 KEYNOTE Balasubramaniam Vengudusamy· Klüber Lubrication München GmbH & Co. KG From Tribology Challenges to Lifetime Extension – Advanced Lubrication Strategies for Modern Wind Turbines.

10:30 – 10:50 Challenges in the Analysis and Evaluation of Industrial Oils Stefan Mitterer OELCHECK GmbH Thomas Dr. Fischer

10:50 – 11:10 Good manners and practices for successful multivariate data analysis in oil condition monitoring (OCM) Alberto Villar Verguizas Tekniker Jose Ignacio Ciria, Ibon Zubicaray

11:10 – 11:30 Chemometrics as a powerful quality tool for OCM Jose I. Ciria Lubrication Management - Bureau Veritas Ibon Zubicaray

12:00 – 12:20 When Dissolved Varnish Becomes a Particle Count Problem: Resolving Temperature Driven ISO 4406 Cleanliness Instability with Ion Exchange Resin Technology Peter Dufresne EPT Clean Oil

12:20 – 12:40 From Thermal Stress to Varnish: Lab Tools for Lubricant Deposit Assessment Vincent BOUILLON Eurofins BfB Oil Research

12:40 – 13:00 Lubricant Varnish: What We've Learned and What We Still Don't Know Greg Livingstone Fluitec Sanya Mathura

14:30 – 15:00 KEYNOTE Borja Armendariz Tekniker Copper oleate–EP synergy in low-viscosity lubricants: antiwear comparison with commercial oils

15:00 – 15:20 Intelligent forecasting of oil changes with onsite oil analysis leads to maintenance cost savings Daniel Walsh Ametek Spectro Scientific Lisa Williams

15:20 – 15:40 Solubility enhancers a solution needed by Lubes Oil companies to Drive efficiency improvements in production processes Juan Jose Salaberri Fluitec

15:40 – 16:00 Modification of stability behavior of friction-stressed lubricating greases Erik Kuhn
Hamburg University of Appl. Sc.

16:20 – 16:40 Progress and Evolution of Coolant Usages in Industry Applications Yesid Antonio GOMEZ Bureau Veritas Spain Adolfo MALAGA, Pablo ARCE, Yesid Antonio GOMEZ, Maialen Aldabaldetrecu (Presenting Author)

16:40 – 17:00 Overview of the Latest Developments Affecting the Grease Industry Terry Dicken ELGI

17:00 – 17:20 Balancing sustainability with reliability for hydraulic oils in wind turbines Jo Ameye Fluitec NV Greg Livingstone, Sanya Mathura

TRIBOLOGY Room 0C

10:05 – 10:30 KEYNOTE Prof. Dr. Tim Hosenfeldt · Schaeffler AG Holistic Tribology for Sustainable and Efficient Motion.

10:30 – 10:50 Assessment of the tribological performance of materials under high pressure hydrogen gas Johnny Dufils IREIS / HEF Group Bogdan Munteanu, Etienne Macron

10:50 – 11:10 Tribological behavior of low viscosity synthetic ester base oils for Electric Vehicles (EVs) under pure sliding electrified conditions Claudia Martínez de Castilla Delgado Fundación Tekniker Bihotz Pinedo, Eduardo Tabares, Vanesa Alonso, Marta Hernaiz, Borja Armendariz, Ainara López-Ortega, Javier Barriga

11:10 – 11:30 Engine oil stress as a consequence of DPF regeneration on urban service vehicles and maintenance improvement aided by AI Bernardo Tormos CMT - Clean Mobility & Thermofluids (UPV) Ramón Sanchez-Marquez, Santiago Ballester, Alvaro Nuevós

12:00 – 12:20 Influence of counterpart and lubricant on wear of DLC coated differential shafts for electric vehicles Pauline Faura IREIS / HEF Group Johnny Dufils, Etienne Macron, Christophe Héau

12:20 – 12:40 Effects of aerospace-grade steel surface topography and coating on lubricated friction coefficient Aitor Arana Mondragon Unibertsitatea Mikel Iribecampos, Ibai Ulacia, Julen Maza

12:40 – 13:00 Combining laser-textured dimples and AlCrN coating to reduce wear on AISI M2 Steel Iker Alfonso Public University of Navarre

14:30 – 15:00 KEYNOTE Anna Andersson ABB Towards grease-free lubrication in electrical switching

15:00 – 15:20 SiToLub project – tribology for safe and sustainable lubricants Francesco Pagano Tekniker Amaya Igartua (Presenting Author)

15:20 – 15:40 Ageing mechanism of non-fossil base oils Ichiro Minami Jessica Pichler, Adam Agocs, Lucia Pisarova, Marcella Frauscher, Nicole Dörr, Francesco Pagano

15:40 – 16:00 Hydrogen related mechanisms influencing the galling behaviour of austenitic stainless steels in threaded components Beatriz Fernandez-Diaz Tekniker Xana Fernández, Fernando José López-Uruñuela, Gemma Mendoza

16:20 – 16:40 Tribological and corrosion properties of PEO/HiPIMS duplex coatings deposited on ZK60 magnesium alloy Adrián Claver Alba INAMAT2, Public University of Navarre

16:40 – 17:00 Prediction and Measurement of Space Lubricant Lifetimes in Angular Contact Bearings Dhanushka Hewaralalage University of Lancashire Ian Sherrington, Nathalie Renevier, Mara Bernabei, Ali Ghanbari

17:00 – 17:20 Simple Models for Mixed and Boundary Friction Ian Sherrington University of Lancashire Ian Taylor

CONDITIONING Room 0D

10:05 – 10:30 KEYNOTE Marc Vila Forteza · Petronor A Proportional Hazards Models perspective on MTBF estimation for centrifugal pumps

10:30 – 10:50 Real Time Monitoring of Water-Glycol Hydraulic Systems: Early Failure Detection Using Optical Particle Counter and Data Analytics Platform in the Caster Main Hydraulic System Rafael Diaz RMSH Rafael Antonio Diaz Giron Marco Suárez (Presenting Author)

10:50 – 11:10 Optimizing the Life Cycle of Online Oil Sensors: Installation, Maintenance Strategies and Performance Management Eneko Gorritategi Atten2 Advanced Monitoring Technologies SL

11:10 – 11:30 Lessons Learned from Online Oil Contamination Monitoring Jan Novák KLEENTEK, spol. s r.o.

12:00 – 12:20 Maintenance 5.0 Riccardo Tognoni BETA FILTRATION

12:20 – 12:40 Reducing Commissioning and Downtime Through Advanced Flushing and Lubrication System Cleaning Techniques Cristian Schmid Sicelub Ibérico SL

12:40 – 13:00 Lubrication Practices, Condition vs. Assumption Haris Trobradovic SDT Ultrasound

14:30 – 15:00 KEYNOTE Sofia Bastidas Virtual Vehicle Investigating combustion engine wear during running-in and an overview of journal bearing performance prediction using a hybrid model approach.

15:00 – 15:20 Vibration-Guided Lubrication for Maintenance Efficiency Janno Gabriels I-Care

15:20 – 15:40 Integrating Fluid Analysis with CMMS & Business Systems (+Case Studies) Gwyn Simmonds POLARIS Laboratories Europe

15:40 – 16:00 Trends in Used Oil Analysis: Insights from MOL-LUB's Diagnostic Laboratory Over the Last Decade Mária Valentné Dr. Sutyinszki MOL-LUB Ltd.

16:20 – 16:40 Modern grease analysis in industry Wojciech Jewula Ecol Sp. z o.o. Jakub Chłodek · Wojciech Majka · Piotr Farbiszewski

16:40 – 17:00 Lubrication Management in CEE II Overview Zoltán Kecskés MOL-LUB Ltd

17:00 – 17:20 Implementing online sensors and cleanliness on a mining ball mill Adrian Goodwin GVS Reliability Products Presenting Author: Eneko Gorritxategi (Atten2)

DAY 2 - 4 JUNE 2026

LUBRICANTS Room 0B

09:30 – 10:00 PLENARY SPEAKER: ESTEBAN BROITMAN SENTYS Tribological Coatings for Wind Turbine Bearings: An Overview

10:05 – 10:30 KEYNOTE Peter Dufresne EPT Clean Oil

10:30 – 10:50 Proactive Substitution Principle in Sustainability Mehdi Fathi-Najafi Nynas AB (pbl)

10:50 – 11:10 Sustainable Solutions in Metal cleaning Processes Dr. Sara Pasquale FUCHS LUBRICANTES SAU

11:10 – 11:30 Development of green lubricants for chasis components stamping Núria Rodríguez Grabalosa FUCHS LUBRICANTES SAU

12:00 – 12:20 Ammonia as a fuel for marine engines – lubricating oil monitoring and chemical analysis of fuel-lubricating oil interactions Richard Tröltzsch Universität Rostock - Lehrstuhl für Kolbenmaschinen und Verbrennungsmotoren Ulrike Schümann

12:20 – 12:40 Challenges for The Grease Analysis and Sampling for Wind Turbines Yesid Antonio Gomez Bureau Veritas Spain – OCM Maria Elena Garcia (Presenting Author)

12:40 – 13:00 Aluminium hot stamping novel lubricant Núria Rodríguez FUCHS LUBRICANTES SAU

14:30 – 15:00 KEYNOTE Gema Del Olmo · FUCHS LUBRICANTES SAU Sustainability in Lubricants Development

15:00 – 15:20 Tailor-made Automation for Oil and Coolant Condition Monitoring Laboratories: Modular, Customer-Centric Solutions from Sample Intake to Analysis Mike Matjeka HF Innovation GmbH

15:20 – 15:40 Race for clean oil – filter efficiency tests Steffen D Nyman C.C. JENSEN

15:40 – 16:00 Achieving super lubricity on hydrogenated diamond-like carbon coatings under electrified sliding conditions with aqueous glycerol lubrication Parveen Kumar Laboratory for Tribology and Interface Nanotechnology, University of Ljubljana Irfan Nadeem, Talha Bin Yaqub, Ardian Morina, Mitjan Kalin

16:20 – 16:40 How potato peels converted into synthetic esters leads to base oils with improved performance and significantly lowered carbon footprint Sabrina Zaini ChainCraft Erwin Zwolsman, Thomas Blundell

16:40 – 17:00 Phosphate Ester – is fill for life possible? Steffen D Nyman C.C. JENSEN

TRIBOLOGY Room 0C

10:05 – 10:30 KEYNOTE Cristian Schmid · Reladyne Tribology for Industry: Closing the Gap Between Knowledge, Application and Measurable Benefits

10:30 – 10:50 OOST Methodology: A Systems-Oriented Optimization of Interconnected Tribological Systems to Enhance Centrifugal Pump Reliability Victor Rubiano Chesterton International GmbH

10:50 – 11:10 A Study of the Effect of Hydrogen Introduction into a Diesel Internal Combustion Engine Ahmad AlFetyani University of Lancashire Graham Calderbank

11:10 – 11:30 Tribotronic System for Piston Ring Lubrication Abdelrahman Youssef University of Lancashire

12:00 – 12:20 Low-Friction Diamond-Like Carbon Coatings for Tapered Roller Bearings: Design, Characterization and Tribological Performance Sofia Gimeno Fersa

12:20 – 12:40 Controlled Synergistic Transition of Friction Mechanism in Ceramics with Lubricant system based on 2D nanostructures WSe₂ as a Tribological Trigger. Kostyantyn Grinkevych Institute of Construction Sciences, CSIC (IETCC-CSIC) Natalia Konih-Ettel · Ostap Zgalat-Lozynskiy Roman Nevshupa

12:40 – 13:00 Minimum energy sliding equilibrium model for redundant kinematic mechanism Mikel Iribecampes Juaristi Mechanics and Industrial Production Department. Mondragon University Mikel Iribecampes Juaristi, Pello Alberdi Quevedo, Aitor Arana Ostolaza, Ibai Ulacia Garmendia

14:30 – 15:00 KEYNOTE Jorge Seabra INEGI Torque loss in an angular contact ball bearing

15:00 – 15:20 Equations for Predicting the Minimum Oil Film Thickness in Reciprocating Contacts Ian Taylor Jost Institute for Tribotechnology, University of Lancashire

15:20 – 15:40 Triboelectric wind turbine for Mars exploration Iban Quintana TEKNIKER Borja Pozo

15:40 – 16:00 Blade Health Monitoring of Turbo Propulsion Systems: Novel Modal-based BTT and BTC Simulator with Experimental Validation Naweendra Jayasundara Mudiyansele University of Lancashire Mohamed Elsayed Mohamed, Ian Sherrington, Kirijen Vengadasalam

16:20 – 16:40 Optical scatterometry-enabled phase-space representation for functional characterisation of tribological contacts Boris Brodmann OptoSurf GmbH Matthias Eifler, Cesar Weigmann

16:40 – 17:00 Development of tribological testing machines in TEKNIKER Amaya Igartua Fundación TEKNIKER Borja Zabala, Francesco Pagano, Ichiro Minami, Bihotz Pinedo, Jose Mari Seara, Javier Barriga

CONDITIONING Room 0D

10:05 – 10:30 KEYNOTE Carlos Mota · GALP ENERGY From Lubrication Practice to Data Driven Asset Insight: A Digital Approach to Lubrication Excellence and Condition Monitoring

10:30 – 10:50 Transforming Lubrication into Operational Intelligence Marcelo Robert Belray

10:50 – 11:10 Standardization of Particle Detection and Counting in Lubricants: Concepts, Landscape, and Future Outlook Guillermo Miró Atten[2]

11:10 – 11:30 A Lightweight Algorithm to Verify Sensor Health in Wind-Turbine Lubrication-Oil Monitoring Riccardo Cocola Tekniker Kerman López de Calle

12:00 – 12:20 Goodbye “Ghost Particles”: Improving Particle Counting Accuracy with the ASTM D7647 Dilution Method Bill Quesnel CINRG Systems Inc. Alistair Geach

12:20 – 12:40 ASSIST® - Collaborative Robotics and AI-Driven Computer Vision for the Spectroil 100 Automation Matteo Campatelli Mecoil Diagnosi Meccaniche srl Adriani Giuseppe

12:40 – 13:00 Inline Oil Condition Monitoring as a Tool to Detect Gear Pitting Djordy Van Maele Ghent University Jean Carlos Poletto, Dieter Fauconnier, Patrick De Baets

14:30 – 15:0 KEYNOTE Jorge Alarcón · Bureau Veritas AI Agents in Condition Monitoring and Predictive Maintenance: Reshaping the Future of Asset Reliability

15:00 – 15:20 Novel Online Sensor Approaches for Water Contamination Detection in Lubricating Oils Bruno Pilotti Atten[2]

15:20 – 15:40 Continuous Optical Monitoring for Predictive Maintenance of Hydraulic Systems Abdelhadi KASSIMI ALME (ALKHAOUARIZMI- LUBES-MAINTENANCES-EXPERTS)

15:40 – 16:00 Mapping Degradation Pathways in Turbine Oils Under Severe Thermal Stress Douglas Purnell Fluitec International Elona Rista (Presenting Author)

16:20 – 16:40 From Crisis Management to Asset Management: 4 Real Cases Where Off-line Filtration Changed the Game Bruno Sánchez C.C Jensen Ibérica, S.L.

16:40 – 17:00 Clean Data Clean Hydraulics Best Practice Hydraulic Sampling Bernie Hall Checkfluid Inc

POSTERS

Evaluating the Compatibility of ZrC and TiC Nanofluids as Electric Vehicle Transmission Fluids with Polymeric Elastomers Josefa FernándezSantiago de Compostela University

Hybrid Ionic Liquid-Polyoxometalate/Ionic Liquid additives for low viscosity oils Josefa Fernández Santiago de Compostela University

Assessment of electric-field-induced lubricant film activation in electrorheological biolubricants by optical interferometry Miguel Angel Delgado Canto Universidad de Huelva

Electroactive Nanocellulose Biolubricant Under Electric Fields: Squeeze-Flow Evidence of Improved Load Carrying Capacity. Moises Garcia MoralesUniversidad de Huelva

The key role of plastic revalorization in the development of sustainable lubricants bases Mireia Sola

BOOK OF ABSTRACT

When sustainability meets performance: a gear oil case study

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Abstract

This work presents a gear oil case study based on a holistic approach to sustainability. The study considers sustainability not as a compromise with lubricant performance, but as an added value in product design. Key aspects such as carbon footprint, renewable raw material content, biodegradability, and responsible use of resources are evaluated from a life-cycle perspective, including especially the impact during use. The case study highlights how lubricant design can contribute to reducing environmental impact while supporting a more sustainable and responsible approach to high-performance gear oil development.

1. Introduction

Sustainability has become a key driver in the development of new lubricant technologies. Traditionally, the sustainability of lubricants has often been evaluated through individual parameters such as carbon footprint, biodegradability, renewable content, or regulatory compliance. However, for functional products such as gear oils, sustainability cannot be considered independently from technical performance. A lubricant must first fulfil its primary function: reducing friction, protecting components from wear, improving efficiency, and extending equipment lifetime.

A gear oil case study will be presented, introducing this new holistic definition of sustainability. The oil design will consider carbon footprint, biodegradability, and renewability not as factors to be balanced against lubricant performance, but as an added value. In this perspective, sustainability becomes an integral part of a high-performance lubricant design.

Synthetic esters are currently used in a wide range of applications, including automotive and marine engine oils, gear oils, compressor oils, hydraulic fluids, and greases, due to their outstanding performance properties. Key characteristics such as biodegradability, low-temperature fluidity, and thermal-oxidative stability can be tailored through molecular design, helping to meet the evolving requirements of the lubricant industry [1].

In this work a gear oil study will be presented where the focus is on the durability of the lubricant, as well as the tribological behaviour in a gear oil. Sustainability is understood as a reduction of the environmental impact as an assessment of the life cycle of the product, which includes: the origin of the raw materials, manufacturing, performance in application and biodegradability.

2. Methods

2.1. Ageing behaviour

An ester degrades by two main mechanisms at high temperatures: physically, evaporation of the volatiles, and chemically, due to oxidation / polymerization but also to an evolution of gases CO, CO₂, especially at higher temperatures [2]. These phenomena cause an increase in viscosity and formation of deposits which may limit the lubricant applications specially nowadays where an extended service life is usually required.

The aging behavior of four different products was investigated. The influence of steric hindrance in the propagation of the polymerization was studied using two different structures: Product A and B. The influence of antioxidant additives on polymerization was investigated adding a mixture of aminic/phenolic antioxidant additives. Product C, product with no additives was compared to product D which has a 0.5 % of additive.

Table 1. Main properties for the products used

	A	B	C	D
KV 40°C (cSt)	67.1	68.7	100	100
KV 100°C (cSt)	10.8	11.7	14.0	14.0
Viscosity index	152	165	141	137
AN (mgKOH/g)	0.09	0.06	0.15	0.36
RSSOT (min)	144	159	247	108
Volatility-TGA(%)	61	45	24	17

Thermo-oxidative properties were studied by means of RSSOT for the oxidation and TGA for its volatility. TGA measurements were measured in a large furnace after a 1h isothermal step at 250 °C. The main properties are shown in Table 1.

Thermal degradation was evaluated using 600 g of product in a round bottom flask, heated with an electrical heater at 180 °C for 168 h. As a catalyst 0.6 g of powder Fe was used. The product was maintained at a constant speed of 60 rpm with a magnetic stirrer and at open air. After the test, the product was vacuum filtered.

The evolution of the aging process was monitored evaluating the change on total acid number, viscosity, weight.

2.2. Tribological behaviour

Tribological behaviour of the gear oil containing also antioxidants, antiwear additives and EP additives was performed using an SRV (Schwing-Reibung-Verschleiss) machine using DIN 51834-4: Apart from that, the lubricants were also tested with DGMK-FZG micropitting short test to evaluate the ability of a gear oil to protect gear tooth flanks against micropitting under controlled operating conditions.

3. Results

3.1 Ageing results

The mechanism by which the products are degraded is a radical mechanism. Initial steps of oxidation originate hydroperoxides, oxo- and hydroxy-compounds and it is initiated by high temperatures. In later stages high molecular weight products are formed [2,7].

The main properties of the thermal aged products are depicted in Table 2. As we can see, viscosity increases in all four cases specially if the sterically hindrance degree is lower (Product A). During the aging process, volatiles have formed due to two main effects: physical effect of evaporation of the initial products and formation of low molecular compounds. Apart from that, the acid number also increases significantly in all cases. Thanks to the addition of an antioxidant, the initiation of polymerization can be delayed as we can see if we compare viscosity of product D with that of product C.

Table 2. Products properties after aging

	A	B	C	D
KV 40°C (cSt)	1194	422	586	146
KV 100°C (cSt)	83.1	41.8	45.6	17.6
Viscosity index	146	151	128	133
AN (mgKOH/g)	26.9	16.5	10.5	5.5
RSSOT (min)	135	103	135	317
Weight loss (%)	22	17	8.6	2.9

3.2. Tribological behaviour

During the use phase, ester-based oils can influence the tribological behaviour of gear oils through their interaction with additives. Because of their polar nature, esters may compete with surface-active additives for adsorption on metal surfaces. This competition can influence the formation and stability of protective tribofilms, which are essential for friction reduction and wear protection. Therefore, controlling and, where necessary, reducing the polarity of ester oils is important to achieve optimal performance in combination with additive systems. Oil polarity can be assessed using the Non-Polar Index, which provides an indication of the relative polarity of the base oil.

$$NPI = \frac{\text{Total number of } C \cdot MW}{\text{Number of carboxylic groups} \cdot 100}$$

The ester-based lubricants represented in Figures 1 and 2 are formulated using ester components with different viscosities. The low-viscosity component contributes to reducing viscous drag, while the high-viscosity component supports lubricant film formation, particularly under boundary lubrication conditions. In the ester-based formulation shown in Figure 1, the low-viscosity component has a low Non-Polar Index, $NPI = 68$. This indicates a higher polarity, which may promote competition between the ester and surface-active additives for adsorption on the metal surface. As a result, the additives may be less able to react effectively with the surface and form stable protective tribofilms.

In contrast, when the low-viscosity component has a higher Non-Polar Index, $NPI = 260$, this competitive adsorption is reduced. This allows the additives to interact more effectively with the surface, resulting in excellent lubricant performance, even when compared with formulations containing PAO.

The good performance of these ester-based lubricants is also confirmed by the DGMK test method. The tested lubricants are classified as GFKT-high class, indicating a high capacity to protect gears against micropitting. This classification is based on the DGMK test method, which is analogous to the FVA-FZG micropitting test, as shown in Figure 3.

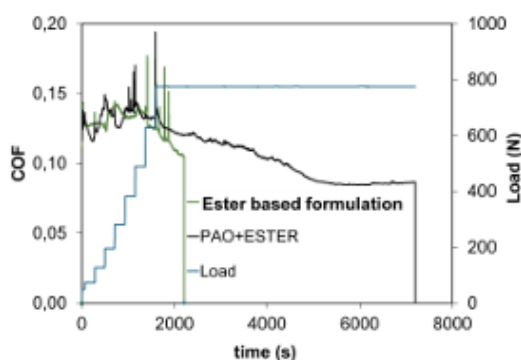


Fig. 1. SRV AW test. Low viscous component $NPI=68$

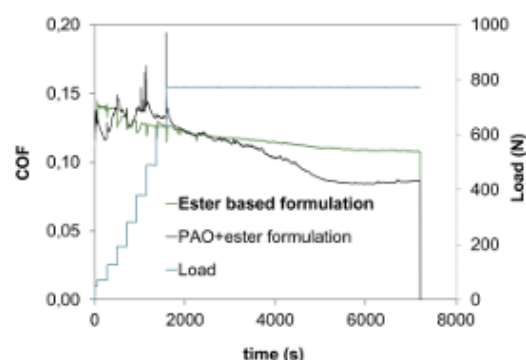


Fig. 2. AW test. Low viscous component $NPI=260$

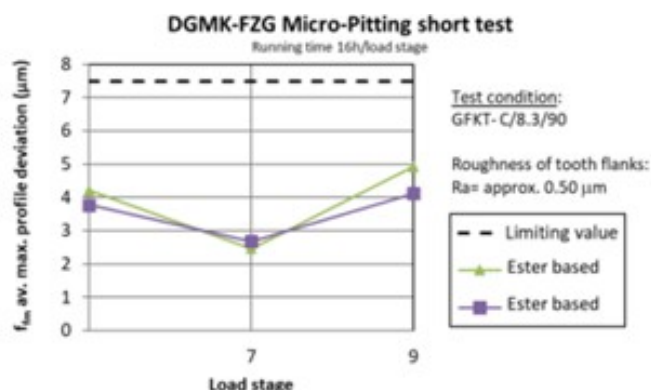


Fig. 3. DGMK-FZG Micro-Pitting short test

4. Conclusions

This gear oil case study demonstrates that sustainability in lubricant design should be considered from a holistic life-cycle perspective, rather than as a compromise with technical performance. The selection and molecular design of synthetic esters can contribute to lower environmental impact through renewable raw material content, biodegradability, and improved resource efficiency, while still supporting the demanding performance requirements of gear oils.

The ageing study showed that ester structure and antioxidant selection have a significant influence on thermo-oxidative stability. Higher steric hindrance and the use of suitable antioxidant additives help reducing viscosity increase, acid formation, and weight loss during ageing, indicating improved lubricant durability and potential for extended service life.

The tribological results further highlighted the importance of balancing base oil polarity and additive response. Ester polarity can influence additive adsorption and tribofilm formation, affecting friction and wear performance. By optimizing the non-polar index of the ester components, it was possible to reduce competition at the metal surface and achieve excellent gear protection, as confirmed by the high micropitting performance in the DGMK-FZG test.

Overall, the study shows that sustainable gear oil design requires the integration of raw material selection, lubricant durability, additive compatibility, tribological performance, and end-of-life considerations. When properly designed, ester-based gear oils can provide both high technical performance and a reduced environmental impact, supporting the concept of sustainability as an added value in lubricant development.

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From Tribology Challenges to Lifetime Extension – Advanced Lubrication Strategies for Modern Wind Turbines

Challenges in the Analysis and Evaluation of Hydraulic, Gear and Engine Oils

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Abstract

Hydraulic, gear and engine oils, as well as greases and coolants, are not only operating materials but also information carriers about machine and lubricant condition. Used-oil analysis is therefore a key tool for condition monitoring and condition-based maintenance. A lubricant laboratory must convert measurement data into clear statements on condition, risk and concrete actions such as oil change, drying or closer monitoring. This presentation highlights challenges throughout the analytical process e.g. when limited sample information is available. How can optimal results be achieved for the customer despite these and other uncertainties?

1. Industries, Domain Knowledge and Input Data

Laboratories serve diverse industries: wind energy, gas engines and turbines, construction machinery, transport, plastics, agriculture, paper, cement and refineries. Each sector has specific operating conditions, failure modes, lubricant types and expectations for response time and report detail. The same measured value can mean something very different in a slow industrial gearbox than in a high-speed gas engine, so broad analytical capability must be combined with strong domain knowledge.

1.1 Scope of Analysis and Laboratory Process

The scope of analysis is tailored to machine type, oil type and criticality. Core parameters across hydraulic (H), gear (G) and engine (E) oils include elemental analysis by ICP, PQ index, viscosity at 40 °C and 100 °C (plus VI), FTIR (oxidation, nitration, soot, glycol, water) and acid number. Application-specific tests refine the picture: particle count and Karl Fischer water for (H) and (G), fuel content, base number (BN) and ipH for (E). Together they provide a comprehensive view of lubricant condition, contamination and indirect machine condition. The lab process usually follows a fixed chain: registration and ID assignment, sample preparation (mixing, dilution, filtration), instrumental analysis, quality control (calibration, blanks, standards, duplicates), expert evaluation by tribologists and engineers and reporting.

1.2 Evaluation Under Uncertainty and Automation

A key challenge is evaluation under uncertainty when information is incomplete or wrong. Example: an oil declared as "H 46 (HLP – mineral oil)" shows water levels that would be critical for a mineral HLP oil. If additive package (Table 1) and FTIR (Figure 1) reveal an ester-based hydraulic fluid, the assessment must be revised because water behaves differently in ester oils. This shows how important correct lubricant identification is and why customers need not just numbers but clear, actionable recommendations.

ADDITIVES			
Calcium	Ca	mg/kg	0
Magnesium	Mg	mg/kg	1
Boron	B	mg/kg	1
Zinc	Zn	mg/kg	7
Phosphorus	P	mg/kg	1517
Barium	Ba	mg/kg	0
Sulphur	S	mg/kg	1236

Table 1: Additives for an ester-based fluid (phosphorous and sulfur)

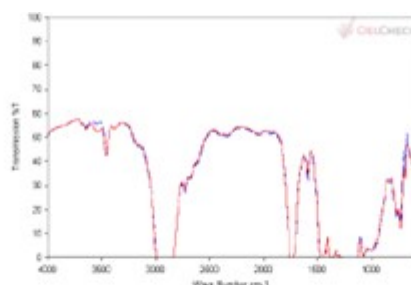


Figure 1: FTIR spectrum of an ester-based fluid

Automation helps detect critical samples and protect instruments. In ICP analysis, extremely high silicon values can reveal silicone oil and trigger automatic alarms and special flushing. For fuel dilution, gas chromatography distinguishes gasoline and diesel regions. If the engine's fuel type is misdeclared, GC results may be misinterpreted, so chromatograms must be checked critically and, if necessary, re-evaluated and repeated, with corrections communicated to the customer.

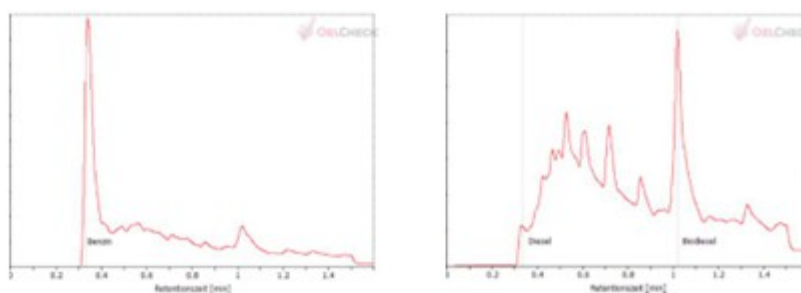


Figure 2: GC chromatogram to detect gasoline (left) or diesel fuel (right) in engine oils

2. Role of Artificial Intelligence (AI)

Artificial intelligence can support labs by pre-classifying samples (e.g. "green" vs. conspicuous), recognizing recurring failure patterns, implementing standardized rules, generating draft comments, detecting implausible information and optimizing workload and batch composition. However, AI depends on high data quality and continuous maintenance and must be embedded in a human-in-the-loop design: typically, only clearly unremarkable samples are released automatically, while tribologists review all conspicuous cases and can override AI suggestions. A practical roadmap includes cleaning and enriching historical data, monitoring incoming data quality, piloting low-risk use cases (such as strict green classification) and designing interfaces that explain AI decisions. Communication with customers should be transparent: AI supports experts but does not replace them. Overall, the central challenges for a lubricant laboratory range from accurate customer data and tailored test scopes through robust lab processes to evaluations that turn complex data into simple, useful recommendations. Rising sample volumes and system complexity make automation and AI necessary, but human expertise and good communication remain the core of high-quality oil analysis.

3. Conclusion

From the perspective of a lubricant laboratory, the challenges in analyzing and evaluating hydraulic, gear, and engine oils are multifaceted. They range from ensuring reliable information flow from the customer, through designing a suitable scope of analysis and maintaining clean, robust lab processes, to delivering evaluations that provide maximum added value for operators. The wide range of analyzed lubricants creates very different issues in the analysis process and requires adaptable methods and extensive expertise. The informative content for the customer is central. Data must be translated into clear assessments and recommendations. As sample numbers continue to rise and industrial systems become more complex, the integration of automation and AI is not just an option but a necessity. However, the essence of high-quality oil analysis remains human. It is the expertise of tribologists and engineers—supported by data, technology, and strong internal collaboration—that ultimately unlocks the full message "spoken" by the oil about the condition of both machine and lubricant.

Good manners and practices for successful multivariate data analysis in oil condition monitoring (OCM)

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This work aims to provide useful advice for a successful multivariate data analysis applying chemometrics methods in lubrication management, since the data pre-processing up to validation stage. For this purpose, this work will introduce some theoretical aspects necessary for the developing of chemometrics methodology and propose some tips for the successful implementation in an Oil Condition Monitoring (OCM) laboratory.

1. Introduction

Chemometrics can be defined as the discipline that applies machine learning (ML) methods to extract the maximum relevant information from chemical system by multivariate data analysis [1]. According to this definition, the results obtained by ML methods should have a chemical meaning that should be considered during calibration model's validation, helping to the interpretability of the model. This, which seems obvious, sometimes is not put in practice when ML methods are applied as a complex black box. The interpretability of the model is a concept emphasized by Explainable Artificial Intelligence (XAI), which in recent years has been gaining importance helping to the successful integration of the ML models in real applications. In this context, this work aims to provide practical advice for a successful multivariate data analysis since the data pre-processing up to the validation stage. For this purpose, this work shows the results of applying ML to spectroscopic data for oil condition monitoring (OCM) purposes, including real examples provided by Lubrication Management laboratory. The implementation of the chemometrics methodology can provide significant benefits to OCM laboratory such as the improvement of the productivity by higher automatization, and the reduction of cost analysis, turnaround analysis (TAT) and chemical waste (carbon footprint).

2. Methodology

A classic chemometrics methodology for multivariate calibration purposes has the following steps: (i) exploratory analysis; (ii) spectra pre-processing; (iii) development of the mathematical model; (iv) validation of the model; and (v) implementation and maintenance of the model. In each of this stage there are key aspects to consider and decisions to be made that will determine the degree of success in developing and implementing the analytical method. [2]

3. Good manners and practices

The previous step before the multivariate data is the sampling which will define the dynamic range of the calibration model and the proper selection of training and validation set. Both group of samples must be representative of expected oil condition for a defined application.

3.1. Exploratory Data Analysis

One key aspect is the reliability of the reference measurements which should be obtained by standard laboratory methods. Then, the quality of the spectra must be checked by manually plotting the spectra and identifying any incorrect spectra or automatically by tools such as IR-index. Another important aspect is the blanking of the spectra to delete this spectroscopic information that is no meaningful or can introduce non-desirable spectroscopic features (e.g. environment CO₂ presence).

3.2. Pre-processing strategy

One of the main purposes of pre-processing is to remove sources of variations which can affect the multivariate data analysis. But there is no magic in this process, if the spectroscopic data are of poor quality, the multivariate calibration model will not work. There is no gold rule, the experience of the data

analyst and lab staff is crucial. It is necessary to point out that 2 or 3 combinations of pre-processing methods should be enough to improve the quality of the spectra.

The first step is the transformation from transmittance (%T) to absorbance (Abs), since according to Lambert-Beer the linear correlation with the concentration of the target compound is with the Abs. Although this may seem obvious, it is sometimes overlooked due to a lack of spectroscopic knowledge of the data analyst. Then, spectroscopic data usually requires a degree of smoothing, taking care when selecting the window size to not delete relevant spectroscopic information. When applying derivatives remember that these contains a smoothing function. Moreover, consider that the 2nd derivative will enhance the spectroscopic noise. Related to scatter correction methods, Standard Normal Variate (SNV) and Multivariate Scatter Correction (MSC) almost have the same effect in the spectra, but MSC is dependant of the training set. Finally, spectra centered is mandatory, even there are some software packages that applies it by default [2].

Furthermore, when working with full spectroscopic range there are useful variable selection techniques such as iPLS or Generic Algorithms (GAs) that gives satisfactory results, especially when working with less common oil quality parameters where the spectral ranges of interest are unclear [3,4].

3.3. Development of the mathematical model

Partial Least Square Regression (PLSR) tries to maximize the variance, thus capturing the variance and correlating the predictor and responsible variables together. On the other hand, Principal Component Regression (PCR) just captures the variance of the predictor variables. PLSR usually gives better results than PCR. There are two alternatives to solve non-linearity problems of the model: (i) the logarithmic transformation of reference measurement (log-Y) or (ii) the selection of Support Veco Machine Regression (SVMR) as regression method.

One key question is the outlier's detection. There are diverse ways to detect them: score plot, influence plot, X-Y residual sample variance plot, and more. However, with the aim to improve the validation results do not carry out an indiscriminate removal.

The validation strategy can be performed by combination of a cross validation (trying to avoid the leave-one-method) with external test validation. At this point, the same question always comes up, how many Latent Variables (LVs) or Principal Components (PCs) should my model have? The author recommends a maximum number of 10 PCs/LVs, considering that the fewer components there are, the more robust the model is. Finally, the uncertainty (interval of confidence, $\pm$) of the prediction can be easily determined as the double of Standard of Performance (SEP). [5]

3.4. Interpretation of the model

The PLSR model should not be considered a black-box. Apart from the numerical statistics (r^2 , bias, RMSEP, SEP,...), it gives a lot of information that help us to understand and improve the model. For instance, by the scores plot it is possible not only the outlier's detection but also samples patterning recognition. The loadings plot shows how much each original variable contributes to each PC/LVs indicating if they have positive or negative effect [6]. All this information will help us to the interpretability of the model, linking with a new paradigm that has gained significant prominence in recent years, the XAI. It proposes create a suitable ML methodology that produce more explainable models while maintaining an important level of learning performance. Interpretability of the model helps ensure the impartiality in decision-making, facilities the provision of robustness and guarantee that only meaningful variables have impact in the model performance [7]. In this context, it is mandatory to point out that all the results obtained from the multivariate data analysis should be checked with the OCM lab staff to validate them.

4. Conclusions

The multivariate data analysis should be considered a multidisciplinary approach being important not only the skills of the data analyst but also the knowledge of OCM laboratory staff. It is this combination that will ensure the success in the multivariate calibration process.

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Chemometrics as a Powerful Quality Tool for Oil Condition Monitoring

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Abstract

Chemometrics combined with Fourier Transform Infrared Spectroscopy (FTIR) has become a valuable tool for improving quality control, reliability, and operational efficiency in Oil Condition Monitoring (OCM). This work describes the practical implementation of chemometric methodologies integrated with Laboratory Information Management Systems (LIMS) for lubricant analysis and predictive diagnostics. The study highlights the importance of spectral quality, sample screening, spectral region selection, and robust model construction to improve prediction reliability and reduce analytical uncertainty. In addition, the IR-Index is presented as a global indicator of lubricant health, enabling rapid assessment of oil degradation and contamination. The integration of chemometric workflows with automated decision systems contributes to improved data integrity, reduced retests, and enhanced laboratory productivity.

Keywords: Chemometrics, FTIR, Oil Condition Monitoring, Lubricant Analysis, IR-Index, LIMS.

1. Introduction

Oil Condition Monitoring (OCM) laboratories continuously seek analytical methodologies that are faster, more reliable, and more sustainable. Traditional wet chemistry techniques provide accurate results but are often associated with high operational costs, increased reagent consumption, and long turnaround times.

In this context, chemometrics has emerged as a strategic approach capable of transforming complex spectroscopic data into actionable information. Combined with FTIR spectroscopy, chemometric models can estimate lubricant properties, identify contaminants, detect degradation patterns, and support predictive maintenance strategies.

The successful implementation of chemometric systems requires multidisciplinary collaboration between analytical chemists, tribologists, data analysts, and IT specialists. Reliable spectral acquisition, robust model development, and automated data management are essential to ensure long-term analytical stability and confidence.

This work summarizes the main aspects required for successful chemometric implementation in lubricant analysis laboratories, focusing on spectral quality, model robustness, IR-Index development, and LIMS integration.

2. Spectral Quality and Data Reliability

The quality of the FTIR spectrum directly affects the performance of chemometric models. Poor spectral acquisition introduces noise, baseline distortions, and artifacts that reduce prediction accuracy and may lead to incorrect interpretation of lubricant condition.

Several practical factors must be controlled during analysis as accurate calibration of the transmission cell path length, complete filling of the measurement cell to avoid air bubbles, proper cleaning of the transmission cell, multiple spectral acquisitions to improve the signal-to-noise ratio or selection of the appropriate reference oil spectrum.

Consequently, robust chemometric systems can only be achieved through the generation of high-quality and reproducible spectral data.

3. Robust Chemometric Models

Model robustness is a critical factor in chemometric applications. Excessive data cleaning or aggressive preprocessing may improve calibration statistics artificially while reducing the model's ability to generalize to real industrial samples.

A reliable chemometric workflow should include selection of informative spectral regions, prevention of overfitting, validation using independent datasets and continuous monitoring of model performance.

Not all FTIR spectral regions contribute equally to prediction quality. Water-related bands between approximately 3700–3200 cm⁻¹, for example, contain valuable information regarding moisture contamination, whereas other regions may contribute little useful information.

Focusing on chemically meaningful spectral regions improves prediction stability, enhances robustness, and reduces the probability of model failure.

4. IR-Index as a Global Lubricant Health Indicator

The IR-Index is a composite metric derived from FTIR spectra that evaluates the chemical similarity between a used lubricant and its corresponding new oil reference.

Unlike isolated analytical parameters, the IR-Index integrates multiple degradation and contamination phenomena into a single value. The index reflects changes associated with oxidation, nitration, sulfation, additive depletion, water contamination, fuel dilution, and incorrect oil identification.

A higher IR-Index indicates greater similarity between the used oil and the original lubricant formulation, allowing rapid global assessment of lubricant health.

The IR-Index is also useful for chemometric model management. Samples presenting abnormal spectral characteristics can be automatically identified and excluded from calibration datasets, preventing inconsistencies and improving model reliability.

This screening process is particularly important for industrial oils and engine oils, where lubricant chemistry evolves significantly during service life.

5. LIMS Integration and Automated Decision-Making

The integration of chemometric workflows with Laboratory Information Management Systems (LIMS) enables higher levels of automation, traceability, and operational efficiency.

Automatic transfer of chemometric data into the LIMS reduces manual workload while improving data integrity. Automated decision rules can also be implemented to quarantine or reject samples that do not satisfy predefined statistical or spectral criteria.

Additionally, this approach supports sustainability objectives by minimizing retests, reducing reagent consumption, and improving laboratory productivity.

6. Conclusions

Chemometrics combined with FTIR spectroscopy represents a powerful quality tool for modern Oil Condition Monitoring laboratories. Reliable spectral acquisition, appropriate selection of spectral regions, and robust model construction are essential to ensure analytical confidence and long-term stability.

The IR-Index provides a valuable global indicator of lubricant condition while supporting sample screening and model validation processes. Furthermore, LIMS integration enables automated decision-making, enhanced traceability, and improved operational efficiency.

The successful implementation of chemometric systems requires close collaboration between analytical chemists, tribologists, data analysts, and IT specialists. When properly implemented, these systems reduce turnaround times, minimize retests, improve sustainability, and strengthen predictive maintenance strategies.

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When Dissolved Varnish Becomes a Particle Count Problem: Resolving Temperature-Driven ISO 4406 Cleanliness Instability with Ion Exchange Resin Technology

Abstract

Particle count excursions in lubricating oil systems are typically interpreted as evidence of solid particulate contamination and are commonly addressed using mechanical filtration. However, this power generation case study demonstrates that elevated ISO 4406/NAS particle counts can originate from a different mechanism: soluble oxidation by-products that remain dissolved at operating temperature but precipitate as soft varnish particles when the oil cools. This temperature-dependent phase change creates the appearance of a particulate contamination problem, even though particle contamination is absent at operating temperatures.

This paper examines how soluble varnish precursors can produce unstable particle count results and why conventional fine filtration fails to correct the issue. In the case reviewed, a high-efficiency mechanical filter cart was unable to reduce elevated particle counts because their root cause was not “hard” particulate contamination. Instead, the cause of the high particle counts was a soluble-insoluble varnish equilibrium-driven by oil chemistry and temperature. Treatment using ion exchange resin filters removed the soluble varnish that was responsible for particle formation, reducing the temperature-driven discrepancy between warm and cool particle counts and restoring stable lubricant cleanliness.

The findings challenge the conventional assumption that high particle counts must be solved with particulate filtration alone. In varnish-affected turbine oils, ISO 4406 cleanliness instability may be a symptom of dissolved oxidation contamination. By removing soluble varnish before it precipitates, ion exchange resin-based technology can resolve a, previously unsolvable, particle count problem at its chemical source.

Introduction

Particle contamination in turbine oils, hydraulic fluids, and critical lubrication systems is commonly evaluated using ISO 4406 cleanliness codes or NAS cleanliness classes. ISO 4406 is used to simplify particle count data by assigning cleanliness codes based on the number of particles per millilitre at defined particle size thresholds. For automatic particle counters, the code typically reports counts at $\geq 4 \mu\text{m(c)}$, $\geq 6 \mu\text{m(c)}$, and $\geq 14 \mu\text{m(c)}$. Each increase in ISO code generally represents a doubling of the particle concentration.

Because ISO 4406 is based on counted particles, users often interpret a high ISO code as evidence of solid particulate contamination. This interpretation is reasonable when the contaminants are dirt, wear metals, fibers, or other hard particles. However, ISO particle counters do not identify the chemical origin of the counted material. They detect and classify particles based on optical response and apparent size.

This creates an important limitation: if dissolved oxidation products precipitate into suspended soft particles during cooling, they may be counted as particulate contamination at lower temperatures even though their origin is chemical degradation rather than external dirt ingress or mechanical wear.

This limitation is contrary to conventional approaches that when a lubricant system analysis shows elevated particle counts, the typical corrective action is to install finer mechanical filtration. In many cases, this approach is correct where hard contaminants are removed using appropriate mechanical filter elements. However, not all particle count increases originate from conventional solid contamination. In some lubricant systems, especially those affected by varnish, the particles counted by optical particle counters may be formed from oil degradation products that change phase depending on oil temperature.

An Unusual Observation: Particle Counts Increased When the Oil Cooled

At a power generation facility, the turbine was using an ISO 46 oil within a 12,000-litre reservoir. The lubricant had a moderate MPC varnish potential, but the end user was more concerned with high particle cleanliness readings. After an SVR® soluble varnish-removal system was moved to another turbine, particle cleanliness deteriorated even further in the following months.

A mechanical filtration cart using a 3-micron element with a high beta ratio was installed when particle counts began to rise. However, the filtration cart did not resolve the cleanliness issue. This raised a critical question: why would a fine filter fail to correct a particle count problem?

The answer emerged through oil assessment and lab-scale ion-exchange filtration.

Particle count results at different temperatures showed a major discrepancy between room-temperature and elevated-temperature measurements. Indeed, the ISO 4406 4-micron particle count was 7 x higher at room temperature than it was at 60 C. At the lower temperature, oxidation-derived varnish came out of solution and appeared as countable soft particles. At a higher testing temperature (that was more representative of operating conditions), this same material redissolved into the oil, and the particle count dropped.

In other words, the “particle contamination” was not stable insoluble matter. It was temperature-dependent varnish precipitation.

The Root Cause: Soluble Oxidation Products Becoming Insoluble Particles

Oil oxidation produces polar degradation products. As these products accumulate, they may remain dissolved in the oil under certain conditions, especially at higher operating temperatures. However, their solubility is limited. When the oil cools, its ability to hold these degradation products in solution decreases.

Once the concentration of oxidation products exceeds the oil’s solubility limit at the lower temperature, the material can separate from the oil phase. This separated material may appear as soft varnish, sludge, or suspended organic particles. It can also form harmful varnish deposits on equipment surfaces. These insolubles can then be detected during particle counts.

The process can be summarized as follows:

- At operating temperature, oxidation by-products remained dissolved or semi-dissolved in the oil. The oil showed lower particle counts because the varnish precursors were not present as discrete particles.
- During cooling, the solubility of the oxidation products decreased. Material that was previously dissolved became insoluble and formed soft suspended particles.
- During particle counting at lower temperature, the optical particle counter detected the precipitated soft varnish particles, resulting in elevated ISO 4406 or NAS cleanliness readings.
- When reheated to 60 C for particle counting, the soft varnish material redissolved, reducing the apparent particle count.

This explained the unusual observation that the particle count problem “went away” when the oil was heated back to operating temperature.

Implications for Oil Filtration & Conditioning

Mechanical filtration is designed to remove particles that are physically present and sufficiently solid to be captured by sieve-type filter media. It is highly effective for hard particles and many forms of insoluble contamination. However, it may be ineffective against temperature-sensitive soft varnish for several reasons. This is because varnish precursors are typically dissolved while the oil is warm. If the contaminant is in solution, it is not a particle and cannot be removed by a mechanical filter. Even when they are insoluble, soft varnish particles may be deformable or gelatinous. Unlike dirt or wear debris, soft varnish may pass through sieve-type filter media. Finally, particulate filtration does not change the

chemical equilibrium of the oil. Even if some precipitated varnish particles are captured, the dissolved oxidation products remain in the oil. When temperature changes again, this dissolved material can come out of solution, recreating the original particle count problem.

The failure to remove apparent particles in this system wasn't the result of poor practice or filtration media. It was simply a case of using the wrong tool for this specific task.

By contrast, ion exchange resin technology directly removes soluble and soft polar degradation products from lubricants. This is different from conventional mechanical filtration. Instead of only targeting particles that already exist, the resin media targets the dissolved oxidation material that can later become varnish or soft particulate. This explains why ICB® treatment can solve a particle count issue even though ion exchange resin is not traditionally thought of as a particle filter. It also explains why the particle counts on our case study system only increased once the SVR® skid using ICB filters was moved to a different unit. Clearly, ion-exchange resin removed the varnish material that was dissolved at elevated temperature but insoluble at room temperature.

Following bench-scale ion-exchange filtration, a large discrepancy between 20°C and 60°C ISO particle counts (6 ISO codes for the 4-micron reading) was reduced to two ISO codes (Table A). This critical result demonstrated that the oil no longer produced particles simply because it cooled. Indeed, the ion-exchange media changed the oil's chemistry so that it no longer caused the same level of varnish precipitation. This finding was corroborated by the filtered oil's MPC varnish potential and varnish precursor acid levels, which fell by 91% and 85%, respectively. By removing soluble varnish, the formation of insoluble varnish was eliminated.

Table A: Condition of the In-Service Turbine Oil Sample Provided by the Case Study Power Plant Prior to and Following Lab-Scale SVR® Treatment.

Sample	MPC ΔE	Patch Photo	AN (mg KOH/g)	ISO Particle Count @ 20°C	ISO Particle Count @ 60°C
Unit A	26.6		0.27	24/18/12	17/16/10
After "V"	2.4		0.04	18/16/9	16/14/9
Change	- 91%	N/A	- 85%	-6/-2/-3	-1/-2/-1

At first glance, it seems unusual that an ion exchange resin system would solve a high particle count issue. Particle contamination and dissolved contamination are often treated as separate categories. This case, however, showed that particle count instability was a symptom of unmanaged lubricant chemistry. The counted particles at room temperature were a visible expression of a dissolved contamination problem. Therefore, the correct treatment was not only to remove soft particles after they formed, but to remove the soluble precursors (varnish and other oxidation products) that led to their production.

This case study also demonstrated several important implications for turbine oil maintenance and condition monitoring:

1. ISO 4406 Cleanliness Codes Can Reflect Phase Behaviour.

ISO 4406 codes are valuable, but they do not identify contaminant chemistry. A high ISO code may reflect hard particles, soft particles, water-related artifacts, air bubbles, or precipitated degradation material depending on the sample condition and test method. In varnish-affected oil, the ISO code may change because the oil's varnish solubility equilibrium changes with temperature.

2. It may be useful to interpret particle counts with temperature context.

If particle counts vary significantly depending on sample temperature, the issue may not be conventional dirt or wear debris. A large difference (≥ 3 ISO codes) between room-temperature and elevated-temperature particle counts can indicate soft varnish precipitation. Particle count data should therefore be evaluated alongside sample temperature, operating temperature, MPC varnish potential, and other oil chemistry indicators.

3. Mechanical filtration failures may a may be diagnostic of chemistry problems.

When high-efficiency mechanical filtration fails to improve cleanliness, the conclusion should not automatically be that the filter was underrated or defective. Perhaps the contaminant of interest was not truly a stable solid particle under operating conditions. If high particle counts are caused by soft varnish formation, mechanical filtration may be treating a symptom while leaving the dissolved varnish disease untouched.

4. Varnish removal can reduce deposit formation and particle counts.

Varnish removal systems are often associated with reducing deposits on servo valves, bearings, reservoirs, and heat-exchangers. This case demonstrated an additional benefit: removing varnish precursors also stabilized and reduced particle counts.

Conclusion

This power generation case study demonstrated an important (and often overlooked) aspect of the primary lubricant failure mechanism: oxidation products can remain dissolved in warm turbine oil, then precipitate as soft particles when the oil cools. These particles can drive elevated ISO 4406 or NAS cleanliness readings, creating the appearance of a particulate contamination problem when the true issue is, in fact, an oil chemistry problem.

Indeed, the root cause of the high particle counts at this site was not conventional hard particles. It was unmanaged oil chemistry, which failed to address soluble varnish precursors. This explains why fine mechanical filtration failed to correct the issue. The contaminant was not present as a filterable particle under operating conditions. It was, instead, a soft, deformable, ephemeral contaminant. Worse still, the particles that were being produced were continuously regenerated from this dissolved material.

The varnish-removal skid that had been installed on the unit of interest and the bench-scale ion-exchange filtration of the oil sample addressed the true root cause of the fluid's high particle counts by removing the soluble oxidation products responsible for varnish formation. By removing these oil breakdown products, ion-exchange media prevents the formation of soft varnish particles during cooling. The result is more stable particle counts because the previous, temperature-driven increase in particle counts was eliminated.

In conclusion, high particle counts are not always indicative of simple mechanical filtration problems. In varnish-affected oils, particulate cleanliness can be governed by solubility, oxidation chemistry, and temperature-dependent phase changes. In these cases, ion exchange-based varnish-removal systems can solve apparent particle contamination issues by eliminating the dissolved contamination that created the particles in the first place. These soluble varnish-removal systems can also mitigate the risk of deposit-related failures in the most critical industrial applications.

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From Thermal Stress to Varnish: Laboratory Tools for Lubricant Deposit Assessment

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Abstract

Deposit formation is one of the main limiting factors for lubricant performance in automotive and industrial applications. Sludge, varnish, lacquer, and carbonaceous deposits negatively impact heat transfer, fluid circulation, component durability and overall equipment reliability. Deposit formation is mainly driven by thermal stress and oxidation processes and is strongly influenced by base oil chemistry, additive technology, and operating conditions. This paper reviews common deposit types and degradation mechanisms and presents selected laboratory bench tests used to assess deposit formation tendencies. Particular emphasis is placed on oxidation tests, the Micro Coking Test (MCT), and Panel Coker Tests (PCT GFC and PCT FTM), which provide complementary information for formulation screening and performance ranking under severe operating conditions

1. Introduction

Sustainability, carbon footprint reduction, and circular economy objectives are major drivers for lubricant development today. High performance lubricants contribute directly to equipment efficiency, durability and energy savings during their use phase. However, deposit formation remains a major root cause of wear, failures and productivity losses across industrial and automotive sectors. In hydraulic systems, varnish may lead to valve sticking and control instability; in engines, sludge and lacquer impair oil circulation and promote ring sticking; and in high temperature components such as turbochargers, coke formation may cause oil starvation and rapid failure. Beyond technical impacts, deposits increase maintenance costs, shorten oil drain intervals and reduce equipment lifetime. As modern lubricants increasingly rely on Group II, Group III and synthetic base oils with lower solvency, reliable laboratory tools are essential to evaluate deposit risks and support formulation optimization.

2. Deposits: type, appearance and location

Lubricant deposits differ by appearance, chemical nature and formation mechanism. **Sludge** is a soft, dark, high viscous material formed mainly by oxidation, water contamination and insufficient dispersancy, typically found in engine sumps, gearboxes and hydraulic systems with high water content. **Varnish** appears as a thin, hard, adherent film composed of oxidized insoluble, soluble at high temperature but precipitating at lower temperature, frequently affecting hydraulic valves, turbines and compressors. **Lacquer** is a harder, glossy and more thermally baked deposit formed under severe thermal stress, commonly observed on piston skirts and valve spools. **Coke** consists of hard, black, carbon rich residues generated by thermal cracking at very high temperatures, typically found in local hot spots turbochargers, piston under crown areas and hydraulic system under micro-dieseling effect.



3. Degradations leading to deposits

Deposit formation results from combined chemical and physical degradation mechanisms. Oxidation leads to organic acid generation, sludge formation and varnish precursor accumulation, accelerated by high temperature, catalytic metals and antioxidant depletion. Thermal degradation causes base oil cracking and polymerization, producing lacquer and coke. Additional contributors include micro-dieseling, electrostatic discharge, additive depletion, contamination, base oil solvency limitations and operating conditions involving repeated hot and cold cycles.

4. Assessment of deposits formation by laboratory tests.

Laboratory bench tests provide controlled, reproducible, and cost-effective tools to assess lubricant degradation and deposit formation tendencies under accelerated conditions. A wide variety of test methods has been developed over the years to address different degradation mechanisms, operating environments, and lubricant applications. Rather than relying on a single parameter, combining complementary tests allows a more realistic evaluation of deposit-related risks.

This paper focuses on a selection of commonly used oxidation and thermal deposit formation tests, representative of different stress modes.

4.1. Oxidation TOST (Sludge, Dry)

Oxidation tests such as the Turbine Oil Stability Test (TOST) and its variants are widely used to assess a lubricant's resistance to thermos-oxidative degradation. These methods typically expose the oil to elevated temperature, oxygen flow, water (or dry conditions), and metal catalysts such as copper and iron.

Classical TOST mainly evaluates oxidation lifetime based on acid number increase, while modified versions such as Sludge TOST and Dry TOST extend the assessment to sludge and insoluble formation. These tests provide valuable information on antioxidant reserve, sludge generation tendency, and interactions between oxidation products, water, and metal catalysts, all of which are closely related to varnish and deposit formation in service.



4.2. Micro-Coking Test (MCT)

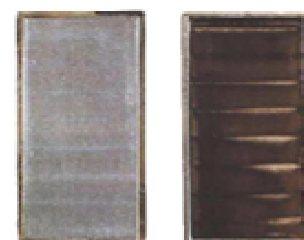
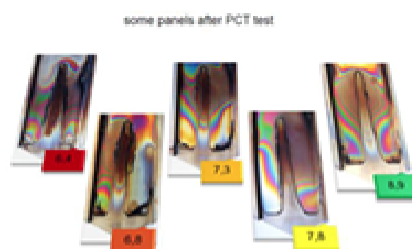
The Micro-Coking Test (MCT) complements oxidation testing by specifically targeting high-temperature deposit and insoluble formation under confined conditions. In this test, lubricant samples are subjected to severe thermal stress in contact with catalytic materials, promoting the formation of carbonaceous residues and insoluble by-products.

The MCT enables rapid discrimination between formulations based on their tendency to generate thermal residues, copper corrosion products, and solid deposits. As such, it is well suited for early-stage formulation screening and for evaluating lubricant robustness under localized high-temperature conditions not fully addressed by classical oxidation tests.

4.3. Panel Coker Test (PCT)

Panel Coker Tests are designed to simulate lubricant exposure to hot metal surfaces, representative of critical engine and turbine components. In PCT methods, oil flows over or contacts heated metal panels under controlled oxidation conditions, promoting the formation of surface-bound deposits.

Both PCT-GFC and PCT-FTM allow visual inspection and gravimetric quantification of deposits formed on the panels, providing direct information on varnish, lacquer, and high-temperature deposit tendencies. When combined with oxidation, Panel Coker Tests offer an effective means of ranking lubricant formulations and improving the prediction of deposit-related performance issues observed in the field.



5. Conclusions

Evaluating deposit formation through dedicated laboratory tests is essential to ensure lubricant cleanliness, durability and long-term performance. Bench tests such as oxidation tests, MCT and Panel Coker provide complementary information on thermal stability, oxidation resistance and deposit tendencies. Their combined application supports formulation optimization, improves performance ranking and contributes to reliable equipment operation throughout the lubricant service life.

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Lubricant Varnish: What We've Learned and What We Still Don't Know

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Abstract

Twenty years ago, the industry had no consistent way to measure a turbine oil's tendency to form varnish, deposit-control chemistry was poorly understood, and mitigation options were limited and largely unproven. We also did not fully appreciate the many pathways that lead to varnish, or why deposits build rapidly in some parts of a system while leaving others clean. A lot has changed since. Better test methods, more robust formulations, and field-proven removal technologies have significantly improved how we prevent, detect, and manage varnish in critical equipment. Important unknowns remain. This presentation summarizes the advances that have shaped today's best practices, challenges misconceptions that still drive the wrong maintenance decisions, and highlights the key open questions that must be addressed to move closer to truly deposit-free operation in rotating equipment.

1. Introduction

The lubrication community has spent the last quarter-century building the vocabulary, the test methods, and the chemistry needed to talk about varnish. None of that existed twenty-five years ago. A reliability engineer looking at a sticking servo-valve or a tripped turbine had no quantitative way to confirm what they were seeing, no agreed nomenclature for the deposit, and no commercial product capable of removing it from the fluid. Today the industry discusses MPC values the way it once discussed acid number. It is worth pausing to see how far the field has travelled before pointing out how far it still has to go.

2. What we have learned (2000–2026)

The first big shift was measurement. The Membrane Patch Colorimetry method began life as an ASTM draft in 2006 and was published as ASTM D7843 in 2012 [1]. For the first time, operators could put a number on something that until then had been described in general adjectives. RULER, RPVOT, FTIR, and UC filled in around it, and root-cause work became something more rigorous than simply guessing.

The second shift was the turbine oils themselves. Twenty-five years ago a typical turbine oil had a short useful life and developed deposits quickly. Today the commercially available products are roughly an order of magnitude better in both oxidative life and deposit control. Two stress tests drove that change. MHI's Dry TOST, later codified as ASTM D7873, gave formulators a reproducible way to see deposit tendency under accelerated thermal-oxidative stress and reshaped how additive systems were balanced. The Turbine Oil Performance Prediction (TOPP) test built on the same accelerated conditions but added the standard condition-monitoring suite, RPVOT, RULER, MPC, and FTIR, so that oxidative life and varnish propensity could be benchmarked side by side [2]. The feedback loop between formulators and these two tests produced a step change. Modern Group II and III turbine oils now routinely outperform their predecessors by a significant margin in accelerated bench data, and the field record largely confirms it.

The third shift was treatment. Through the 2000s the industry tried to filter its way out of the problem. Electrostatic units, balanced-charge agglomeration, and depth filters moved insolubles around but did almost nothing to the dissolved degradation products that drive varnish formation. Ion-exchange resins targeting soluble oxidation by-products became commercially available in 2009 and finally addressed the right molecular fraction. Solubility enhancers entered the market in 2012, and the chemistry took a decisive step in 2018 with the next iteration, a long-term solution that re-dissolves varnish already deposited on metal surfaces while preventing new deposition.

The fourth shift was conceptual. Oxidation is no longer treated as a single failure mode. We now recognise micro-dieseling caused by adiabatic compression of entrained air, electrostatic spark discharge in low-conductivity fluids, thermolysis at hot-spot surfaces, additive-contaminant interactions, and most recently shear-stress deposits formed where high load, high speed, and a thin film converge. Each pathway leaves a different chemical fingerprint and responds to a different mitigation strategy. Treating them all as oxidation, as the field did for years, explains why so many early interventions failed.

The newest piece of the puzzle is the bearing itself. Two recent papers by Jang, Khonsari, Soto and Livingstone [3, 4] provide the most detailed modelling of varnish on journal-bearing performance to date.

The findings are sobering. The papers modeling shows that a varnish layer just twenty percent of the bearing clearance roughly halves minimum oil-film thickness, raises peak hydrodynamic pressure five to eightfold, and lifts bearing surface temperature by twenty-eight degrees Celsius, with another twenty-five added under mild misalignment. Varnish acts as a thermal insulator, dropping local conductivity by two to four orders of magnitude, so the heat the bearing generates can no longer escape into the housing. The threshold of dynamic instability drops by fifteen to thirty percent, meaning a machine designed to run safely at 3,000 rpm may now whirl at 2,600. Each effect feeds the next: reduced film raises temperature, higher temperature accelerates degradation, more degradation produces more varnish, and the loop closes. Field data confirms the modelling. The sawtooth temperature trace reliability engineers now associate with shear-stress deposits is the macroscopic signature of this cycle, and by the time it appears on a trend chart the bearing has been operating in degraded territory for months.

3. What we still don't know

The gaps are larger than the recent advances suggest. Four stand out. First, the unit-to-unit variability problem. Three identical centrifugal compressor trains, same OEM, same fluid, same duty cycle, in the same petrochemical plant. Two operate cleanly for years. The third varnishes constantly. We do not have a satisfying explanation. Subtle differences in flushing practices, start-up frequency, load profile, micro-gas ingestion, or local hot-spot geometry are all plausible, but no one has produced a predictive framework that correlates with real fleet data.

Second, predicting where shear-stress deposits will form. We can describe the conditions in retrospect, high speed, high load, thin film, in Group II through IV base stocks. We cannot yet take a new compressor design and forecast which bearing locations will deposit. Reynolds-equation modelling is a step forward, but still assumes a uniform varnish layer rather than the patchy, asymmetric reality found in pulled bearings.

Third, monitoring. MPC does not see shear-stress deposits because the relevant degradation products are consumed at the metal surface, not transported back into the bulk fluid. Standard oil analysis returns clean numbers on a machine actively varnishing its bearings. The industry needs new monitoring chemistry, new sensor modalities, or both. Real-time infrared, dielectric, optical, and acoustic sensors are emerging, but none has yet shown the sensitivity and specificity to replace bench testing for this failure mode. Defining what a meaningful real-time varnish signal even looks like is itself an open question.

Fourth, the hydraulic gap. Almost everything above has been worked out on rotating equipment, primarily large gas and steam turbines and centrifugal compressors. Hydraulic systems experience the same chemistry under harsher conditions, with smaller fluid volumes, more aggressive thermal cycling, and tighter servo-valve clearances. Yet hydraulic users still treat varnish as an oddity rather than a primary failure mode. Mobile equipment, injection moulding, and metal forming all show classic varnish symptoms in the field, and the monitoring infrastructure to address them barely exists. Closing this gap is probably the single biggest commercial and reliability opportunity in the next decade of varnish research.

4. Conclusions

Twenty-five years of work have turned varnish from craft knowledge into a measurable, treatable, increasingly well-understood phenomenon. We have credible test methods, dramatically better turbine oils, multiple effective treatment chemistries, and a far richer model of how degradation proceeds. The frontier has moved from "what is varnish" to "why this machine and not that one," from "how do we remove it" to "how do we see it forming in real time," and outward into hydraulic systems quietly suffering the same fate. The next quarter-century will be judged on whether the industry closes those gaps with the same rigour it brought to the first.

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Copper oleate–EP synergy in low-viscosity lubricants: antiwear comparison with commercial oils

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Abstract: The reduction of lubricant viscosity is a current strategy to improve the energy efficiency of industrial gear transmissions. However, this approach may promote boundary lubrication conditions, increasing friction and wear unless effective additive systems are employed. In this work, the tribological performance of a low-viscosity lubricant formulated with copper oleate and sulfur- and phosphorus-based EP additives is evaluated and compared with commercial fully-formulated gear oils of higher viscosity. The results show that the proposed formulation provides competitive friction behavior and enhanced anti-wear performance, highlighting the beneficial synergistic interaction between copper oleate and EP additives.

1. Introduction

The continuous demand for increased energy efficiency in mechanical systems has driven the development of low-viscosity lubricants for industrial gear applications. Lower viscosity oils reduce hydrodynamic losses, contributing to improved transmission efficiency. However, the reduction of lubricant viscosity generates thinner lubricant films, leading to boundary or mixed lubrication regimes, where direct asperity contact can result in elevated friction and accelerated wear.

Extreme pressure (EP), friction modifier and anti-wear (AW) additives are included in the gear oil formulation to increase the lifespan of the components and improve the efficiency of the transmission. For this reason, it is important to analyze the interaction between these additives. Previous studies have reported a synergistic wear-protection effect between copper oleate and sulfur- and phosphorus-containing EP additives, attributed to the formation of tribofilms composed of iron phosphates and copper oxides [1].

As a continuation of previous work, the present study is focused on assessing the anti-wear and friction performance of this synergy in comparison with conventional higher-viscosity commercial gear lubricants.

2. Materials and Methods

The lubricant under study consisted of a mixture of PAO8 and di-ester as base oil, formulated with copper oleate and sulfur- and phosphorus-based EP additives (hereafter referred to as BO+CO+SP). Its tribological performance was benchmarked against three fully formulated commercial gear lubricants: a mineral ISO VG 150 oil (MIN150), a mineral ISO VG 320 oil (MIN320), and a synthetic ISO VG 320 polyalphaolefin-based oil (PAO320).

Tribological tests were carried out using a ball-on-disc configuration in an SRVIII tribometer under reciprocating sliding conditions, following the ASTM D6425 standard, which is commonly applied to the evaluation of lubricants containing EP additives. During these tests, the coefficient of friction was continuously monitored. Once the test was completed, wear volume was measured by confocal microscopy and Sliding Wear Rate (SWR) was calculated for each lubricant. Additionally, the worn disc surfaces were examined by scanning electron microscopy (SEM) coupled with energy-dispersive X-ray spectroscopy (EDX) to characterize the morphology and chemical composition of the tribofilms formed during sliding.

3. Results and discussion

Despite its significantly lower viscosity and reduced lubricant film thickness, the BO+CO+SP formulation exhibited friction coefficients comparable to those measured for the higher-viscosity

commercial gear oils. This result indicates an effective friction-reducing capability of the additive package.

According to Fig. 1, SWR results revealed that the anti-wear performance of the BO+CO+SP lubricant was superior to that of the commercial MIN150 and PAO320, and only slightly inferior to that of the MIN320 formulation. These results highlight the potential of the copper oleate–sulfur–phosphorus synergy to provide effective surface protection even under thin-film lubrication conditions.

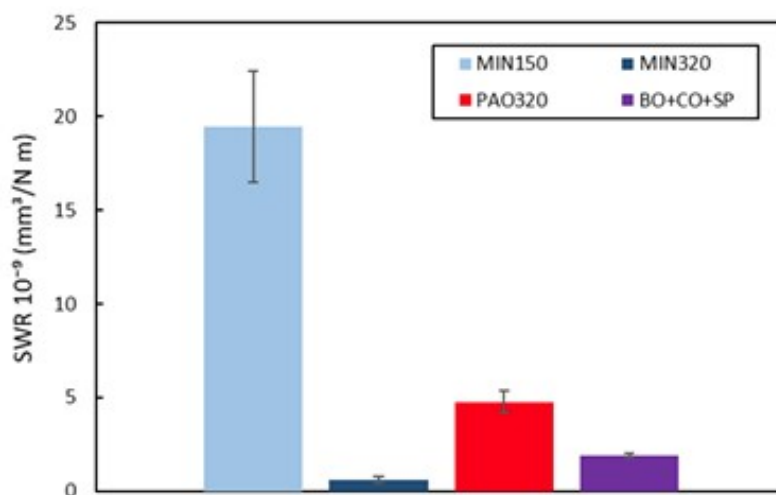


Fig. 1: Sliding Wear Rate of the different lubricants tested under reciprocal sliding ball-on-disc tests.

SEM/EDX analyses confirmed the formation of sulfur- and/or phosphorus-containing tribofilms on the surfaces lubricated with the commercial gear oils, consistent with the action of conventional EP/AW additives. In contrast, the tribofilm generated by the BO+CO+SP formulation also exhibited a clear presence of copper, evidencing the participation of copper oleate in tribochemical reactions at the sliding interface. The presence of Cu, S, and P in the tribofilm supports the hypothesis of a synergistic mechanism responsible for the observed wear reduction.

4. Conclusions

The tribological evaluation of a low-viscosity lubricant formulated with copper oleate and sulfur- and phosphorus-based EP additives demonstrated that:

- Comparable friction performance to higher-viscosity commercial gear oils can be achieved despite reduced oil film thickness.
- The anti-wear performance of the low-viscosity formulation is competitive, being surpassed only by a high-viscosity mineral ISO VG 320 oil.
- SEM/EDX analysis confirmed the formation of a copper-containing tribofilm, highlighting the active role of copper oleate and its synergistic interaction with EP additives.

These findings indicate that the proposed additive strategy is a promising route for the development of energy-efficient low-viscosity gear lubricants without compromising wear protection.

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LUBR 7 ID 80 Intelligent forecasting of oil changes with onsite oil analysis leads to maintenance cost savings

Solubility Enhancers are Becoming a Valuable Tool for Lube Oil Companies to Increase their Customers' Production Efficiency

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Abstract

Lube oil companies have traditionally competed on formulation quality, brand, and price. The technical conversation with the customer has been dominated by specifications, OEM approvals, and analytical limits. A shift is now underway. Industrial customers are measuring lubricant suppliers against the production losses they prevent, not the litres they deliver. Solubility enhancers, used in service to dissolve and re-suspend the polar degradation products that drive varnish, valve sticking, bearing instability, and unplanned outages, give lubricant companies a credible technical lever to attach to their fluid sales. This paper describes the chemistry, summarizes the field evidence, and frames why solubility enhancement belongs in the modern lubricant companies commercial offering rather than as a third-party aftermarket fix.

1. Introduction

The metric that matters to an industrial customer is rarely litres of oil purchased. It is overall equipment effectiveness, planned-versus-unplanned downtime, and the cost of a single forced outage. A 5,000-gallon turbine charge sits underneath equipment whose lost-generation cost can run from a quarter of a million to over a million dollars per day [1]. The economics of the customer relationship are therefore dominated by what the lubricant prevents, not what it costs. Lube oil companies that recognise this are repositioning around outcomes. Solubility enhancers are one of the cleanest examples of how a fluid supplier can move that conversation forward, because they tie a specific chemistry to a particular class of avoided failure that the customer can measure on their own equipment.

2. Varnish as a production-efficiency problem

Varnish is no longer an exotic failure mode confined to large-frame gas turbines. It appears in steam turbines, centrifugal and reciprocating compressors, hydraulic systems on injection-moulding machines, wind-turbine pitch and yaw drives, paper-machine circulating systems, and the gearboxes of mining and metal forming equipment. The mechanism is consistent. Polar degradation products generated by oxidation, micro-dieseling, electrostatic spark discharge, thermolysis, or shear stress accumulate in the fluid faster than the base stock can hold them in solution. They drop out onto the coolest, slowest, or most static surfaces in the system, which are usually the servo valves, control surfaces, and bearing zones the customer cares most about. Recent journal-bearing modelling shows that even modest varnish deposits halve the minimum oil film thickness, raise peak bearing pressure five to eight-fold, and lower the safe operating speed by 15 to 30 percent [2].

From the customer's production perspective, the consequences are unscheduled trips, sticking valves, slow start sequences, lost capacity, and emergency oil flushes that take equipment out of service for days. Conventional oil analysis is partially blind to the problem. MPC, RULER, and RPVOT capture parts of the picture but miss shear-induced deposits formed at the metal surface itself. The customer often cannot see the failure in the lab even while their bearings are quietly degrading [3].

3. The chemistry, in plain terms

A solubility enhancer is a fluid-soluble molecule whose Hansen Solubility Parameter coordinates expand the effective solubility envelope of the base stock without altering its bulk properties [4]. Polar degradation products that would otherwise precipitate are held in homogeneous. Existing varnish on metal surfaces is gradually re-dissolved into the bulk fluid. The chemistry of a solubility enhancer has three properties that make it commercially attractive to a lubricant company. It is added as a small percentage of the existing fluid charge while the equipment is running, requiring no flush, no shutdown, and no capital investment by the customer. It is non-surface-active, which means demulsibility, air release, and antiwear performance are preserved. And it is stable under sustained thermal and oxidative stress, validated by extended Turbine Oil Performance Prediction (TOPP) testing on commercial fluids [5].

The technical literature now supports the chemistry across a wide range of applications. Published case studies cover gas turbines, hydraulic systems on plastic injection-moulding machines, centrifugal compressors, steam turbines [3, 5] and mining equipment. The same fluid-soluble approach has also been shown to restore demulsibility in roughly half of in-service Group II turbine oils that previously failed water separation, by re-solubilizing the polar contaminants responsible for the failure [6].

4. Why this belongs inside a lubricant company's offering

Three commercial dynamics are pushing solubility enhancement from an aftermarket service into the core lubricant offering. The first is customer expectations. Industrial buyers increasingly evaluate fluid suppliers on a total-cost-of-ownership basis that includes downtime, oil changes avoided, and waste fluid avoided. A supplier who can demonstrate, with the customer's own data, that an enhanced fluid programme has prevented a varnish-driven trip or extended an oil drain interval has a structurally stronger position at contract renewal than one selling on price alone.

The second is the sustainability ledger. Avoiding a single varnish flush on a 5,000-gallon turbine avoids approximately 18 metric tonnes of CO₂e when the new oil, the disposed oil, and the associated logistics are counted. API's lifecycle guidance now formally allows avoided-emissions claims for longer drain intervals and improved in-use efficiency [7]. Lubricant companies under pressure to decarbonize their product portfolios can credit those avoided events against their footprint, and the customer can do the same.

The third is technical differentiation. Base oil quality has converged across the industry. Most additive packages are built from the same component pool. Genuine product-level differentiation is increasingly hard to defend on a data sheet alone. A solubility-enhanced fluid programme, backed by field data and lifecycle accounting, gives the lube company something specific to point to that competitors cannot match by simply matching a specification. The shift parallels what has happened in other mature industrial markets, where the supplier who solves the production problem wins, not the supplier with the cheapest input.

5. Conclusions

Solubility enhancement is a quiet but durable move for any lube oil company with industrial customers. The chemistry is mature, the field evidence is broad, and the commercial logic is straightforward. Customers are paying for production uptime, not for fluid. A supplier who brings a solubility-enhanced offering, with the field data to support it, is helping the customer protect the metric they actually care about. The opportunity is not to repackage solubility enhancers as a niche aftermarket product, but to integrate them into the technical and commercial conversation a lubricant company has with its largest accounts. The companies that move first will set the standard the rest of the market eventually has to meet.

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Modification of stability behavior of friction-stressed lubricating greases

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Abstract

This study investigates the possibility of the occurrence of unstable states under frictional loading of lubricating greases

1. Introduction

In a grease-lubricated tribological contact, not only the surface regions of the interacting bodies but also the applied lubricating grease itself is subjected to friction and its effects. Lubricating greases are colloidal-dispersed systems and, in addition to a base oil, contain a solid component (referred to as a thickener). This solid, often a metal soap, forms the structural framework of the grease.

Experimental investigations using a rheometer simulate the frictional conditions within the grease film. When a friction process begins, the grease is supplied with energy, which, under continuous friction, leads to time-dependent process behavior. The process exhibits unstable behavior. An existing energy gradient acts as the driving force for a possible reorganization of energy dissipation.

A steady state acts as an attractor, and different mechanisms may be initiated to reach this state. One possible outcome is the formation of dissipative structures. A prerequisite for this is the occurrence of an instability. This is the subject of the results presented here.

2. Instability in investigated processes

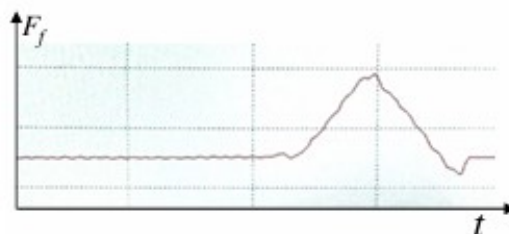


Fig.1 Disturbance near the equilibrium (stationary state)

For a proper understanding, the following concepts are essential [1]:

- Friction is the input of mechanical energy into a tribological system.
- Wear is the dissipation of frictional energy accompanied by the simultaneous production of entropy

A friction process in the grease film, which is in a steady state, will be investigated. Due to altered process conditions, a *new* friction process is initiated, and the steady state is continuously disturbed (see Fig.2)

The starting point is a process of continuous energy input (friction process). Two consequences of the process will be observed:

1. The energy input leads to the initiation of an energy dissipation process (e.g., material6 removal, structural changes in the grease, etc.)
2. The energy input leads to the production of entropy

Now, in the steady-state process condition, the process is disturbed. This leads to:

1. Disturbance of the initiated energy dissipation process
2. Disturbance of the entropy production

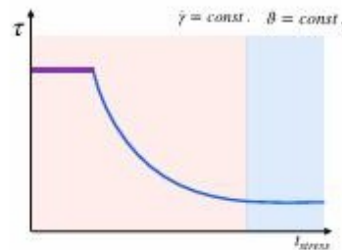


Fig.2 Continuous disturbance of the stationary state in the rheometer experiment (illustration)

The reorganization of energy-dissipating mechanisms leads to a change in the structure of the tribologically stressed lubricating grease (Fig. 3).

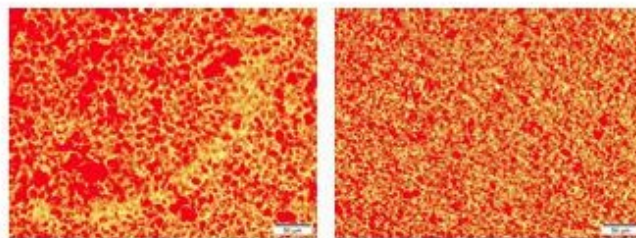


Fig. 3. Low and high stressed samples

The stability behavior, the possibility of the occurrence of unstable states, and the interaction between the dissipation mechanism and the associated stability criterion are investigated in this paper.

$$\frac{1}{2} \frac{\partial}{\partial t} (\delta^2 S) = \sum_i (\delta X_i \cdot \delta J_i) \quad [1]$$

By applying the stability criterion in Equation 1 [2], [3], the behavior of selected parameters can be observed, and the possibility of unstable states can be assessed.

5. Conclusions

The study shows that instabilities can occur in tribologically stressed lubricating greases. This enables the formation of new structures. In interaction with the dissipation mechanism, it becomes evident that the stability criterion changes. In addition, this study attempts to generalize the findings to tribological processes.

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LUBR10 ID 83 Progress and Evolution of Coolant Usages in Industry Applications

Overview of the Latest Developments Affecting the Grease Industry

Abstract

This paper discusses factors affecting the grease industry, it will examine sustainability in the grease industry, which provides the most challenging scenario of all lubricants. Their life cycle analysis and carbon footprint requires significant data processing and consideration, sourcing of raw materials, manufacturing procedures, user applications and end of life factors all give the grease manufacturer a complex set of issues to overcome, not only in Europe but world-wide and how this could affect Asia.

It will showcase the ELGISTC (the European Lubricating Grease Institute Sustainability Technical Consortium). Consisting of grease producers, raw material suppliers, equipment manufacturers, test houses, institutions and end users. Membership of the consortium spans the USA, Europe and Asia.

The presentation will examine the removal of hazardous materials, such as PEFAS and the latest developments in the toxicity of lithium salts.

Introduction

The lubricating grease industry is facing significant challenges amid growing environmental, regulatory, and technological changes. Key issues shaping the industry's future include concerns over per- and polyfluoroalkyl substances (PFAS), evolving regulations on lithium hydroxide—a vital component in grease production—and increasing demands for sustainability.

In addition, the conflict in the Middle East is causing supply chain issues and cost pressures on raw materials. MOSH and MOAH is also an issue for food grade greases.

This paper, however, will focus on the PFAS, lithium and sustainability issues.

Sustainability Challenges and Opportunities

Sustainability is becoming a central focus for the lubricating grease industry, driven by consumer demand, regulatory pressure, and corporate responsibility goals. Several challenges need addressing:

Raw Material Sourcing: Grease manufacturers are encouraged to reduce reliance on non-renewable petroleum-based oils and controversial additives

Biodegradability: There is a growing push for greases that break down more easily without harming the environment, especially in applications prone to leakage or disposal in the wild.

Circular Economy: Initiatives to recycle grease and container materials are gaining attention to minimise waste. But we may have to accept grease may not be a circular economy.

To meet these challenges, the industry is innovating with bio-based base oils, environmentally friendly additives, and advanced recycling technologies. Collaborations with suppliers and regulators are essential to developing sustainable yet effective lubricating greases.

The ELGI sustainability consortium ELGISTC addresses these issues through 5 Task Forces: Communication, Product Life Cycle, End User, Product Carbon Foot Print and End Of life. The ELGISTC take a unified industry approach, with consortium members representing: Grease manufacturers, Raw material suppliers, End users, Test equipment suppliers, Other technical & trade institutions, Lubricant equipment suppliers and lubricant distributors.

Members of the consortium are represented from Europe, USA and the Far East, these members meet face to face twice a year but have regular virtual meetings to discuss their work load and objectives.

PFAS Concerns

PFAS are a group of synthetic chemicals widely used for their resistance to heat, water, and chemicals. In the lubricating grease industry, PFAS-containing additives have been used to enhance performance, especially under extreme conditions. However, PFAS are now under intense scrutiny due to their persistence in the environment, potential to bioaccumulate, and harmful health effects.

Regulators worldwide are proposing stringent restrictions or outright bans on PFAS. This presents a challenge for grease manufacturers to reformulate products without compromising lubricating performance. The industry is investing in research to identify safer alternatives while ensuring that critical functional properties like thermal stability and corrosion protection are maintained.

There are thousands of PFAS materials used in the world today some are extremely toxic others less so but they are very stable compounds and known as the “forever chemical” which have a huge environmental impact. In greases the main PFAS compounds are PTFE and perfluoro polyether fluids and many of these are being withdrawn from formulations, but there is no “silver bullet” no one compound can replace these chemicals particularly in terms of chemical resistance, oxygen compatibility and being able to withstand ultra-high vacuum applications.

It is possible that some applications for PFAS lubricants could be made but at the time of writing no such exemptions have been made and the danger is that if such exemptions are made the quantities required by end users maybe small and commercially unviable and so may disappear from the market place anyway.

Proposed Lithium Hydroxide Regulations

Lithium hydroxide is a key thickener in many lubricating greases. Lithium greases have been available since the 1940's. Their favourable properties include excellent high-temperature stability and mechanical performance. However, lithium extraction and processing have raised environmental and geopolitical concerns. Additionally, regulatory bodies are increasingly focusing on the sustainability and ethical sourcing of raw materials, potentially tightening controls on lithium hydroxide production and use.

However, lithium and in particular lithium hydroxide, a key ingredient of lithium greases is likely to be regulated in the EU as a Repo Toxin class 1 A and 1B, a substance that adversely affects **human fertility** and can cause **developmental harm** to offspring

In the European Union, hazardous chemicals are classified and labelled under the CLP Regulation (EC No 1272/2008). This classifies substances as:

Reproductive Toxicity Category 1A when they are known to cause damage to reproductive health or development in humans based on human evidence or strong inference from data.

Reproductive Toxicity Category 1B when there is a presumed human hazard.

Reproductive Toxicity Category 2 when there is a suspected human hazard based on limited evidence. In 2019 ANSES (France) made a proposal: Lithium carbonate, hydroxide and chloride were suggested Reproductive Toxicity Category. In the light of these developments the European Commission formally asked RAC (Risk Assessment Committee) to re-evaluate their proposed classification.

RAC responded by reaffirming its earlier harmonised classification of lithium carbonate and the other lithium salts as Reprotoxic Category 1A. In February 2026 the European Commission accepted the ECHA proposal.

There has been reaction and disagreement from Scientific & Industry communities, globally the EU is an outlier. Independent expert toxicologists and epidemiologists and the governments of USA, Argentina, Chile, Australia and the UK do not agree with the EU. In fact, Australia state: “An appropriate hazard classification for the three named lithium salts is, at worst Category 2 “

The classification could restrict or complicate the supply of raw materials used in grease thickener manufacture. It is possible/likely that consumer uses of lithium grease will be regulated and restricted. Manufacturers are looking at alternative thickener systems, calcium , aluminium based and poly urea thickeners have been around for many years and offer similar performance characteristics as lithium-based greases but, have generally been more expensive and more complicated to manufacture. However, we are now seeing a decline in lithium-based greases in favour of these alternative soaps

High levels of free Lithium Hydroxide above the thresholds (0.1 wt%) USA and India and 0.3 wt% EU-27) in grease will trigger labelling on finished greases. Currently no approved standardised test method is available. Some companies might need to reformulate products with alternative thickeners.

Conclusion

The lubricating grease industry is at a crossroads, influenced by mounting pressures related to PFAS restrictions, proposed lithium hydroxide regulations, and the drive toward sustainability.

Navigating these issues requires innovation, alternative material development, and strategic partnerships to ensure that future products meet evolving environmental and regulatory expectations while delivering reliable performance.

LUBR12 ID 13 Balancing sustainability with reliability for hydraulic oils in wind turbines

KN2 Tim Hosenfeldt SCHAEFFLER

Holistic Tribology for Sustainable and Efficient Motion.

Assessment of the tribological performance of materials under high pressure hydrogen gas

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Abstract

The present study investigates the tribological performance of diamond-like carbon (DLC) coatings under gaseous hydrogen environments. The results show that these DLC coatings significantly reduce friction and wear compared to steel-steel contacts, with the DLC/DLC configuration even achieving supralow friction. Applying such DLC to only one surface already provides substantial performance improvements, while coating both contacting bodies further minimizes wear. In DLC/steel contacts, the roughness of the steel counterpart plays a critical role in friction and wear behavior. Polished steel surfaces reduce wear on the DLC-coated ball but lead to higher friction. Overall, the DLC coatings tested demonstrate strong potential for improving the durability and reliability of components operating in high-pressure hydrogen applications, particularly in energy and mobility systems.

1. Introduction

The development of hydrogen-based technologies is constrained by major challenges related to materials performance. In addition to achieving economically viable green hydrogen production, materials must ensure long-term durability and reliability of components and systems running in hydrogen, for it to be considered as an effective clean energy carrier. These challenges are especially critical in hydrogen compression and distribution systems, where components operate under pressures above 700 bar and are subjected to severe friction and wear conditions [1]. Addressing these constraints requires ongoing research into advanced materials and surface treatments that can withstand these severe hydrogen environments.

Hydrogen systems involve four principal types of tribological contacts [2], each associated with distinct degradation mechanisms. Lubricated metal-metal contacts depend on additives whose efficiency can be compromised by hydrogen, while dry metal-metal contacts require protective coatings or hydrogen-resistant alloys. Polymer-metal contacts are limited by hydrogen-induced polymer degradation, and ceramic-based contacts benefit from superior resistance to hydrogen embrittlement.

Among potential solutions, diamond-like carbon (DLC) coatings show strong potential due to their low friction and high wear resistance in hydrogen atmospheres [3,4]. This study therefore aims to enhance the tribological performance of DLC coatings under high-pressure hydrogen by assessing coating configurations and the influence of steel surface roughness on friction and wear behaviour.

2. Materials and methods

Materials and coatings were assessed using a ball-on-flat configuration on a high-pressure hydrogen tribometer (TE60, Phoenix Tribology). Tests were performed under reciprocating sliding at a maximum Hertzian contact pressure of 975 MPa in gaseous hydrogen at 100 bar and room temperature. The stroke amplitude was set to 10 mm with a reciprocating frequency of 1.75 Hz. The total sliding distance was 100 m. Hydrogenated amorphous carbon (a-C:H) DLC coatings were deposited by PECVD onto both balls and flats. DLC-coated balls were tested against DLC-coated steel flats as well as against uncoated steel flats. The results were compared with those obtained for uncoated steel-steel contacts.

To evaluate the influence of the steel counterpart topography on the tribological behaviour of the DLC-coated balls, three surface finishes of the steel flats were examined:

- a polished surface with $R_a = 0.03 \mu\text{m}$,
- ground surfaces with $R_a = 0.4 \mu\text{m}$ and grinding lines oriented parallel to the sliding direction,
- ground surfaces with $R_a = 0.4 \mu\text{m}$ and grinding lines oriented perpendicular to the sliding direction.

3. Results and discussion

3.1. Influence of DLC coating of one body or both contacting bodies

The results presented in Fig. 1 show that DLC coating on the ball enabled to strongly reduce friction and wear both on the ball and on the flat compared with steel-on-steel contact configuration. The DLC/DLC contact showed the best results with a friction coefficient below 0.01 (= supralow friction) and very low

wear. Supralow friction of DLC/DLC contacts in low-pressure hydrogen environment is already reported in previous studies. According to Obuko et al. [3], it is due to a hydrogen-rich tribofilm formed on the surfaces.

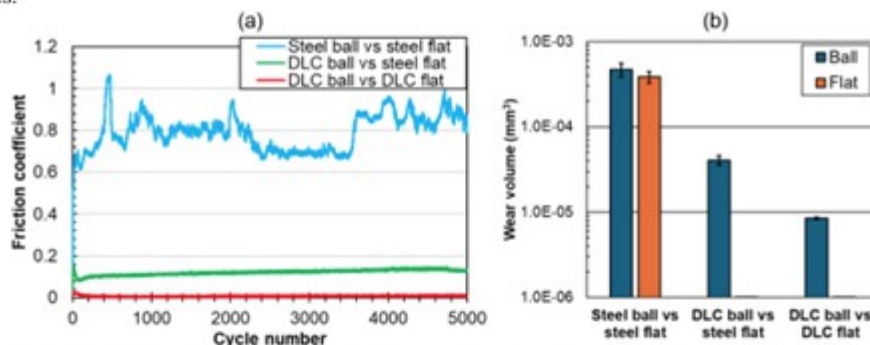


Figure 1: (a) Evolution of the friction coefficient as a function of cycle number, (b) wear volume on the ball and the flat for the steel/steel, DLC/steel and DLC/DLC contacts

3.2. Influence of the roughness of the steel counterpart in DLC/steel contacts

Polishing the steel flat enabled to minimize wear on the DLC-coated ball but it resulted in maximum friction coefficient among the three surface conditions for the steel flat (see Fig. 2). A tribofilm is observed on the steel surfaces. The coverage of the tribofilm was higher on the polished steel surface than on the ground steel surfaces and may explain the difference in friction behaviour between polished steel and ground steel.

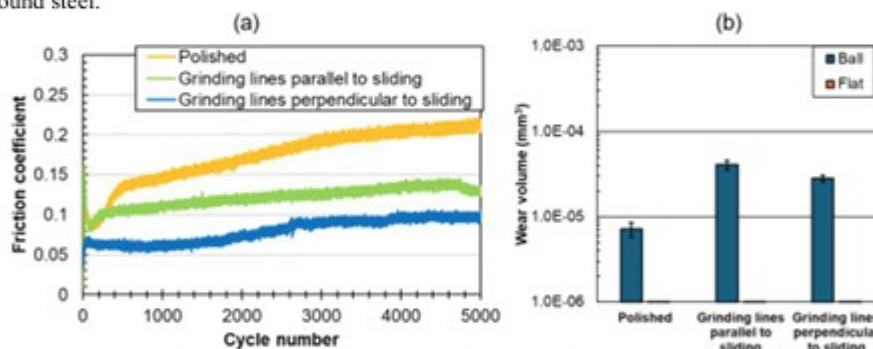


Figure 2: (a) Evolution of the friction coefficient as a function of cycle number and (b) specific wear rate on the ball for the 3 surface conditions of steel flat

4. Conclusions

Applying the DLC coatings tested to at least one surface in dry metal-metal contacts under 100 bars of hydrogen at room temperature significantly reduces friction and wear. DLC-coating the ball alone already leads to substantial friction and wear reduction. Supralow friction can be obtained with such self-mated a-C:H DLC coatings. Coating both the ball and the flat leads also to a further decrease in wear. In DLC/steel contacts, polishing the steel flat minimizes wear but results in higher friction. The use of DLC coatings on the ball significantly reduced both friction and wear, demonstrating their potential for improving the tribological performance of components running in a hydrogen gas environment especially in the energy and the mobility applications fields.

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Tribological behavior of low-viscosity synthetic ester base oils for Electric Vehicles (EVs) under pure sliding electrified conditions

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Abstract

The automotive industry's shift from internal combustion engine vehicles (ICEs) to electric vehicles (EVs) as more energy-efficient and environmentally friendly alternative has driven the need for new lubricants (E-Fluids) that can withstand the demanding operating conditions of EV drivetrains. In this study, three low-viscosity synthetic esters with high biodegradability and adaptability to industrial needs and a PAO8 (as base reference) were selected. Tribological behavior was evaluated through ball-on-disk tests under non-electrified (0 A) and DC-electrified (3 A) conditions, complemented by wear analysis using confocal microscopy. Clear correlations were observed between tribological performance and the rheological and electrical properties of the lubricants. Both the synthetic ester base oils and PAO8 exhibit an increase in the coefficient of friction (CoF) values when tested under current flow along with signs of electrical discharge damage (EDD).

1. Introduction

The current state of the automotive industry reflects a progressive transition from conventional internal combustion engine vehicles (ICEVs), which are associated with significant environmental impacts, to electric vehicles (EVs), a more energy efficient and potentially more sustainable alternative that is becoming increasingly established. This shift has accelerated notably in recent years, with reports indicating that in 2024 more than 20% of all new cars sold worldwide were electric vehicles.

Electric vehicles operate under more demanding conditions than internal combustion engine (ICE) systems, as their electric drive units are subjected to high torques, elevated temperatures, and rotational speeds that can reach up to 30,000 rpm. Moreover, EV powertrains are exposed to stray currents coming from the inverter, which tend to concentrate on the roller bearings of the rotor. These parasitic currents can induce electrical discharge events generating electrical discharge damage (EDD), accelerating bearing degradation and ultimately leading to electrical breakdown of the lubricating film. Therefore, lubricant formulation and lubrication strategies for EVs must meet new requirements, combining suitable electrical properties (such as controlled electrical conductivity and sufficient dielectric strength to prevent breakdown) with appropriate rheological and thermal characteristics, including low viscosity, adequate thermal conductivity, and compatibility with copper components[1,2].

This study evaluates the tribological behavior of low-viscosity synthetic ester base oils under electrified sliding conditions, compared with a conventional PAO oil used for EVs.

2. Materials and methods

Three low-viscosity synthetic ester base oils with different dielectric strength and viscosities were selected due to their favorable electrical properties and biodegradability, and compared with a polyalphaolefin (PAO8) oil, used in commercial EV drive fluids. These esters are: Trimethylolpropane (TMP), Pentaerythritol (PE) and Neopentyl Glycol (NPG).

As no standardised testing procedure is yet available, an internal procedure has been developed to evaluate the tribological behavior (friction and wear) and the relationship with the rheological and electrical properties of different lubricants for EVs under no electrification (0 A) and DC electrified conditions (3 A). Tribological tests have been performed in a unidirectional tribometer with a ball-on-disc configuration using AISI 52100 steel (100Cr6) discs ($\varnothing=24\text{mm}$, $t=8\text{mm}$) and balls ($\varnothing=10\text{mm}$) as the counterface. The tribometer was coupled to a power supply for the application of a stable current during tests, forming a two-electrode based cell. Wear scars and track profiles on both discs and balls were quantified by 3D optical profilometry, with wear volume and track depth as key factors of lubricant performance.

3. Results and discussion

Preliminary results show that both synthetic ester base oils and the PAO8 reference exhibit a rise in friction under electrical current, attributed to two main factors:

- The direct influence of electrical current passing through the tribological contact
- Local thermal effects causing viscosity reduction and altered lubrication regimes

Wear performance of electrified tests produced deeper wear tracks and evidence of electrical discharge damage (EDD) with different intensities depending on each oil's dielectric strength and rheological properties. Among the base oils, the PE synthetic ester showed a performance close to the PAO8 reference, exhibiting the same coefficient of friction (0.13) and a wear volume of $1.71 \times 10^{-3} \text{ mm}^3$, compared with $1.19 \times 10^{-3} \text{ mm}^3$ for PAO8.

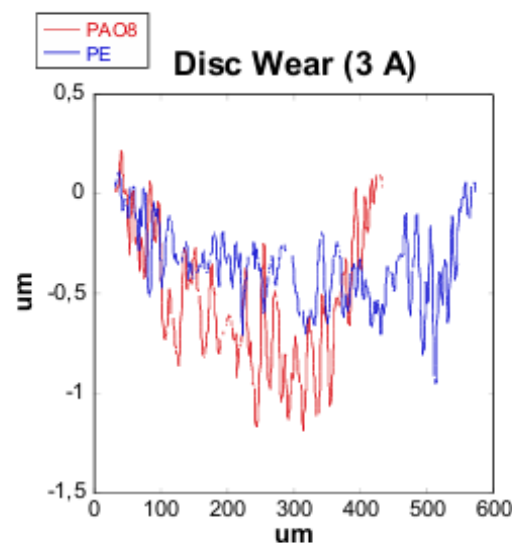


Figure 1. Disc wear scar obtained under DC-electrified tests with PE (blue) and PAO8 (red).

4. Conclusions

The preliminary conclusions indicate that both the synthetic ester base oils and PAO8 exhibit an increase in CoF values when tested under current flow. This behavior is attributed to the passage of electrical current and to the viscosity reduction caused by local thermal effects within the tribological contact. Wear is clearly affected as well, with electrified tests showing deeper wear tracks than nonelectrified conditions, along with signs of electrical discharge damage (EDD) of varying intensity depending on the dielectric and rheological properties of each oil.

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Engine oil stress as a consequence of DPF regeneration on urban service vehicles and maintenance improvement aided by AI.

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Abstract (Maximum length: 10 lines)

Urban bus operation is characterized by frequent stop-and-go cycles, low average speeds, and extended idling periods, which hinder effective Diesel Particulate Filter (DPF) regeneration under EURO VI-D conditions. This leads to increased engine oil degradation, primarily driven by soot accumulation, which can reduce oil drain intervals from approximately 60,000 km to 15,000 km when soot content reaches 3%. This work analyzes real operational data from urban buses to investigate the relationship between operating conditions, DPF regeneration behavior, and oil degradation. A data-driven approach applying explainable artificial intelligence (XAI) techniques, including SHAP and Partial Dependence analysis, is used to identify the key variables influencing regeneration efficiency. The results provide insight into the control behavior of the system and allow the identification of operational thresholds in key variables that promote more effective regeneration, supporting improved maintenance and operational decision-making.

1. Introduction

Urban bus fleets operate under demanding conditions characterized by frequent stop-and-go cycles, low average speeds, and extended idling periods. These conditions directly affect the performance of exhaust after-treatment systems, particularly Diesel Particulate Filters (DPF), whose regeneration requires sustained high-temperature operation. In urban service, such conditions are rarely achieved, leading to incomplete or inefficient regeneration processes.

From a tribological perspective, these conditions have a direct impact on engine oil degradation. Repeated failed regeneration attempts lead the engine to operate under suboptimal conditions, increasing oil stress and promoting soot accumulation in the lubricant. For the fleet under study, compliant with the EURO VI-D standard, oil drain intervals have been observed to decrease from approximately 60,000 km to 15,000 km when soot levels approach 3%. This reduction significantly increases maintenance costs and affects fleet availability (Figure 1). In addition, the analysis of wear metals such as iron in the engine oil provides further evidence of the accelerated degradation processes (Table 1).

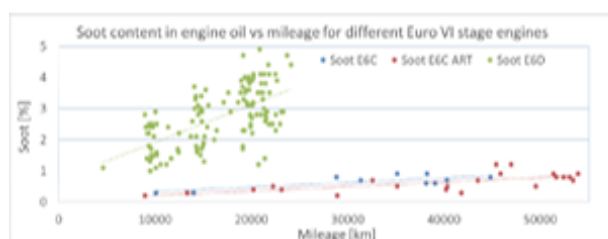


Figure 1. Soot content comparison between different EURO VI stages

Engine type/ stage	Average Fe rate (ppm/1000 km)
E6C	1,14
E6C ART	1,38
E6D	2,01

Table 1. Iron content comparison between different EURO VI stages

Despite the relevance of this problem, limited access to detailed information on DPF control strategies restricts the ability of maintenance teams to fully understand the factors governing regeneration behaviour. As a result, decisions are often based on empirical observations rather than a clear interpretation of the system dynamics [1]. In this context, the objective of this work is to analyse the relationship between operating conditions and DPF regeneration behaviour using real operational data from urban buses. To achieve this, a data-driven approach based on explainable artificial intelligence (XAI) is employed to identify the key variables and operational thresholds that influence regeneration efficiency, enabling a better understanding of the system and supporting improved maintenance and operational strategies.

2. Methodology

The analysis is based on operational data collected from EURO VI-D urban buses through the OBDII system over an extended service period. The dataset includes variables related to the exhaust after-treatment system, such as temperatures, pressures, nitrogen oxide levels, vehicle speed, and engine speed, as well as the categorical variable representing the DPF regeneration status.

To focus the analysis on relevant conditions, only data corresponding to active regeneration states were considered, while inactive periods and anomalous events were filtered out. Feature engineering was applied to capture key system dynamics, including variables such as temperature variation rates and pressure differentials, which are indicative of thermal and flow behaviour within the after-treatment system.

A supervised learning approach was used to model the different regeneration states, allowing the identification of operating conditions associated with each state. The analysis emphasizes model interpretability through explainable artificial intelligence (XAI) techniques. In particular, SHAP (SHapley Additive exPlanations) values and Partial Dependence analysis were employed to quantify the influence of each variable and to identify operational thresholds affecting regeneration efficiency.

3. Results and Discussions

The SHAP results show that the outlet temperature of the diesel oxidation catalyst (DOC) is the dominant variable influencing regeneration behaviour, confirming that thermal conditions are essential for achieving effective regeneration. In addition to temperature, engine speed and vehicle speed emerge as some of the most relevant operational variables, indicating that regeneration is strongly linked to the operating demand imposed on the engine.

Further analysis using SHAP dependence plots reveals the existence of operational thresholds. Vehicle speed exhibits a non-linear relationship with regeneration behaviour. Very low speeds are associated with unfavourable conditions, while intermediate urban speeds (typically below 30 km/h) do not provide sufficient demand to sustain effective regeneration. Higher speeds, combined with adequate thermal conditions, are more likely to promote favourable regeneration states. This behaviour highlights the limitations of typical urban operation, where the required conditions for efficient regeneration are rarely maintained over time.

From a practical perspective, these results enable the definition of operational strategies to mitigate oil degradation. For instance, assigning vehicles to routes with higher average speeds or modifying operating conditions to increase engine demand can promote more effective regeneration. These strategies provide a basis for improving maintenance planning and reducing the impact of oil degradation in urban bus fleets.

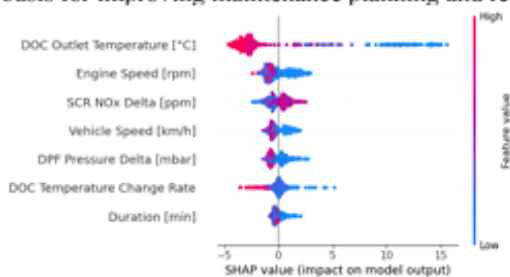


Figure 2. SHAP Feature Importance Analysis for DPF Regeneration Behavior

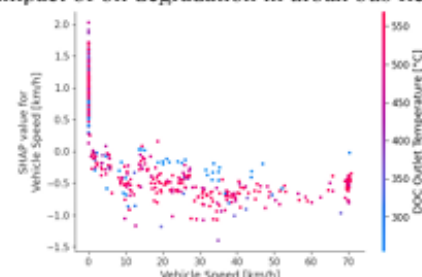


Figure 3. SHAP Dependence Plot - Vehicle Speed and DOC Outlet Temperature

4. Conclusions

Advances in vehicle electronics are enabling new approaches that were not previously feasible for maintenance management. By leveraging the data generated by the buses themselves, it is possible to apply advanced analytical techniques that enhance system understanding. In particular, the use of explainable artificial intelligence (XAI) has proven effective in extracting valuable insights into DPF regeneration control behaviour. This analysis allows a better understanding of the system and the identification of operational thresholds that can serve as a basis for improving vehicle operation and maintenance strategies.

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Influence of counterpart and oil formulation on wear of DLC-coated differential shafts for electric vehicles

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Abstract: The contact differential shaft/planet gear undergoes higher tribological stress in electric vehicles (EVs) than in internal combustion engines (ICEs) vehicles. In this context, protective diamond-like carbon (DLC) coatings seem well-indicated to cope with these specific running conditions and extend the differential system durability. DLC-coated shaft samples were tested under high load and speed. The presence of a manganese phosphate conversion coating on counterpart helps reduce DLC wear extension and prevents adhesive wear. Two commercial differential oils were tested. In one case, surface failure through scuffing occurred. This highlights the major role of oil formulation in DLC-coating's performance. For configuration with MnP and oil A, the coated shafts were able to terminate the test without seizure, however some degradation as cohesive flaking inside the DLC are observed.

1. Introduction

Electric motors in electric vehicles (EVs) generate higher torque at start-up compared to conventional internal combustion engines (ICEs) [1]. This results in greater torque transmission to the differential subsystem, thereby increasing scuffing failure risk on its components. In this context, diamond-like carbon (DLC) coatings are emerging as a preferred surface treatment for differential shafts in EVs [2]. This study investigates the impact of manganese phosphating on the counterpart surface as well as the influence of the lubricant formulation on both wear resistance and friction behaviour of DLC-coated differential shafts.

2. Material and method

A dedicated test setup was developed to replicate the contact kinematics of the differential shaft/planet gear contact (Fig. 1 a-b). The shaft is fixed in a stationary sample holder and the ring sample mounted in a housing connected to a rotating shaft. The shaft/bore clearance is 0.14 mm and the contact is a 4 mm-long line. The latter is achieved by machining two 2 mm-wide shoulders inside the ring for system stability. The samples are immersed in oil heated at 50°C. A normal load is applied to the shaft by a hydraulic cylinder while the ring is set in rotation. Strain gauge sensors measure both normal and tangential friction forces.

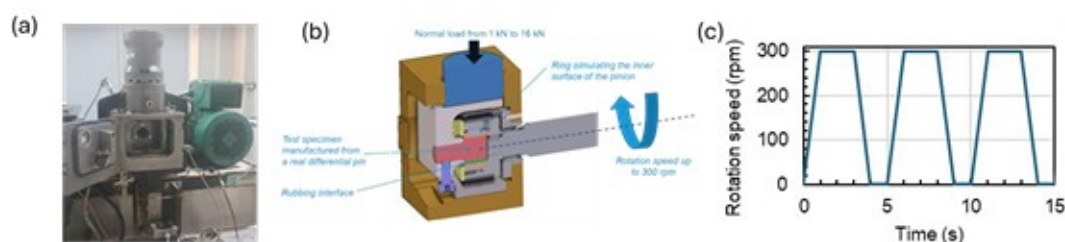


Fig. 1 (a) Shaft bearing tribometer and its main features, (b) specific test set up for differential shaft-gear contact (IREIS Design), (c) evolution of the ring rotation speed during the stop/start cycle

The test protocol consisted of two phases of 8 hours during which a stop/start cycle are repeated (Fig. 1c). An 8 kN ($P_{max} = 290$ MPa) load was applied during the first phase, 11 kN ($P_{max} = 350$ MPa) during the second phase. The three tested configurations are detailed in Table 1.

Configuration	Shaft	Ring	Oil
DLC-Steel-Oil A	20MnCrB5 steel	20MnCr5 steel as machined (steel)	Oil A: grade 75W80
DLC-MnP-Oil A	coated with a:C-H DLC	20MnCr5 steel treated by iron-manganese phosphatating (MnP)	
DLC-MnP-Oil B			Oil B: grade 75W70

Table 1: Description of the tested configurations

3. Results and discussion

The average friction coefficient during both phases for each configuration is shown in Fig. 2a. For configuration “DLC-MnP-Oil A”, the mean friction coefficient is about 0.10 during phase 1 and 0.09 during phase 2. Configurations “DLC-steel-Oil A” and “DLC-MnP-Oil B” show a higher mean friction coefficient, around 0.11 during phase 1. For both, the second phase was interrupted prematurely due to a sharp increase of the tangential force indicating scuffing occurrence. The combination of MnP conversion coating and oil A allows lower friction coefficients and inhibits scuffing initiation throughout whole test protocol. At the beginning of the test, friction is lower for the configurations with the MnP coated ring (COF $\approx$ 0.07, Fig. 2b). The friction coefficient gradually increases during the first minutes of the test and stabilizes at a higher friction coefficient. This may be caused by a rapid wear of the MnP layer.

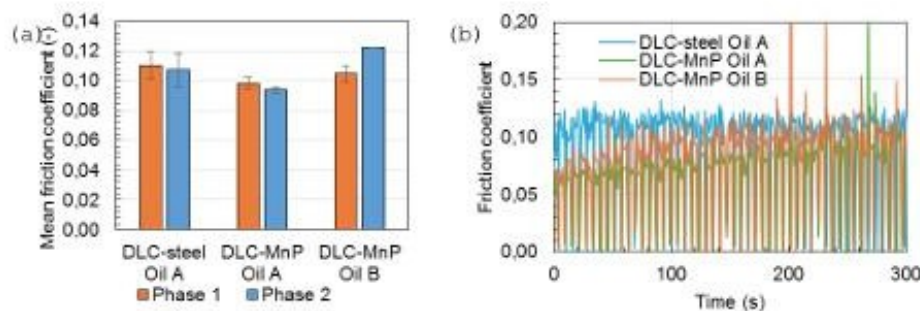


Fig. 2(a) Average friction coefficient, (b) friction curves at the beginning of the tests

Binocular images of the wear scars on the shaft for the three configurations are shown in Fig. 3. For all configurations, observations after the first phase show polishing of the DLC (dark coloration) and cohesive flaking within the a-C:H layer (grey areas). Configuration with Oil B shows a larger damaged area. After the additional 8h-phase, configurations with Oil A show larger areas where the DLC is removed and more smooth wear down to underlayer and/or the substrate in some areas. The configuration with uncoated ring shows a larger damaged area and adhesive wear (light grey at the edge of the contact). Thus, the presence of MnP on the counterpart provides better protection against wear. In case of oil B, the wear scar shows that scuffing occurred within the whole contact surface after phase 2. These observations indicate that Oil A shows better anti-wear properties than Oil B in the present conditions. Further analyses on the worn surfaces such as EDS analysis were performed to better understand the wear mechanisms.

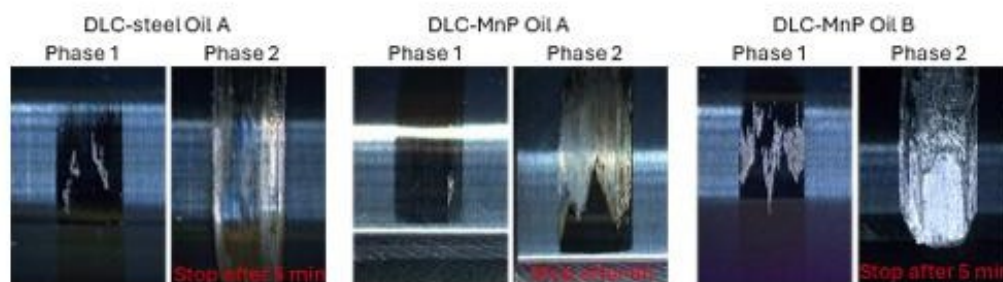


Fig. 3 Binocular observations of the shaft surface at the left ring shoulder contact level after 8h at 8 kN (phase 1) and an additional time at 11 kN (phase 2)

4. Conclusions

The tribological performances of DLC-coated differential shaft samples were investigated using a test setup that replicates the planet gear/differential shaft contact conditions. The presence of manganese phosphate conversion coating on the counterpart reduces the wear extension of the DLC. The use of Oil B instead of Oil A led to a higher wear rate and failure of the interface by scuffing.

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Effects of aerospace-grade steel surface topography and coating on lubricated friction coefficient

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Abstract

Reducing friction losses in aeronautical gear systems is essential to improve efficiency and reduce fuel consumption. This work presents an experimental tribological study on the lubricated friction behaviour of AISI 9310 and 32CDV13 aeronautical steels, analysing the influence of surface topography, hardness, and the application of a WC/C coating. Surface characteristics are evaluated by optical interferometry and microhardness measurements, while tribological behaviour is analysed with traction, Stribeck, and dry-running tests conducted on a ball-on-disk tribometer lubricated with a MIL-PRF-23699 oil. Various load, speed, and temperature levels are investigated reproducing boundary to full EHL lubrication regimes. Results show that friction in uncoated materials is mainly governed by asperity contact, whereas thermal effects dominate in coated surfaces. The combination of low surface roughness and coating proves beneficial across all lubrication regimes, contributing to high efficiency in aeronautical gear applications.

1. Introduction

Aerospace gear transmission designers focus on minimizing frictional losses to improve drivetrain efficiency and reduce fuel consumption; with surface roughness, coatings, and advanced lubricants playing a key role in tribological performance. Previous studies show that isotropic superfinishing can reduce friction by up to 30% compared to conventional grinding [1–3]; however, differences relative to more cost-effective processes such as polishing, lapping, or vibro-finishing remain unclear due to the largely variable specific film thickness. Moreover, advanced coatings like tungsten diamond-like carbon (W-DLC) further reduce friction and enhance durability, particularly under dry or boundary lubrication. Although the EHL traction behavior of such coatings is multiphysical [4], the mixed lubrication regime remains insufficiently studied, especially with non-Newtonian, additivated aerospace lubricants.

2. Methodology

The experimental study uses a commercial ball-on-disc Mini Traction Machine from PCS Instruments for the comparative analysis of the tribological performance of four test specimens with different surface topographies and hardnesses, representative of conventional gear manufacturing and finishing processes (see Figure 1). Two high performance steels for aircraft transmissions have been used for the discs: i) an AISI 9310 carburized steel and ii) a 32CDV13 nitriding steel. In all cases a final 0.3+0.4 mm nitriding layer has been applied. A conventional AISI 52100 polished sample has been included in the set as reference for the traction, Stribeck and timed tests. In all cases, tests pairs are lubricated with *Mobil Jet II* oil, complying MIL-PRF-23699 standard. Surface topography has been analysed using a *Sensofar S-Neox* optical interferometer and micro-hardness has been measured using a 100 g Vickers indenter.

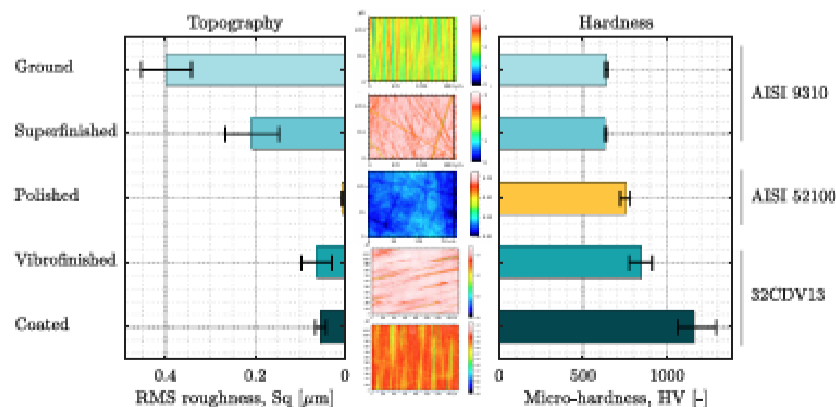


Figure 1: Root mean square height, visual topography and micro-hardness of selected specimens

Three different tests (with three repetitions per condition) have been carried out: i) traction tests to analyse full EHL friction behaviour, ii) Stribeck tests for the mixed lubrication region and iii) timed dry-running tests for the boundary case. In all cases two load levels have been applied: 27 N and 72 N, which result in contact pressures of 900 MPa and 1250 MPa respectively when applied on a 3/4" ball. Oil sump temperature has been kept constant at 60°C and 90°C and a 10 kOhm Electrical Contact Resistance (ECR) has been applied to qualitatively study the amount of asperity interactions.

3. Results and discussion

The experimental campaign has shown that ground surfaces produce high friction coefficients (up to 0.07) in all test types, with considerable deviations between repetitions. Largest values arise when the rolling speed decreases, thus reducing the oil film thickness and increasing asperity interactions, which is confirmed by ECR measurements. Meanwhile, vibrofinished sample behaviour is very close to the polished reference in the full EHL regime, while small differences arise at the lowest entrainment speeds from the Stribeck tests. The application of a DLC coating (*Balinit-C* from Balzers) does not further enhance EHL nor mixed lubrication behaviour, with slightly higher friction coefficients relative to the vibrofinished case at low entrainment speeds. However, when timed dry-running tests are analysed it is observed that friction coefficient remains lower and constant during the test. The analysis of ECR measurements shows that the amount of asperity interactions of the coated specimen is similar to the vibrofinished case thus pointing out that friction coefficient is ruled by the coated layer shear resistance rather than the oil rheology remaining in the interface. Similarly, in EHL tests conducted at high temperatures, DLC coated specimens have shown slightly lower friction coefficients due to thermal effects in the contact. Finally, results for the superfinished sample fall between the ground and vibrofinished/coated cases in all tests, which results from the asperity height distribution of the surface which is smaller than the former but higher than the latter (see Figure 1).

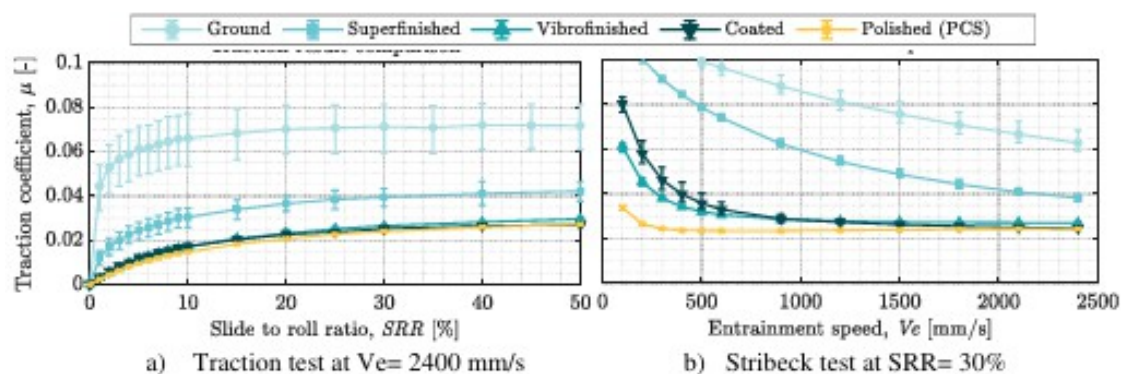


Figure 2: Test results for different specimens at 60°C sump temperature and 27 N load

4. Conclusions

An extensive tribological experimental study has been carried to analyse the frictional behaviour of four aeronautical steels with different surface topographies and hardnesses, typical from gear applications. Results show that the application of vibrofinishing after grinding and a final nitriding layer produces low friction coefficient in all conditions, comparable to the polished case. The application of a DLC coating on top of the nitrided layer does not further enhance tribological behaviour but proves to be beneficial in dry-running conditions, where low and constant friction coefficients are kept. Therefore, the application of coating must be considered when off-design conditions such as loss of lubrication are expected.

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Combining laser-textured dimples and AlCrN coating to reduce wear on AISI M2 Steel

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Abstract – Femtosecond laser surface texturing (LST) and AlCrN HiPIMS coating were combined on AISI M2 high-speed steel to evaluate their synergistic tribological effect under fine blanking-representative conditions. Dimple textures (50 μm diameter, 14 μm depth) at 10%, 15% and 20% surface density were fabricated and coated with $\sim 1.5 \mu\text{m}$ AlCrN. The coating showed hardness $\sim 33 \text{ GPa}$, Class 1 adhesion (ISO 26443) and complete dimple coverage. Friction coefficients (0.10–0.15) were stable under 10–50 N for all configurations, consistent with mixed-EHD lubrication. The AlCrN coating alone reduced the wear coefficient by $\sim 90\%$ vs. uncoated steel. The 10%-textured coated sample (CT10) matched this performance; higher densities caused exponential wear increase due to third-body abrasion from debris trapped in dimples. Uncoated textured surfaces showed no wear benefit.

1. Introduction

Fine blanking tools operate under contact pressures exceeding 3000 MPa and temperatures $\sim 400^\circ\text{C}$ [1], making wear protection critical. AlCrN coatings deposited by HiPIMS provide high hardness, oxidation resistance up to 1000°C and good tribochemical interactions with lubricants [2, 3]. Laser Surface Texturing (LST) can complement coatings by creating micro-dimples that act as lubricant reservoirs and debris traps [4]. However, combining both strategies yields results highly dependent on testing conditions, and the underlying mechanisms are not fully understood [5, 6]. This work systematically evaluates LST dimple density (10–20%) combined with AlCrN HiPIMS coating on AISI M2 steel under lubricated ball-on-disk conditions representative of fine blanking at laboratory scale.

2. Material and Methods

AISI M2 steel disks ($\varnothing 25 \times 10 \text{ mm}$, $S_a = 22.3 \text{ nm}$) were textured with a femtosecond Nd:YVO₄ laser ($\lambda = 1030 \text{ nm}$, $P = 1.2 \text{ W}$, $f = 750 \text{ kHz}$) producing hexagonal dimple arrays ($\sim 50 \mu\text{m}$ diameter, $\sim 14 \mu\text{m}$ depth) at 10%, 15% and 20% density. AlCrN ($\sim 1.5 \mu\text{m}$) was then deposited by HiPIMS (AlCr 70/30 at.% target, Ar/N₂ 450/200 sccm, 4 kW, -90 V bias, 350°C , 150 min) over a Cr adhesion interlayer. Eight configurations were tested: N, T10, T15, T20 (uncoated), C, CT10, CT15, CT20 (textured and AlCrN coated). Characterisation included GD-OES, SEM/EDX, nanoindentation (Berkovich, QCSM, $<10\%$ film thickness), Rockwell adhesion test (ISO 26443), confocal microscopy (S_a , S_q) and static contact angle. Ball-on-disk tests used Al₂O₃ balls ($\varnothing 6 \text{ mm}$), 200 rpm, 6 mm track radius, 50 N, 20000 cycles, with 0.05 mL of Tadal 1095 lubricant. Wear coefficients were measured by confocal microscopy (SensoSCAN method [7]) following ASTM G99-17.

3. Results and Discussion

GD-OES confirmed an AlCrN layer ($\sim 1.5 \mu\text{m}$, 45 at.% Al, 35 at.% N, 20 at.% Cr) over a $\sim 300 \text{ nm}$ Cr interlayer. Nanoindentation yielded $H \sim 33 \text{ GPa}$; Rockwell test indicated Class 1 adhesion. EDX confirmed complete coating coverage inside dimples. All samples exhibited stable COF (0.10–0.15) throughout 20000 cycles regardless of texture density or load (Table 1), consistent with calculated λ ratios of 0.95 (N) and 0.75 (C) placing the contact near the mixed-EHD lubrication boundary.

Regarding wear, uncoated textured surfaces (T10–T20) showed wear coefficients nearly two orders of magnitude higher than N, with no benefit from dimpling alone. In contrast, sample C achieved $k \approx 6.1 \times 10^{-9} \text{ mm}^3/\text{Nm}$ ($\sim 90\%$ reduction vs. N). CT10 matched this performance; CT15 and CT20 showed an exponential-like increase in wear. SEM/EDX of worn surfaces confirmed that abrasive wear dominates for uncoated samples, while coated samples at higher densities show coating delamination (Fe signal) and accumulation of oxidised debris within dimples acting as third-body abrasives [8]. These results indicate that, above 10% density, debris entrapment outweighs the lubricant reservoir benefit.

Sample	Textured	AlCrN	COF	k [mm ³ /Nm]
N	–	–	0.12±0.01	(6.1±2.1)×10 ⁻⁸
T10	10%	–	0.15±0.01	(3.4±0.5)×10 ⁻⁶
T15	15%	–	0.12±0.01	(3.0±0.2)×10 ⁻⁶
T20	20%	–	0.13±0.03	(4.0±0.4)×10 ⁻⁶
C	–	Yes	0.12±0.01	(6.1±3.2)×10 ⁻⁹
CT10	10%	Yes	0.10±0.01	(1.5±1.1)×10 ⁻⁸
CT15	15%	Yes	0.12±0.01	(2.1±0.3)×10 ⁻⁷
CT20	20%	Yes	0.12±0.01	(6.2±0.4)×10 ⁻⁷

Table 1. COF and wear coefficient k (SensoSCAN) for all samples tested at 50 N, 200 rpm, 20000 cycles.

4. Conclusions

Femtosecond LST dimples (10–20% density) and HiPIMS AlCrN coating were deposited on AISI M2 steel and tested under lubricated ball-on-disk conditions. The AlCrN coating alone reduced the wear coefficient by ~90%. The 10%-textured coated sample (CT10) matched this performance, while higher densities caused exponential wear increase due to third-body abrasion from debris entrapment. Uncoated textured surfaces showed no wear benefit. All configurations maintained stable COF (0.10–0.15) independent of load and texture density. These results demonstrate that surface texturing beyond 10% density does not improve tribological performance over a plain hard coating under the tested conditions, and further validation under real fine blanking conditions is recommended.

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KN5 Anna Andersson ABB

Towards Grease free lubrication electrical switching

TRIBO 7 ID 96 SiToLub project – tribology for safe and sustainable lubricants

TRIBO 8 ID 117 Ageing mechanism of non-fossil base oils

Hydrogen related mechanisms influencing the galling behaviour of austenitic stainless steels in threaded components

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Abstract

Threaded stainless steel connections are critical to ensuring safety and leak-tightness in Underground Hydrogen Storage (UHS). While galling is a well-known failure mechanism in threaded connections used in conventional energy infrastructures, the influence of hydrogen on galling behaviour remains insufficiently understood. This knowledge gap complicates the direct transfer of materials and design approaches from oil and gas to hydrogen related applications. This study examines the tribological behaviour of an austenitic stainless steel widely used in threaded connections, comparing its response in the virgin condition and after controlled hydrogen uptake. Dry sliding tests representative of tightening operations were combined with surface analyses to understand frictional and wear mechanisms. Results show that hydrogen does not intensify galling damage and instead leads to a reduction in friction, supporting the use of conventional stainless steels in hydrogen-rich underground storage environments.

1. Introduction

UHS has emerged as a promising solution for balancing energy supply and demand in future low-carbon energy systems, particularly in connection with renewable hydrogen production [1]. In such installations, hydrogen is transported and injected through pipeline networks incorporating threaded joints, often fabricated from corrosion-resistant stainless steels. Similar to the operational requirements in the oil and gas sector, these connections must maintain mechanical integrity and sealing performance throughout repeated assembly cycles, where galling represents a significant risk [2].

Galling, driven by adhesive interactions between metallic surfaces under high contact pressures, is especially problematic for austenitic stainless steels. While extensive research exists on galling behaviour in hydrocarbon applications, the potential influence of hydrogen on this damage mechanism remains insufficiently quantified. Hydrogen uptake may alter near-surface properties, dislocation mobility or oxide film stability, thereby modifying frictional behaviour during sliding contact.

Given the transition toward hydrogen based energy infrastructures, assessing whether traditional materials remain suitable under hydrogen exposure is crucial. To address this gap, an experimental programme was designed to examine how hydrogen affects the galling response of stainless steel used in threaded components.

2. Methods and Results

The material selected for this investigation was a 28Cr (UNS N08028) austenitic stainless steel grade, frequently applied in threaded connections subjected to demanding service conditions. Two material states were evaluated: the as-supplied condition and a hydrogen-enriched condition obtained through artificial electrochemical charging aimed at introducing diffusible hydrogen into the metal lattice.

Tribological performance was studied using dry reciprocating pin-on-disc testing. The applied loads, sliding distances and contact configuration were selected to approximate the mechanical conditions experienced by threads during tightening operations. Following testing, surface damage was characterised using optical microscopy and scanning electron microscopy (SEM), complemented by energy dispersive X-ray spectroscopy (EDX) to identify material transfer and wear features.

Surface observations revealed qualitatively similar galling features for both material conditions, including adhesive wear scars and plastically deformed regions. However, significant differences emerged in the frictional response. The hydrogen charged specimens consistently exhibited lower friction levels

throughout the tests compared to the untreated material, indicating that hydrogen presence influenced the interfacial sliding mechanism.

3. Conclusions

Within the scope of the experimental conditions applied, hydrogen absorption in the investigated 28Cr austenitic stainless steel did not lead to an increased susceptibility to galling. On the contrary, the reduction in friction observed for hydrogen-charged specimens suggests that hydrogen may facilitate smoother sliding between contacting surfaces, acting effectively as a friction reducing agent.

This behaviour could offer practical advantages for threaded connections in UHS installations, where repeated make-up and break-out operations are unavoidable. The findings presented here provide valuable experimental evidence supporting the continued use of stainless steel grades originally developed for oil and gas applications in hydrogen storage environments, thereby contributing to the safe deployment of underground hydrogen storage technologies.

4. Acknowledgments

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Tribological and corrosion properties of PEO/HiPIMS duplex coatings deposited on ZK60 magnesium alloy

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Abstract – Duplex coatings combining Plasma Electrolytic Oxidation (PEO) and HiPIMS TiN Physical Vapour Deposition were deposited on ZK60 magnesium alloy to improve its wear and corrosion resistance for biomedical applications. The PEO process was optimized to achieve ~15 µm thick layers ($R_a \sim 1 \mu\text{m}$), subsequently coated with 1.5 µm TiN by HiPIMS at 150 °C. Both polished and unpolished PEO intermediate layers were evaluated. Nanoindentation, Daimler-Benz adhesion tests, pin-on-disk tribology and potentiodynamic polarization in 1M NaCl were performed. The duplex coatings showed wear rates two orders of magnitude lower than the substrate and one order lower than each individual coating. PEO polished + TiN achieved the best corrosion performance ($j_{\text{corr}} = 0.85 \mu\text{A}/\text{cm}^2$) while maintaining good adhesion and smooth wear tracks.

1. Introduction

Magnesium alloys are attractive for biomedical implant applications due to their low density, biodegradability, biocompatibility and elastic modulus close to bone [1]. However, their fast corrosion degradation and poor wear resistance severely limit clinical use. Surface functionalization strategies — including PVD, CVD, Micro-Arc Oxidation (MAO/PEO) and sol-gel coatings— have been explored to overcome these limitations, but issues of poor adhesion, surface defects and limited deposition temperature (50–180 °C) restrict their industrial applicability [2]. Duplex approaches combining a ceramic PEO interlayer with a hard PVD top coat offer a promising route: PEO creates a well-bonded porous oxide layer that improves PVD adhesion and provides additional corrosion barrier properties [3]. This work evaluates PEO + HiPIMS TiN duplex coatings on ZK60 Mg alloy, studying the influence of PEO polishing on tribological and corrosion performance.

2. Material and Methods

Five sample configurations on ZK60 Mg alloy were prepared: uncoated substrate, PEO only, TiN only, PEO unpolished + TiN (duplex-U) and PEO polished + TiN (duplex-P). PEO was performed using a pulsed and synchronized power source (Ingeniería Viesca S.L., max. 20 kW) at TEKNIKER: 200 Hz, 600 µs pulse width, $I^+ = I^- = 4 \text{ A}$, $V^+ = 650 \text{ V}$, $V^- = 300 \text{ V}$, 5 min in a 5 L electrochemical cell. TiN (~1.5 µm) was deposited by HiPIMS using a Ti target (Ar 9%/44 sccm, N₂ 3%/5.5 sccm, 6.3×10^{-3} mbar, 2000 W, bias -40 V, 150 °C, 300 min) on a custom PVD system (UPNA/Nano4Energy). Characterisation included confocal microscopy (Sa, ISO 25178), SEM cross-section, nanoindentation (Anton Paar NHT3, 1–5 mN), Daimler-Benz Rockwell C adhesion test (INSTRON WOLPERT 751) and pin-on-disk tribology (Microtest MT, 1 mN, 2000 cycles, 150 rpm). Corrosion resistance was evaluated by potentiodynamic polarisation (PDP) in 1M NaCl using an Autolab PGSTAT302N: $\pm 250 \text{ mV}$ vs. OCP at 1 mV/s; Tafel extrapolation for E_{corr} and j_{corr} .

3. Results and Discussion

The PEO process produced uniform coatings ~14–18 µm thick (centre/edge) with $R_a \sim 1 \mu\text{m}$, meeting the target specifications. After polishing, S_a decreased from 1350 to 600 nm; TiN deposition slightly reduced roughness on the unpolished sample due to ion bombardment during cleaning (S_a : duplex-U 1070 nm, duplex-P 640 nm). Nanoindentation results (Table 1) show that TiN is the hardest coating ($H = 18.6 \text{ GPa}$). In the duplex samples the effective hardness is lower (10–12 GPa) owing to the softer PEO sublayer. The H/E and H^3/E^2 ratios indicate better resistance to plastic deformation for TiN, while duplex coatings remain intermediate. The Daimler-Benz test showed improved adhesion for duplex coatings vs. TiN alone, with no delamination on the PEO + TiN samples.

Pin-on-disk tests showed that duplex coatings achieved wear rates two orders of magnitude lower than the substrate and one order of magnitude lower than each individual coating. Abrasive wear was observed on uncoated and TiN samples; adhesive wear on PEO; smooth wear tracks on duplex samples. Regarding corrosion (Table 1), PEO alone yielded the lowest j_{corr} ($0.02 \mu\text{A}/\text{cm}^2$), confirming its excellent barrier

effect. TiN alone worsened corrosion significantly ($j_{corr} = 106 \mu\text{A}/\text{cm}^2$) due to galvanic coupling through coating defects. The duplex coatings combined both effects: duplex-U achieved $j_{corr} = 2.2 \mu\text{A}/\text{cm}^2$ and duplex-P = $0.85 \mu\text{A}/\text{cm}^2$, both far superior to TiN alone. Post-test images confirmed that TiN failed completely while PEO remained practically unaffected, and duplex samples showed only localised penetration through TiN defects, with the PEO layer acting as a secondary barrier.

Sample	H (GPa)	E (GPa)	E_{corr} (V)	j_{corr} ($\mu\text{A}/\text{cm}^2$)	Wear rate (rel.)
Mg ZK60	1.1 ± 0.1	49 ± 3	-1.48	71 ± 1	Reference
PEO	6.6 ± 0.9	93 ± 11	-1.58	0.02 ± 0.01	-10× lower
TiN	18.6 ± 2.1	163 ± 8	-1.52	106 ± 5	-10× lower
Duplex-U	12.0 ± 0.8	185 ± 33	-1.34	2.2 ± 0.1	-100× lower
Duplex-P	10.6 ± 1.7	170 ± 19	-1.35	0.85 ± 0.1	-100× lower

Table 1. Nanoindentation and corrosion data for all samples. Duplex-U: PEO unpolished + TiN; Duplex-P: PEO polished + TiN.

4. Conclusions

PEO + HiPIMS TiN duplex coatings were successfully deposited on ZK60 Mg alloy. The PEO process was optimized to 15 μm thickness and $R_a \sim 1 \mu\text{m}$. TiN alone showed the highest hardness (18.6 GPa) but poor corrosion resistance due to galvanic coupling through defects. Duplex coatings achieved wear rates two orders of magnitude lower than the substrate and one order lower than each individual coating, with improved adhesion and smooth wear tracks. Polishing the PEO layer before TiN deposition had limited effect on wear but improved corrosion resistance significantly ($j_{corr} = 0.85$ vs. $2.2 \mu\text{A}/\text{cm}^2$). The best overall performance was achieved by duplex-P, combining good wear resistance, improved adhesion and low corrosion current. Further characterization (SEM, GD-OES) is ongoing to complete the understanding of the coating microstructure and failure mechanisms.

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Prediction and Measurement of Space Lubricant Lifetimes in Angular Contact Bearings

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Keywords: Space Mechanisms, Lubricant lifetime, Lubricant degradation

Abstract

Lubricant lifetime plays a crucial role in determining the operational longevity of bearings utilised in space mechanisms. However, results from testing and predictive models can sometimes differ significantly. This study compares data from one specific lubricant lifetime model with test results obtained from a back-to-back angular contact bearing pair of SKF 7204 ball bearings lubricated with Fomblin® Z25.

1. Introduction

For spacecraft missions, lubricant failure in bearings can limit the operational duration of a mechanism [1]. PFPE lubricants like Fomblin® Z25, Z60, and Brayco 815Z are commonly used for bearings operated in space due to their low vapour pressure and wide operating temperature range. However, as PFPE degrades, and liberated fluorine reacts with iron forming FeF₃, a catalyst which accelerates lubricant molecule breakdown, shortening operational life [1]. Lubricant degradation is manifest as increased bearing friction torque. High friction torque can lead to increased power requirements, and this can lead to issues for space-based systems where energy to operate mechanisms can be limited [2].

2. Modelling and experimental test set-up

Commonly, lubricant life predictions use semi-empirical models fitted to lubricant data obtained from the Spiral Orbit Tribometer (SOT) [2,3]. Bearing simulation packages like CABARET [4] are used to calculate the kinematics of bearing assemblies in the space industry, and can account for preload, lubricating film thickness and bearing cage dynamics [5].

In the work presented here, the authors have used Palladino et al.'s SOT-life model [3], with contact pressure corrections to a Fomblin® Z25 lubricated 7204 bearing to estimate lubricant lifetime. A quasi-static analysis of the back-to-back 7204 bearing pair was performed in CABARET to acquire basic performance data such. These data were then used as inputs for lifetime modelling using equation 1 from Palladino et al., which presents a relationship between SOT ball-orbits and bearing revolutions by integrating SOT-specific lifetime data, L (in units of orbits/ μg) [2], lubricant mass, m , and ball pass frequency, N_{bp} [2,3].

$$N_{revs} = 2 L m / N_{bp} \dots \dots \dots \text{(Eq 1)}$$

In the test apparatus two 7204 angular contact bearings were mounted back-to-back in a bespoke torque-measurement apparatus at 100 N axial preload, each lubricated with 0.0538 μL of Fomblin® Z25. The equipment was run at 100 rpm in ambient laboratory air (22 °C, 30 % RH), targeting the boundary regime. Running torque and inner-race temperature were logged throughout the test.

4. Results

Figure 1(a) illustrates the modeled lubricant lifetime as a function of the lubricant volume utilized within the bearing for three mean Hertzian contact pressures: 1.5 GPa, 1.75 GPa, and 2.0 GPa. Lifetime can be seen to increase with lubricant volume at a fixed contact pressure, and rapidly decreases as pressure increases. Using a lubricant volume of 0.0538 μL per bearing, the modeled lifespan is 26.7 hours at 1.5 GPa, and 5.0 hours at 2.0 GPa. The slope of the graph is consistent with the inverse-fourth-power trend reported in the SOT data [5].

To compare the model data with experimental data, experiments were conducted at the same lubricant volume of 0.0538 μL per bearing. The back-to-back bearing assembly operated at a consistent torque of 14 mN·m for around 26 hours until the friction torque gradually increased over a period of approximately three and a half hours to reach a plateau near 90 mN·m (Figure 1(b)). This friction torque is well above

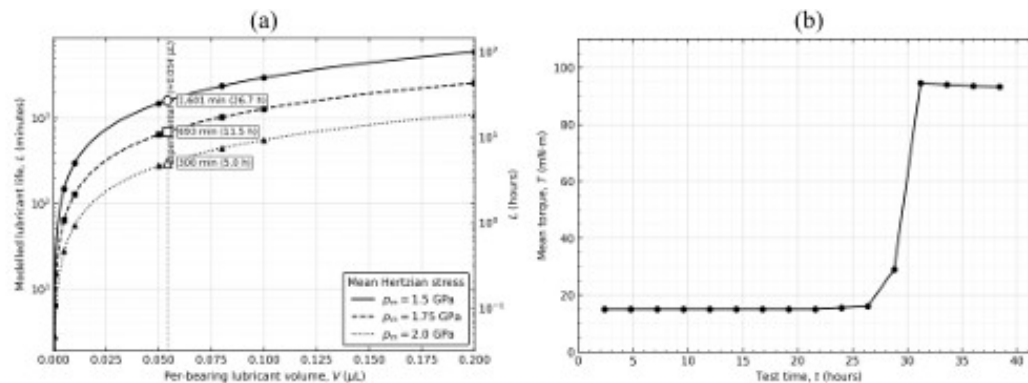


Fig. 1.(a): Modelled bearing lifetime as a function of lubricant volume for an SKF 7204 bearing lubricated with Fomblin® Z25 at 100 rpm at three contact pressures. (b): Torque variation from the test rig data

the ECSS criterion for failure, (specified as three times the steady state friction torque) and therefore, indicative of lubricant failure. The temperature of the inner race exhibited only a small temperature increase of 3 °C over the entire duration of operation, indicating that the failure was not thermally induced. A valuable observation was that an observable increase in torque noise occurred about one hour prior to the abrupt change in the absolute value. If this increase in noise is always present, it may form a valuable indication of incipient failure.

This early data suggests that the SOT semi empirical model constitutes a reliable predictor of bearing life under the tested starved lubricant conditions. Although this agreement is encouraging, the experiment does not account for the complex interplay of lubricants in the cage, oxide layers, and preload change, which may alter the degradation process. It is also notable that the model is very preload-sensitive due to an inverse-fourth-power dependence of life on mean Hertzian contact pressure.

5. Conclusion

This study has shown that the SOT-data, when appropriately corrected for operating Hertzian pressure, can be used to predict the bearing-level lifetime of a 7204 pair lubricated with Fomblin® Z25 for at least analysing interactions between rolling elements, and examining temperature and atmospheric effects. Despite these limitations, the integrated modelling and component testing approach presented here provides a valuable initial step toward establishing a fully validated lifetime prediction framework for PFPE-lubricated angular contact bearings used in space mechanisms.

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Simple Models for Mixed and Boundary Friction

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Abstract

This presentation outlines a simple method for predicting friction coefficients in the mixed friction regime. It is based on a “normalisation” of the axes of the Stribeck curve. When plotting experimental friction data using the proposed normalisation, a “universal curve” results that can be modelled using a reverse sigmoid fit. Evaluation of the best-fit parameters for this sigmoid curve produces an equation that can be used to predict friction coefficients in the mixed regime. The method provides a simple yet accurate approach that can be easily applied in engineering design and analysis. Other approaches of this type developed by these authors, as well as other researchers, will be discussed in the presentation.

1. Introduction

The Stribeck curve is commonly used to characterise lubrication modes using the product of viscosity and speed divided by load as the dependent variable. However, while Stribeck curves for different lubricants and interface materials generally have the same form, quantitative evaluations of the Stribeck curve lead to an infinite number of curves when different lubricants, speeds and load are employed. These curves are also found to be influenced by a wide range of other parameters such as the character and scale of the surface topography, the presence of lubricant additives, the mechanical properties of the interface materials, etc. This extensive range of influences appears to suggest that only complex modelling involving calculations of rough surface deformation, asperity shear, lubricant flow, load sharing between asperities and fluid pressure, etc. can be used to predict mixed friction. As a consequence, accurate modelling mixed and boundary friction has proved challenging for many decades. This situation has tended to mean that mixed and boundary friction is either ignored completely or severely over-simplified in machine element analysis unless a highly skilled tribologist is available to conduct the modelling.

2. Method

To address this challenge a number of researchers including these authors [1] have considered various approaches to “normalising” the Stribeck curve. This has led to several accessible approaches for estimating friction in the mixed regimes, including situations where friction modifiers and anti-wear additives are present [2]. In the method developed by these authors there are two steps. The first involves using the Lambda Ratio as the x-axis parameter. The second requires a normalisation of the y-axis mixed/boundary friction values, so that they can be interpreted as a proportion of the boundary friction to mixed friction. In this approach if f_o is the boundary friction coefficient and f_{EHD} is friction coefficient measured under fluid film conditions, normalised y-axis values, X , are given by:

$$X = \frac{f - f_{EHD}}{f_o - f_{EHD}}$$

3. Results

Plotting measured friction data using the modified Stribeck curve axes described in section 2, results in a near “universal curve” as illustrated in figure 1. The data in figure 1 can be modelled by a reverse sigmoid curve which relates the Lambda Ratio to the proportion of boundary friction in the mixed regime, X , as follows:

$$X = \frac{1}{(1 + \lambda^k)^a} \quad \text{Where } k = 3/2 \text{ and } a = 4/3$$

Hence, a knowledge of the Lambda ratio for given operating conditions allows X to be determined allowing friction forces to be predicted. Boundary friction is given by $F_B = f_o \cdot X \cdot W$ and total friction in the mixed regime is $F_{TOT} = (f_o X + f_{EHD}(1 - X)) \cdot W$. The approach can be used directly for base oils and simple modifications can be made to facilitate the modelling of lubricants with additives.

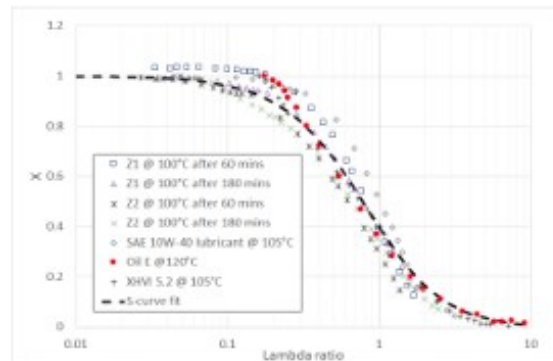


Figure 1 The variation of the proportion of mixed/boundary friction (X) with Lambda Ratio for a range of base oils [1]

4. Discussion

Modelling of mixed lubrication seems to be becoming increasingly important, and the simple approach described here can be used to provide valuable insight into the frictional losses in machine elements without excessive effort. More recent research on this topic has examined the impact of the character of the interface surface topography and has led to further equations to predict mixed friction which are based on the overlap between the interface asperities. These equations do not contain fitting parameters, but they still provide a strong fit to experimental data. The main purpose of this research was to develop simple expressions to predict mixed friction in contacts while taking account of differing surface height distributions, particularly for the purpose of modelling of the impact of changes in surface topography on friction during wear and running-in. [3].

While the approaches developed by the authors offer simple and effective approaches to calculating mixed friction, it should be noted that other researchers have also proposed equations relating X to λ [4, 5, 6]. However, these equations have not been widely adopted.

5. Conclusions

This study has led to a number of simple equations for predicting friction in the mixed regime. Our aim has been to provide tribologists and other engineers with analytical equations that can be applied easily to complete “back of the envelope” calculations, or to implement spreadsheet type calculations that give reasonably accurate predictions with very effort avoiding the need to resort to complex modelling which requires the insight of experts and significant implementation time.

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KN3 Marc Vila PETRONOR

A Proportional Hazards Models Perspective on MTBF Estimation for centrifugal Pumps

Real Time Monitoring of Water-Glycol Hydraulic Systems: Early Failure Detection Using Optical Particle Counter and Data Analytics Platform in the Caster Main Hydraulic System

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Instructions: The following guidelines concern the preparation of extended abstracts to be submitted to LUBMAT 26. All documents should be formatted according to these guidelines.

1. Introduction

Water-glycol hydraulic systems are widely used in the steel industry due to their fire-resistant properties; however, they present challenges related to fluid degradation, component wear, and contamination control. Additionally, real-time monitoring in water-glycol fluids presents significant technical difficulties for conventional laser-based particle counters, due to differences in refractive index, light scattering behavior, and the presence of dissolved water, which can affect measurement accuracy and reliability.

To improve reliability, the use of online monitoring systems has become essential. Unlike traditional periodic sampling, online monitoring enables continuous evaluation of both fluid condition and system performance, allowing early detection of abnormal behavior.

This study presents the implementation of an integrated online monitoring system combining optical wear-particle detection with multi-variable data acquisition. The objective is to detect early-stage failures through real-time analysis and correlation of key parameters in a water-glycol hydraulic system.

2. Monitoring Architecture

A multi-variable online monitoring system was implemented, integrating the following parameters:

- Pump discharge
- Water-glycol fluid temperature (~40°C baseline)
- Hydraulic reservoir level
- Pump casing-drain flow (indicator of internal leakage)
- Differential pressure across filters (contamination/saturation indicator)
- Vibration in Pumps and motors (velocity and acceleration)
- Real-time particle monitoring using Atten2 OilWear S120 LCD

All signals were collected and processed through a Python-based data analytics platform, enabling:

- Real-time visualization
- Historical trending
- Alarm thresholding
- Cross-variable correlation

3. Results and Discussion

3.1 Baseline Conditions

Under normal operation, the system maintained stable cleanliness levels around ISO 4406 ~14/13/12, with low particle generation, stable drain flow, and consistent filter differential pressure.

3.2 Failure Development and Detection

The failure event followed a clear timeline:

- Initial failure condition (not detected by conventional parameters)
- Abnormal particle increase detected by S120 sensor
- Corrective action executed

A rapid increase in contamination was observed:

- ISO 4 µm: up to ~22
- ISO 6 µm: up to ~20
- ISO 14 µm: up to ~18–20

This behavior correlated with:

- Rising filter differential pressure
- Moderate increase in vibration levels

3.3 Failure Identification

The failure was confirmed as:

Cavitation-induced damage in a Rexroth vane pump caused by seal degradation

This resulted in:

- Internal leakage increase
- Accelerated wear particle generation
- System contamination

3.4 Corrective Actions

The following actions were implemented:

- Pump replacement
- Offline filtration using 3-micron elements
- Restoration of system cleanliness

ISO levels were reduced from ~22/20/18 to ~15/14/13, confirming effective contamination control and system recovery.

All actions were performed during runtime and a planned shutdown, avoiding production impact.

3.5 Key Findings

- Optical particle monitoring detected failure earlier than pressure, temperature, or vibration
- Water-glycol systems require continuous monitoring due to rapid failure propagation
- The combination of particle data, drain flow, and filter ΔP provides a reliable diagnostic approach
- Digital platforms enable effective correlation and faster decision-making

4. Conclusions

This study demonstrates that the integration of optical wear monitoring with a multi-variable digital analytics platform enables early detection of hydraulic failures in water-glycol systems.

The implemented solution allowed identification of a cavitation-induced pump failure within hours of its onset, enabling controlled intervention within the same shift. This approach prevented unplanned downtime, reduced risk to critical components, and improved system reliability.

The results confirm that digitalization and online monitoring represent a scalable and effective strategy for condition-based maintenance in critical hydraulic systems within the steel industry.

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COND2 ID 85 Optimizing the Life Cycle of Online Oil Sensors: Installation, Maintenance Strategies and Performance Management

Lessons Learned from Online Oil Contamination Monitoring

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Abstract — Contamination control is a primary driver of extended lubricant life and improved machine reliability. Drawing on more than a decade of field deployments across diverse industrial assets, this paper integrates periodic laboratory analysis with continuously operating online sensors to deliver practical, high-impact oil condition monitoring programmes. Emphasis is placed on online monitoring of particulate contamination and the reasons why online sensors characteristically report lower cleanliness codes than laboratory analysis on the same fluid. Three industrial case studies — a gearbox wear-to-failure experiment, a gas turbine with start-up-correlated fatigue particle generation, and a bearing degradation episode with online-guided maintenance intervention — demonstrate how continuous contamination data, combined with particle morphology analysis and complementary diagnostics, enables earlier fault detection, more targeted maintenance decisions, and measurable reliability improvement.

1. Introduction

Online particle monitoring of lubricating and hydraulic fluids has matured considerably over the past two decades, yet it remains underutilised in many industrial applications. Routine maintenance practice in the majority of facilities still relies on periodic offline oil sampling at intervals of one to six months — a frequency that is fundamentally inadequate for capturing the dynamics of contamination events that unfold over hours or days. This paper presents lessons drawn from more than a decade of continuous oil contamination monitoring deployments across several installations, with the aim of providing practical, evidence-based guidance for practitioners.

Three distinct questions motivate the work: (i) Why do online sensors consistently report lower cleanliness codes than laboratory analysis on the same machine, and what does this mean for interpretation? (ii) What diagnostic information does particle shape classification add beyond a particle count? (iii) How should continuous contamination data be integrated into a multiparameter maintenance decision process? The paper addresses each in turn, grounded in case study evidence.

2. Online Sensors Versus Laboratory Analysis: Sources of Discrepancy

Online sensors characteristically report ISO 4406 cleanliness codes one to three classes lower than laboratory measurements on the same machine. Several mechanisms contribute. Sampling artefacts — including contact of the sample with ambient air, contamination from the sample bottle, and insufficient purging of the sampling point — add particles to the laboratory sample that were not present in the circulating fluid. The temperature effect can be quantitatively significant in some applications: oil oxidation precursors are soluble at operating temperature but precipitate and agglomerate as the sample cools during transit to the laboratory, substantially inflating the particle count [1]. The online sensor, permanently installed in the warm flowing circuit, does not experience this precipitation. These differences are not a sensor deficiency — they confirm that the online sensor is measuring the true in-service condition.

Additional sources of uncertainty include inter-laboratory variability of two to three ISO 4406 classes even for identical samples measured under calibrated conditions, and the sensitivity of light extinction sensors to soft particles: entrained air bubbles and water droplets that are optically indistinguishable from solid debris. Understanding these mechanisms is a prerequisite for correct interpretation of online monitoring data.

3. Case Studies

3.1 Gearbox wear experiment: laser vs. optical sensor comparison

A controlled load-to-failure experiment on a spur gearbox provided simultaneous measurements from a laser light extinction sensor and a direct optical imaging sensor installed side-by-side in the same oil circuit. The gearbox was loaded through three phases and sensors tracked the ISO 4406 cleanliness code, showing a clear exponential rise in particle counts during Phase 2 transition to seizure. The optical imaging sensor additionally classified particle morphology: the dominance of platelike fatigue particles during Phase 1 and the transition to large irregular fragments in Phase 3 were identifiable from the shape distribution data, providing a mechanism signature that the count alone could not supply. The comparison confirmed that both sensors track the same contamination event, but that the optical sensor delivers substantially richer diagnostic information for the same measurement point.

3.2 Gas turbine: start-up-correlated fatigue particle generation

Online direct-imaging monitoring of a gas turbine lubrication system revealed a characteristic pattern of fatigue-morphology particles coinciding with machine start-up events and subsiding within minutes of reaching steady-state operating conditions. The start-up transient subjects tribological contacts to a brief period of high load with insufficient oil film thickness — a period of elevated wear rate that is invisible to any periodic sampling programme collecting samples during steady-state operation. Periodic laboratory sampling had not flagged any anomaly. The online finding corroborated an emerging vibration anomaly and led to a targeted gearbox inspection during the next planned outage, confirming early-stage gear flank pitting consistent with the observed particle morphology. The case illustrates the unique capability of online monitoring to capture transient wear events that periodic sampling systematically misses.

3.3 Bearing degradation: online-guided filtration and maintenance decision

Online monitoring of a large industrial bearing identified progressive contamination growth confirmed by visual filter inspection. Initial offline oil sampling returned marginally elevated but non-alarming cleanliness codes, underestimating the true particle burden due to the sampling artefacts described in Section 2. The online sensor, by contrast, showed a clear rising trend in large-particle counts consistent with incipient spalling. An offline filtration skid was deployed; the online sensor confirmed in real time that filtration was effectively removing particles and stabilising the cleanliness level. Subsequently, a second rising trend was detected, indicating that the rate of particle generation from the deteriorating bearing exceeded the filtration capacity. This finding, combined with vibration data, provided the basis for a scheduled maintenance shutdown rather than an unplanned failure. Particle morphology classification during the deterioration phase additionally indicated boundary-regime lubrication, informing a lubricant additive intervention that reduced bearing operating temperature and slowed the progression of damage until the planned outage.

4. Practical Implications for Contamination Monitoring Programmes

The case studies collectively illustrate four assumptions with direct practical relevance. First, the value of online monitoring derives primarily from its temporal resolution: the detection of transient events and the ability to observe the response to interventions in near-real time are capabilities that periodic sampling cannot replicate, regardless of how frequently samples are taken. Second, particle morphology classification — enabled by direct optical imaging sensors — adds a mechanistic dimension to contamination monitoring that transforms a cleanliness indicator into a wear mechanism indicator. Third, the combination of online contamination data with complementary signals (vibration, temperature, oil chemistry) consistently enables earlier and more specific diagnosis than any single parameter. Fourth, installation quality governs data integrity.

5. Conclusions

Online oil contamination monitoring, when correctly installed, interpreted, and integrated with complementary condition monitoring methods, delivers measurable reliability and maintenance efficiency benefits that periodic offline analysis cannot match. The systematic discrepancy between online and laboratory results reflects the elimination of sampling artefacts rather than sensor deficiency. Particle morphology classification enables earlier and more specific fault identification. The transition from periodic sampling to continuous monitoring represents not an incremental improvement but a qualitative change in the information available to the maintenance engineer, enabling genuinely condition-based maintenance decisions grounded in the real-time behaviour of the machine.

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Reducing Commissioning and Downtime Through Advanced Flushing and Lubrication System Cleaning Techniques

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Abstract

Proper lubrication system cleaning during commissioning and plant shutdowns is critical to ensure equipment reliability and minimize downtime. However, many industrial flushing procedures still rely on low-flow circulation methods that do not comply with current ASTM D6439 [1] best practices, resulting in poor contaminant removal and extended execution times.

This paper discusses the evolution of high-velocity flushing techniques and the importance of applying turbulent flow conditions, high-efficiency filtration, and proper contamination control. Drawing from operational experience in Latin America and Europe, the paper highlights how modern flushing methodologies improve commissioning schedules and startup reliability.

1. Introduction

The increasing complexity of modern turbomachinery and lubrication systems has transformed flushing into a critical activity during commissioning and maintenance turnarounds.

Historically, many flushing procedures were performed using low-flow oil circulation through the system's original pumps and filters. Although still common in countries such as Argentina, Mexico, Brazil, and Spain, these practices frequently provide poor cleaning efficiency and excessively long execution times.

Current international standards such as ASTM D6439 establish the importance of performing flushing operations under turbulent flow conditions using external high-flow pumping systems, high-efficiency filtration, and contamination monitoring techniques. Proper application of these methodologies significantly improves startup reliability and operational availability.

2. Development

2.1. Importance of Proper Flushing Practices

Studies performed by General Electric [2] identified that approximately 19% of turbomachinery failures were associated with lubrication-related problems, many occurring during startup after commissioning or major maintenance activities.

Therefore, flushing has evolved from a secondary maintenance activity into a strategic reliability process directly linked to operational continuity and asset availability.

2.2. Evolution of ASTM D6439

ASTM D6439 has become the principal international reference for lubrication system cleaning and flushing.

The original 1999 version focused mainly on mechanical contaminant removal using Reynolds numbers above 4,000. Current versions incorporate a much broader reliability approach, emphasizing:

- Reynolds numbers above 10,000
- High-efficiency absolute filtration
- Chemical contamination and varnish control
- MPC varnish detection methodologies
- Enhanced monitoring and documentation

This evolution reflects the growing understanding that effective flushing requires not only oil cleanliness, but also removal of contaminants adhered to internal piping and component surfaces.

2.3. Turbulent Flow and Cleaning Efficiency

One of the most critical aspects of effective flushing is achieving sufficient turbulent flow inside the lubrication system.

The Reynolds number can be expressed as:

$$Re = \frac{21200 \cdot Q}{v \cdot d}$$

Where:

- Q = Flow rate (L/min)
- v = Kinematic viscosity (cSt)
- d = Internal pipe diameter (mm)

High Reynolds numbers generate turbulent conditions capable of removing contaminants adhered to internal surfaces, while laminar flow only circulates oil without effectively cleaning the system.

Many industrial practices still confuse flushing with simple filtration. Kidney-loop filtration systems may improve oil cleanliness, but they cannot replace proper flushing because they do not remove contaminants attached to piping and internal surfaces.

2.4. Practical Reynolds Number Comparison

The following example compares three operating conditions for a lubrication system using ISO VG 32 oil and a 6-inch (152 mm) pipe diameter.

Conventional Practice

Many conventional flushing procedures still use the turbine lubrication pump with flow rates close to 200 L/min: This configuration reaches a Reynold number around 900, which is laminar flow conditions with very poor cleaning efficiency.

ASTM D6439 (1999)

To achieve Reynolds 4,000, a minimum flow rate of approximately 920 L/min is required.

Current Best Practice – ASTM D6439-23

To achieve Reynolds 10,000, a minimum flow rate of approximately 2,300 L/min is required.

This comparison clearly demonstrates the difference between conventional circulation practices and modern high-velocity flushing methodologies.



Fig 1 Evolution of Flushing Best Practices

3. Case Study

A practical example involved the commissioning flushing of a gas turbocompressor lubrication system for an EPC contractor in Italy. The client was searching for an alternative methodology after a previous similar project required more than 25 days using conventional flushing practices with the system's own pumps and filters.

For the new project, an advanced flushing methodology was implemented using:

- External high-flow pumping units for reaching Reynold number around 10,000.
- High-efficiency absolute filtration
- Continuous contamination monitoring

By applying these techniques according to ASTM D6439 best practices, flushing duration was reduced to only 14 days.

Beyond the direct reduction in commissioning time, the improved cleaning process also increased startup reliability by ensuring significantly higher initial cleanliness conditions inside the lubrication system.

5. Conclusions

High-velocity flushing techniques using external pumping systems, turbulent flow conditions, and high-efficiency filtration significantly improve contaminant removal, reduce commissioning delays, and increase startup reliability.

The evolution of ASTM D6439 reflects the growing importance of lubrication system cleanliness as a strategic reliability factor. Organizations that properly apply these practices can reduce startup failures, premature equipment damage, and operational downtime while improving overall asset availability and project execution efficiency.

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Lubrication Practices - Condition vs. Assumption Ultrasound-Guided, Condition-Based Greasing

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Introduction

Over the past several decades, the industry has undergone a significant shift from time-based to condition-based practices, wherever applicable. This transition has been driven **evidence provided by** CM technologies. This shift has led to a **Condition-Based mindset**—a culture where decisions are guided by measurable conditions rather than predefined schedules. In one word – DATA. **Lubrication is a critical and strategic task**, but still, mostly left out of the evidence framework.

Lubrication by Assumption

Fixed re-greasing intervals and quantity, are highly dependent on often unknown variables such as load and speed variations, environmental contamination, temperature fluctuations, bearing condition and wear, start/stop operating regime, imperfections such as misalignment, unbalance and others.

As a result, two common and equally damaging outcomes occur: Over-lubrication and Under-lubrication.

Both outcomes introduce unnecessary costs and reduce equipment reliability through increased friction, wear, lubricant degradation, increased energy consumption, and many other damaging effects.

Paradoxically, the most important question remains unanswered: **Is bearing better now?**

- We don't know if the bearing needs to be re-greased - **We still do it**
- We don't know how much grease - **We assume**
- We don't know what the outcome was - **We hope**

Instead of asking and answering proper questions, the outcome of the re-greasing task is:

A checkmark 

In the 21st century, when data powers even more than we think, saying that there is no data should be considered a blasphemy.

But there is an interesting aspect that might explain this paradox: Time-based lubrication is a fantastic excuse! Whatever happens ... "It wasn't me, I just followed the schedule." Sad, but true.

Ultrasound Technology

Modern Ultrasound, being highly sensitive to friction changes, identifies the exact moment when lubrication is required, guides grease application in real time, and confirms the outcome

Ultrasound-Guided Approach to Lubrication

A practical and effective approach consists of three essential steps:

As-Found Condition Assessment – Is grease needed?

Real-Time Guided Replenishment – How much?

Post-Lubrication Confirmation – Is it better now?

Controlled and verifiable process, as shown in screenshots below:

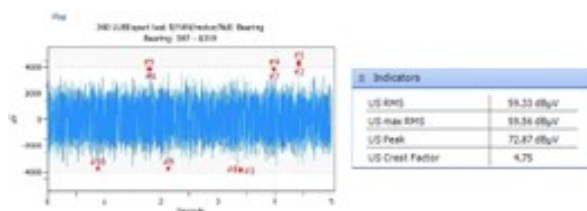


Fig. 1: As-Found condition
Alarm triggered – re-greasing needed

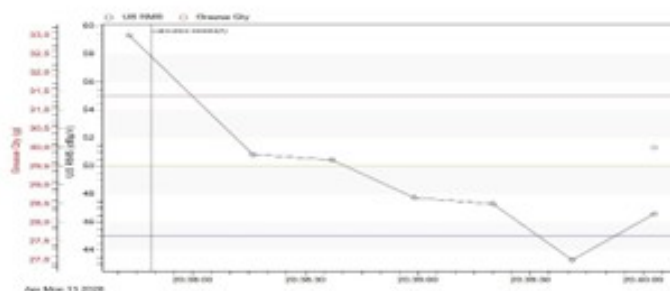


Fig. 2: Step-by-Step process
Guided real-time, onboard the instrument

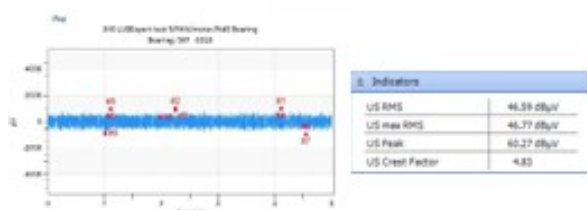


Fig 3: Outcome condition
Successful re-greasing confirmed

Proven Impact in Industry

Organizations that adopted ultrasound-guided lubrication consistently report reduced bearing failures, improved asset reliability, increased consistency in maintenance execution, and decreased energy usage.

Perhaps most importantly, lubrication becomes **repeatable, measurable, and auditable**

From Manual Practice to Automation

As technology continues to evolve, ultrasound is no longer limited to manual processes due to modern systems now capable of integrating ultrasound sensors into automated lubrication systems, using algorithms to trigger lubrication events, and adjusting grease delivery based on real-time conditions

Conclusion

There is no debate in modern maintenance: **condition-based practices outperform time-based assumptions** in all cases where the failure mode is not time-dependent. Given the critical importance of lubrication, continuing to rely on estimation rather than measurement is no longer justified.

Ultrasound-guided lubrication provides a practical and proven way to:

- Align lubrication with the Condition Monitoring mindset
- Eliminate guesswork
- Improve reliability and efficiency

The industry embraced condition-based maintenance long ago
Greasing must evolve — from assumption to evidence/data.

KN6 Sophia Bastidas VIRTUAL VEHICLE

Investigating combustion engine wear during running-in and an overview of journal bearing performance prediction using a hybrid model approach.

COND 7 ID I Care Vibration-Guided Lubrication for Maintenance Efficiency

Integrating Fluid Analysis with CMMS & Business Systems + Case Studies

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Abstract

Integration Possibilities

Just like your phone, computer or tablet; Engines, Hydraulics, Gearboxes, and other types of industrial equipment are now connected devices. This means that the integration possibilities are endless in relation to the Industrial Internet of Things (IIOT). However, this does not mean that this is common practice in many companies' maintenance and reliability programs. Many companies and Equipment Manufacturers continue to manage and operate data in individual silos which is both inefficient and lacks the prescriptive nature that integrated data can provide to the user.

1. Introduction

Depending on your industry, how you import, measure, store, and interpret data will differ according to the data you are gathering. Mining Excavators will use Telematics to measure certain parameters related to the equipment and operating environment. An industrial gearbox may be monitored by several Condition Monitoring techniques, including Vibration, Thermography, Ultrasound as well as Fluid Analysis. With all of this data stored in either an Off-the-shelf, or bespoke CMMS system, alongside additional data from sensors or management data. Thirdly, many organisations manage multiple data streams in an ERP type system. Regardless of what industry or data management system you use, the connections between these data streams and your Fluid Analysis results are inherently possible with the technologies and services available today. Integrating as many data points as possible will improve operational efficiency, lower Total Cost of Ownership (TCO) and increase Equipment Reliability.

2. Understanding the value

Most users will not understand the true value of data connectivity until they see the benefit for themselves. Many companies operate in such a way that, 'it has always been like this' – and are used to working in multiple systems and manually cross-checking multiple types of data. However, the true value of integrating data can be seen when all data is viewed together, in the same system, on the same screen, making decisions quicker and more accurate based on the information available. Take an example of an Oil Analysis report showing Fuel Dilution, historically the laboratory would suggest checking several aspects of the Engine or operation to confirm the issue, but if this data is connected to integrated systems, the Telematic data may show that Injector No.2 is faulty, leading the operator to accurately understand the Root Cause of the fuel dilution in the Engine. This results in a more prescriptive interpretation of the sample data and a more accurate recommendation to the user on the reason for issue.

3. Capabilities

Once the connection is made, the possibilities of utilising the data are endless. The data can be used in different ways depending on the individual requirements of the users. As well as integrating the results from Fluid Analysis Samples, the connections can also be used for

- Sample Submission
- Manage Equipment
- Generate Maintenance Work Orders
- Provide 'real-time' information to the lab
- Set Notifications on certain results
- Create Sampling Schedules

5. Conclusions

Many global companies are now benefiting from these integration capabilities where lower operating costs, improved reliability and reduced maintenance tasks are now commonplace in reaching the desired state. Incorporating continuous improvement, improved training and visibility of all data sets allow companies to better understand problems, resolve issues more efficiently and keep equipment running longer.

Trends in Used Oil Analysis: Insights from MOL-LUB's Diagnostic Laboratory Over the Last Decade

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Used oil analysis is a widely applied condition monitoring method supporting early fault detection and optimized maintenance decision-making. MOL-LUB Ltd. has operated a dedicated used oil diagnostic laboratory since 1997 and has been a member of the WearCheck International network for more than two decades.

This paper summarizes key trends observed in the period between 2016 and 2025 based on laboratory data from five Central and Eastern European countries. The analysis focuses on the evolution of sampling practices, dominant lubrication system types, and maintenance-related trends linked to digitalization and predictive maintenance. The findings confirm that lubricant diagnostics has become an essential element of modern maintenance strategies aimed at improving equipment reliability and reducing operational risks.

1. Introduction

Modern industrial maintenance strategies increasingly rely on condition monitoring methods capable of detecting early signs of equipment degradation. In this context, used oil analysis provides essential information on machine wear, contamination, additive depletion and lubricant ageing, thereby supporting timely and well-founded maintenance decisions.

Besides its standalone diagnostic value, oil analysis complements other monitoring techniques by offering direct insight into the condition of both the lubricant and mechanical components.

The evaluation of laboratory data collected between 2016 and 2025 allows the identification of changes in sampling practices, dominant lubrication systems and broader industrial maintenance trends. The objective of this paper is to demonstrate how long-term oil diagnostic data reflect the increasing maturity of maintenance practices and support the transition toward predictive maintenance approaches in Central and Eastern Europe.

2. Evolution of Sampling Practices (2016–2025)

Most samples originate from Hungary, while Slovakia and Romania show a gradual increase in sample numbers over the years. In contrast, a decrease can be observed in Ukraine after 2022, which reflects regional external factors rather than changes in maintenance philosophy. Overall, the results confirm the expanding regional role of oil diagnostics (Fig. 1).

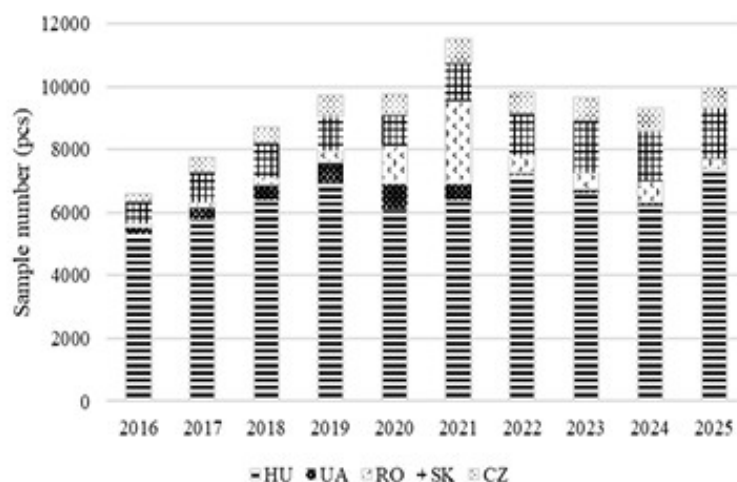


Fig. 1. Evolution of annual sample numbers between 2016 and 2025

It is also noteworthy that a relatively small number of key industrial partners generates the majority of samples. This indicates strong integration of oil analysis into maintenance practices among large asset-intensive users, where systematic sampling is part of standardized maintenance routines.

3. Distribution of System Types

An analysis of sample distribution by lubrication system type shows that engine oils and hydraulic oils account for approximately 56% of the total sample volume (Fig. 2). These systems are typically associated with high operational criticality and strict reliability requirements.

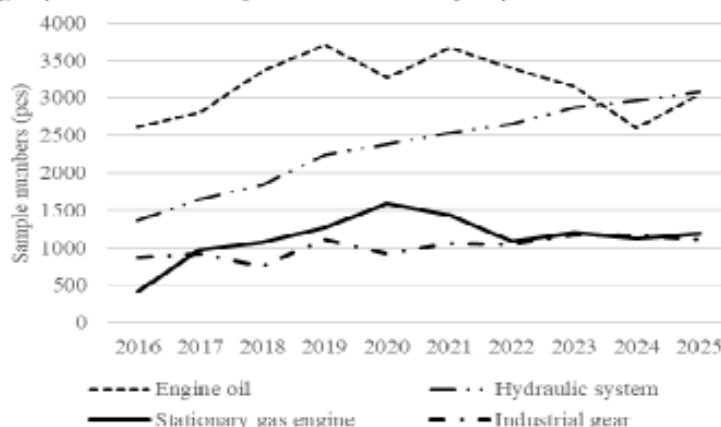


Fig. 2. Distribution of samples by main lubrication system types

The significant share of hydraulic oil analyses is partly driven by increasingly stringent cleanliness requirements defined by equipment manufacturers. Maintaining appropriate oil cleanliness levels is directly linked to extended component lifetime and improved system reliability. Industrial gear oils and gas engine lubricants also represent a considerable portion of the analysed samples, reflecting their widespread application in power generation and heavy industry.

Industry-specific evaluations indicate increasing consistency in sampling intervals and procedures, which points to the growing maturity of maintenance processes and higher acceptance of oil diagnostics as a decision-support tool.

4. Maintenance Trends and Digitalization

The evaluated dataset highlights several consistent maintenance-related trends observed over the investigated period:

- increasing sampling frequency,
- intensified monitoring of critical equipment,
- broader application of trend-based evaluation methods,
- expansion of predictive maintenance approaches,
- growing use of digital data processing tools.

Digital tools, online sensors and automated evaluation methods enable faster diagnostics and support Remaining Useful Life (RUL) estimation. Integration of oil analysis with other condition monitoring techniques improves reliability of maintenance decisions.

5. Conclusions

The evaluation of MOL-LUB laboratory data from 2016 to 2025 confirms the growing role of used oil analysis in industrial maintenance. The steady increase in sample numbers and the broadening of industrial applications demonstrate that lubricant diagnostics has become a key element of predictive maintenance concepts.

Long-term oil analysis trends reflect the maturity of maintenance practices and provide measurable support for reliability improvement and risk reduction. Further development is expected in the fields of AI-supported diagnostics and integrated condition monitoring systems, which will further strengthen the role of oil analysis in improving equipment reliability and maintenance efficiency.

Modern grease analysis in industry

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Modern grease analysis provides new opportunities to detect early signs of wear, monitor lubricant condition, and identify contamination. This work focuses on grease diagnostics, sampling challenges (ASTM D7718), and the Grease Thief Analyzer GTA (ASTM D7918), with additional reference to oil analysis. The GTA enables dynamic consistency testing, offering more accurate insight into grease behaviour in bearings compared to static methods such as cone penetration. It also allows assessment of particle content and identification of their origin, supporting evaluation of grease “cleanliness class.” The technology, already applied in the wind power sector, has broader industrial potential demonstrated through case studies. Sampling standards and methods for obtaining representative grease samples are also discussed. With only two grams of material, comprehensive diagnostic testing can be performed.

Introduction

Grease-lubricated components are widely used across industry, yet grease diagnostics is still less standardized and less exploited than oil analysis. Modern tools now enable more advanced evaluation of grease condition, including contamination, wear particles, and consistency changes during operation. Standards such as ASTM D7718 support representative sampling, while ASTM D7918 defines procedures for quantitative analysis using the Grease Thief Analyzer (GTA). This work presents several practical case studies demonstrating how dynamic consistency testing, particle classification, and comparative evaluation of fresh and used greases can enhance maintenance strategies. The aim is to illustrate real-world applications of modern grease testing methods and highlight their relevance for condition-based maintenance and Industry 4.0 systems.

Main Text

Comparison of Static and Dynamic Consistency Measurements

A key part of this study compares traditional NLGI consistency grades with dynamic measurements obtained using the Grease Thief Analyzer. The introductory case includes a summary table of fresh greases, showing sample identifiers, coded grease names, their NLGI grades, and GTS Load values measured across three trials. These results illustrate that while NLGI Grade provides a static classification, the GTS Load more accurately captures differences in flow behaviour under shear. Comparison graphs further highlight that greases with similar NLGI classifications may behave differently when evaluated dynamically, demonstrating the added diagnostic value of GTA-based testing.

Evaluation of Greases from Real Operating Conditions

The presentation also includes a second dataset consisting of greases collected from machinery under real operating conditions. Here, NLGI grades of fresh greases are compared with GTS Index results obtained from used samples. GTS Index can be established for fresh grease and subsequently used as a reference point for assessing degradation during operation. These comparisons reveal how consistency shifts due to mechanical work, contamination, or over-extended relubrication intervals.

Consistency Changes in Industrial Robots – Case Study

Another case study focuses on consistency changes in industrial robots. Grease samples taken from multiple robot joints operating for different periods were analysed for GTS Index and GTS Loads. A summary table and trend graphs show how consistency decreases or stabilizes depending on operating hours and relubrication history. This dataset demonstrates the potential to monitor grease condition over time and evaluate whether relubrication intervals are appropriate or require adjustment. Photographic documentation of sampling points also highlights challenges related to access and sample cleanliness.

General Overview and Multi-Industry Correlation

The final section provides a broader comparison of greases from a range of machines, not limited to robots. Results illustrate correlations between particle types, iron content, FerroQ values, and overall contamination levels. Several charts present cross-industry patterns, including data from wind turbines. This overview confirms the broad applicability of GTA analysis and supports the development of predictive maintenance models, including AI-based approaches, by integrating consistency trends, contamination profiles, and component wear signatures.

Conclusions

Modern grease diagnostics offers valuable insights into lubrication performance that cannot be obtained through static methods alone. Dynamic consistency measurements from the GTA highlight meaningful differences between greases of similar NLGI grades and reveal how consistency evolves during equipment operation. Case studies demonstrate that fresh grease may contain significant levels of contamination and that grease condition can be effectively monitored in systems such as industrial robots. Proper sampling practices and standardized procedures ensure reliable results even with small sample quantities. Overall, integrating grease analysis into maintenance routines enhances the accuracy of condition monitoring, supports optimization of relubrication intervals, and contributes to predictive maintenance strategies aligned with Industry 4.0.

Lubrication Management in CEE II

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Lubrication management is one of the most important but often overlooked parts of keeping machines running smoothly in industry. Drawing on ten years of Smart Lubrication management workshops, where almost one hundred industrial actors in Central and Eastern Europe mainly from Hungary took part in our self-assessments, this paper looks at how mature different industrial sectors are in their approach to lubrication. The results show that while lubricant consolidation and oil diagnostic usually reach average or good levels, oil sampling, storage and handling, and developing skills are still the biggest challenges. These issues hold back how effective lubrication management can be. We adhere to the ICML 55 standards, which provide a clear framework for addressing these weaknesses and establishing a more sustainable and reliable lubrication management system. To better support our customers, we plan to introduce a lubrication management software developed in accordance with the ICML standard.

1. Introduction

Although the direct cost of lubricants is relatively low, inadequate lubrication leads to significant losses through unexpected downtime, premature failures, energy inefficiency, and reduced asset life. Therefore, the cost of lubricants must be clearly distinguished from the cost of lubrication. Maximum efficiency is only achievable if lubrication is planned, controlled, and continuously improvable process.

2. Systemic Framework – ICML 55

The ICML 55 standards define lubrication management as an integral part of asset management, aligned with ISO 55001. Lubrication decisions are interpreted on multiple levels, creating the structural basis for data-driven analysis and AI-based decision support. [1, 2]

3. Methodology – Self-Assessments

The self-assessment evaluates lubrication management maturity across six dimensions: consolidation (CO), storage and handling (ST), contamination control (CC), oil diagnostics (OD), oil sampling (OS), and training (TR). Assessments conducted between 2016 and 2025 enable cross-industry comparison and trend analysis. It should be noted that the questionnaire used does not aim for comprehensive coverage of the ICML 55 standard; instead, it examines the current state with fewer but well-chosen questions. Nevertheless, it serves as an effective basis for the situational analysis and suitable for identifying development directions. The percentage values used in the assessment indicate the current state compared to the best practices recognizable.

4. Results and Industry Patterns

The maturity of industrial lubrication management varies widely across sectors, as reflected in a decade of self-assessment data (Table 1). Refineries lead with high scores in consolidation and diagnostics but need better sampling and fluid handling. The energy sector excels in diagnostics but falls short in training. Chemical sector performs well in diagnostics and contamination control, yet weak fluid management obstructs progress. Automotive shows balance but remains weak in sampling and training, while plastics/rubber maintain discipline but lack routine diagnostics and training. General manufacturing has the lowest maturity, with isolated improvements and incomplete PDCA cycles. Across all industries, oil sampling and training/competence development remain the weakest links. Without these, even advanced diagnostics bring only limited accuracy and knowledge retention. Industry-wide progress depends on standardizing sampling points and procedures, strengthening lubricant handling standards, and implementing role-based, trackable training systems. These standardized methods and procedures provide the foundation of sustainability and basis of digitalization and

AI-supported higher level decision-making. In summary, the opportunities offered by available technology are often not utilized due to the lack of fundamental processes and competencies. The greatest value of self-assessment lies in highlighting critical development nodes. Without addressing these, robust and reproducible system-level progress cannot be realized.

Sector	CO	SH	CC	OD	OS	TR	Overall Avg.
Plastics	65%	47%	64%	44%	31%	26%	46%
Energy	55%	51%	55%	72%	50%	29%	52%
Manufacturing	53%	43%	47%	24%	18%	25%	35%
Automotive	60%	49%	52%	60%	38%	28%	48%
Chemical	46%	31%	59%	76%	51%	41%	51%
Refining	87%	52%	57%	87%	46%	49%	63%
10-years overall average	57%	45%	54%	56%	34%	32%	46%

Table 1. Self-Assessment Results by Industry Sector

5. Obstacles to Advancement

Advancing lubrication management faces barriers rooted in organizational, procedural, and information management deficiencies, not simply technical limitations. Lubrication tasks are often performed by different organizations within the company, including maintenance, operations, warehousing, purchasing, and external service providers, but managing the activities as an integrated unit is rarely found. As a result, lubrication remains an execution task rather than an organized system. In the absence of SOPs, the basic conditions for the introduction of best practices and the PDCA system that promotes sustainable development are lacking. Most CMMS platforms do not include lubrication-related procedures, leaving valuable machine condition data isolated, if it exists at all. The digital maturity gap is structural: relevant data exists but is not linked or managed consistently. The solution is a digital Lubrication Management System (LMS) that unifies SOPs, oil sampling and diagnostics, roles and responsibilities, simplifies task delegation and reporting, integrated with other software, e.g. CMMS, SAP. This approach enables transparent, developable lubrication management; without it, system-level progress remain limited.

6. Digitalization and AI

The application of artificial intelligence has become an unavoidable topic among lubrication experts. AI serves as a decision support tool, enabling digital instructions, automated checklists, diagnostic interpretation, and predictive analysis. It can consider OEM data, load, and environmental factors when recommending lubricants. AI speeds up feedback and supports the “Check” and “Act” steps of the PDCA cycle, but does not replace professional expertise. Its value is realized only in systems based on consistent data collection and expert supervision.

7. Conclusions

Ten years of industry experience prove that system-level thinking is essential for progress in lubrication management. Consolidation and diagnostics alone are insufficient if sampling, storage, and training are neglected. The ICML 55 standard provides a strong basis for process improvement and future AI applications. Coordinated development of technology, expertise, and company culture is vital for sustainable progress.

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COND12 ID 91 Implementing online sensors and cleanliness on a mining ball mill

KN7 Peter Dufresne EPT Clean Oil

LUBR13 ID 39 Substitution principle; Friends or Foe?

Sustainable Solutions in Metal cleaning Processes

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Abstract

FUCHS Group has consistently been at the forefront of developing sustainable solutions in metal cleaning processes. This article explores the company's innovative approaches, with a focus on low-temperature cleaners specifically for aluminium, multi-metal and ferrous materials. These solutions address the challenges of microbiological contamination, foamability, corrosion protection, and cleaning efficiency, while saving energy and water, reducing waste, and lowering operating temperatures.

1. Introduction

Metal cleaning is a critical process in various industries, including automotive, aerospace, and manufacturing. Traditional cleaning methods often involve harsh chemicals and high energy consumption, leading to environmental and economic concerns. Washing at lower temperatures in the metalworking industry can have a significant impact on the Product Carbon Footprint (PCF). Lower temperature washing generally reduces energy consumption, which in turn decreases greenhouse gas emissions associated with heating processes. This reduction in energy use can lead to a lower overall PCF for metal products, as energy-intensive processes are a major contributor to carbon emissions in the industry. Additionally, washing at lower temperatures can extend the lifespan of washing equipment and reduce maintenance needs, further contributing to a lower environmental impact. However, it is important to balance these benefits against the effectiveness of the washing process, as lower temperatures might not always achieve the desired level of cleanliness, potentially affecting product quality (e.g. poorer corrosion protection).

2. Challenges and Solutions:

Transitioning to lower-temperature cleaning in the metalworking industry can be highly beneficial, but it requires careful planning and implementation.

With a focus on advanced degreasers, cleaning at lower temperatures in the metalworking industry presents several challenges that need to be addressed to ensure efficiency and effectiveness. Some of the key challenges are:

1.Reduced Emulsification Power, 2.Increased Foam Levels, 3.Lower Solubility of Surfactants:..Reduced Corrosion protection. 4. Microbial Control. 5.Compatibility with Existing Equipment. 6 Operational Changes Addressing these challenges involves a combination of advanced chemical formulations, effective foam management, and strategic operational adjustments.

The new RENOCLEAN product range overcome the usual issues of low-temperature cleaning mentioned.

1. Microbiological Contamination: The development of new formulations that include special amines and acids to increase stability and prevent microbiological growth.

2. Foamability: Incorporating new surfactant packages that improve wetting and rinsing while controlling foam levels. In addition, by improving the demulsification properties of the products, it is possible to take advantage of the defoaming effect of the removed oil itself without the need to add a defoamer as a tank treatment.

3. Corrosion Protection: Balancing detergency and demulsification to extend bath life and enhance corrosion protection, as seen with the chloride-free, oil rejection additive found in RENOCLEAN MSO 3008, RENOCLEAN MSO 3006 and RENOCLEAN FSO 4008.

4. Cleaning Efficiency: Using advanced wetting agents and optimizing the synergy between different chemical components to improve overall cleaning performance.

3. A Synergistic and Innovative Approach to Low-Temperature Challenges

The most important aspects studied in the lab are related to comparing traditional cleaner technology to new low-temperature cleaner technology, where changes introduced show a better aspect of the fluids in service (oil content on the top and fresh water on the bottom, which allows for a better disposal of oil and

water reuse). Other important correlations studied are the relations between the superficial tension of the cleaning bath with the foamability of the bath in order to establish the optimum balance, as shown in Figure 1. And the correlation on the type of tensioactive on the study of corrosion protection performance in different substrates after cleaning at different temperatures.

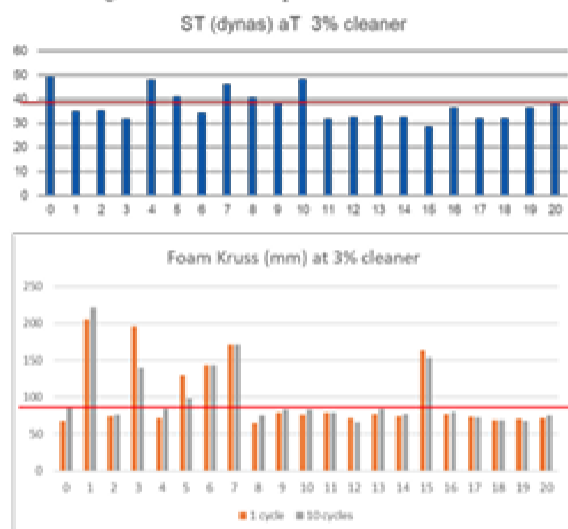


Figure 1

4. Innovative Metal Cleaning Solutions: Automotive industry customer cases

Case 1. A corporate group in northern Spain specializing in spray cleaning of steel and multi-metal parts successfully implemented RENOCLEAN MSO 3008 in their operations. This solution enabled a significant reduction in operating temperature, lowering it from 65 °C to 35 °C. The resulting improvement in energy efficiency translated into annual savings of approximately €33,000, directly enhancing the plant's productivity. From a quality and environmental standpoint, the introduction of RENOCLEAN MSO 3008 led to a notable extension of bath life, reducing the frequency of bath replacement. Furthermore, no complaints were reported regarding cleaning performance throughout the usage period, indicating a stable and reliable cleaning process.

Operationally, the adoption of RENOCLEAN MSO 3008 resulted in a streamlined inventory and a reduction in associated maintenance tasks. This optimization contributed an additional €21,000 in annual savings. Altogether, the company achieved a total reduction in operating costs of nearly €500,000 per year, positioning RENOCLEAN MSO 3008 as a highly efficient and sustainable solution for industrial cleaning processes in demanding environments.

Case 2. A company specializing in the stamping of aluminium and hot-galvanized steel, adopted RENOCLEAN MSO 3006 for its spray cleaning processes, traditionally carried out at 65 °C. The implementation of this solution enabled a substantial reduction in energy consumption, allowing effective cleaning at just 35 °C and resulting in energy savings of approximately 50%. This transition not only improved process efficiency but also contributed significantly to the company's sustainability goals.

The impact on quality and environmental performance was equally notable. The bath life was extended dramatically—from one month to nine months—reducing the frequency of bath changes and associated downtime. Additionally, the company experienced a 70% reduction in cleaning-related complaints, reflecting a marked improvement in cleaning consistency and reliability. Waste generation was also reduced by 75%, further supporting the company's environmental objectives.

Operationally, the use of RENOCLEAN MSO 3006 led to an 80% reduction in the number of stock items required, decreasing from three to one, and simplifying the overall management of cleaning operations.

5. Conclusions

FUCHS Group's commitment to sustainability is reflected in its comprehensive approach to reducing CO2 emissions and promoting circular economy practices. By developing products such as RENOCLEAN MSO 3006, RENOCLEAN MSO 3006 RENOCLEAN FSO 4008, FUCHS not only improves cleaning efficiency but also contributes to significant environmental benefits, including lower energy and water consumption and less waste production and reducing operational costs.

LUBR15 ID 72 Development of green lubricants for chasis components stamping

Ammonia as a Fuel for Marine Engines – Lubricating Oil Monitoring and Chemical Analysis of Fuel-Lubricating Oil Interactions

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Abstract The use of ammonia (NH_3) as a carbon-free fuel is becoming increasingly important in the context of sustainable propulsion systems, particularly in the shipping sector. Current studies on this topic focus primarily on combustion process development and exhaust aftertreatment. The influence of NH_3 on engine lubricating oil has been little researched and described to date. The influence of NH_3 on engine lubricating oil was investigated in laboratory tests. Oil aging was monitored using conventional methods, such as density, viscosity, TAN, TBN, water content, oxidation, and nitration, and aging mechanisms were also determined using a high-resolution mass spectrometry (HRMS) method. Concurrently, lubricating oil monitoring was performed on a test bench engine operating on NH_3 .

1. Introduction

With 706.32 Mt of CO_2 in 2023, global shipping accounts for about 3% of global CO_2 emissions. Against this backdrop, the International Maritime Organization (IMO) has set a goal of making shipping climate-neutral by 2050.^[1] Synthetic fuels produced using renewable energy (Power-to-X) are receiving particular attention in this context. NH_3 is considered as a carbon-free hydrogen carrier and future maritime fuel that can be produced, handled, and transported in large quantities. NH_3 can be used in spark-ignited (SI) engines with a spark plug or pilot-ignited with diesel as the ignition fuel; however, it differs significantly from conventional hydrocarbon fuels in terms of its ignition and combustion properties as well as emission levels. For efficient use in existing internal combustion engines, the fuel's compatibility with the lubricant is crucial. Lubrication is key to high mechanical efficiency, engine longevity, and moderate fuel consumption. Little is currently known about the influence of NH_3 on engine lubricating oils. Nevertheless, lubricant degradation processes have already been investigated in other contexts, including compressors utilizing NH_3 as a refrigerant. Wootton and Livingstone reported on oil analyses of an ammonia compressor, which revealed increased deposit formation and severe oil degradation. Analysis of the deposits revealed mainly primary amides, carboxylic acids, and ammonium salts. They hypothesized that the oxidation of the oil in the presence of water leads to the formation of carboxylic acids, which react further with NH_3 to generate primary amides. The formation of carboxylic acids caused changes in the lubricant, resulting in performance losses and damage to the equipment in use.^[2] This study provides further insights into the effects of NH_3 on various engine lubricating oils. In addition, the methodology used to investigate the lubricants is described.

2. Materials and Methods

Five different base oils from API Groups I–V, which are commonly used in engine lubricants, were selected as test oils. The selection consisted of mineral oils, a polyalphaolefin oil, and a synthetic ester oil. For a basic characterization of the lubricating oils, the total acid number (TAN), total base number (TBN), water content, kinematic viscosity at 40°C and 100°C, density, and elemental contents were determined. The potential NH_3 reactivity of the engine oils was investigated under practical conditions in an internal combustion engine. For this purpose, 50 mL of oil was placed in an autoclave and then gassed with a 0.2 bar NH_3 flow under stirring for 30 min at 120°C. In a further series of experiments, 50 mL of oil was placed in the autoclave and mixed with 3 vol.-% ultrapure water. In this setup, the autoclave was filled with 1 bar of NH_3 and also heated at 120°C for 30 min under stirring. Quantitative detection of NH_3 in the lubricating oil was performed using acid extraction (hydrochloric acid solution) and ion chromatography. Artificial aging tests were conducted in a Rancimat at an air flow rate of 25 L/h and 120°C for 120 h. Direct infusion electrospray ionization Fourier transform ion cyclotron resonance mass spectrometry (ESI-(+)-FT-ICR MS) was used to identify aging products. Accompanying oil analyses were conducted on a medium-duty single-cylinder research engine with a 110 mm bore and a rated power of 45 kW, using an NH_3 -diesel dual-fuel combustion process with NH_3 intake manifold injection and diesel direct injection. In this process, varying NH_3 energy fractions between 65% and 95% were achieved. A 10W40 LOW SAPS DQC IV-18 LA lubricating oil was used, which had been in service for approximately 375 operating hours in NH_3 -diesel operation.

3. Results and Discussion

As shown in Figure 1a, the synthetic ester oil and the API Group III lubricating oil, in particular, exhibit higher NH_3 uptake compared to Groups I, II, and IV. The water content of the ester oil decreased after gas exposure, while all other base oils remained constant at a negligibly low level. Density, viscosity, IR oxidation & nitration, and TAN showed no significant changes after NH_3 exposure. The addition of water in the second series of measurements led in some cases to emulsion formation and, as expected, to increased NH_3 solubility, particularly in oils of API Groups I and V. Overall, NH_3 solubility appears to correlate with oil polarity. Water solubility was highest in API Group I mineral oils (~25,000 ppm), followed by API Group V (~6,800 ppm), and significantly lower in API Group II oils (~140 ppm). Therefore, with regard to minimizing water-induced oxidation, cavitation, and corrosion problems, base oils of API Groups III and IV appear suitable, as they absorb virtually no water.

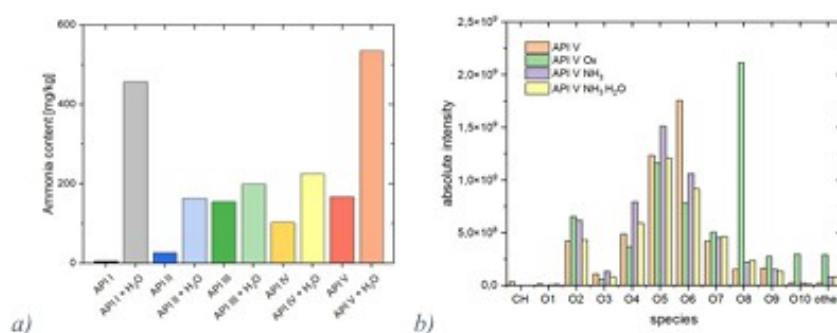


Fig. 1: a) NH_3 content of the base oils subjected to the treatment. b) Change in the distribution of the ester oils compound classes.

As expected, no polar compounds were detected in the unaged base oils of API Groups II, III, and IV using ESI(-)-FT-ICR MS. Furthermore, no effect of NH_3 on lubricant degradation or signs of reactions with the unaged base oils were observed. In future studies, the aged base oils will be exposed to NH_3 and their reactivity will be systematically investigated. Increased reactivity is expected. The ester oil showed no clear reaction to the NH_3 exposure. The presence of water also appears to have no significant influence. In contrast, oxidative aging leads to detectable oxidation products, as evidenced by an increase in the classes of higher oxygen-containing compounds (see Fig. 1b). The accompanying lubricating oil monitoring of the NH_3 /diesel research engine showed a nearly linear increase in copper content over the operating time, with NH_4^+ concentrations between 50 and 300 mg/L. This indicates a corrosive wear pattern. As previously postulated by Obrecht et al.^[3], NH_3 attacks copper through complex formation. Due to the combustion process, a high level of diesel fuel carryover into the lubricating oil and a corresponding decrease in viscosity were observed. All other parameters were within the range typically observed for diesel fuels. Under the described test conditions, no elevated water content was observed in the lubricating oil.

4. Conclusions

Laboratory tests were conducted to determine the solubility of NH_3 in various base oils, with and without added water, and NH_3 concentrations ranging from 6 to 535 mg/L were measured. Subsequently, attempts were made to detect reaction products between NH_3 and the lubricating oil using ESI(-)-FT-ICR MS. Lubricating oil monitoring was performed on a single-cylinder test engine in NH_3 -diesel dual-fuel operation. With the exception of an increasing Cu content, no notable changes in the oil were detected.

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LUBR17 ID 82 Challenges for The Grease Analysis and Sampling for Wind Turbines

LUBR18 ID 74 Aluminium hot stamping novel lubricant

Sustainability in Lubricants Development

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Abstract

Organizations aiming for climate neutrality increasingly rely on Research and Development (R&D) to drive sustainable innovation across the full product lifecycle. This presentation introduces a structured framework to help R&D teams integrate environmental considerations into formulation design, material selection, production processes, and use-phase performance. The approach is built on multi-criteria assessment covering renewable and recycled raw materials, hazard reduction, product carbon footprint, biodegradability, recyclability, energy efficiency, and manufacturing improvements. Importantly, any improvement in any criterion is considered a meaningful sustainability contribution, fostering broad engagement across R&D teams.

1. Introduction

Currently, member states of the EU have the challenge to comply with Regulation (EU) 2021/1119 and become Climate neutral (or net zero) by 2050. With this ambitious target as a framework, entities are preparing themselves for the future. As the definition of net zero means: "Net greenhouse gas (GHG) emissions = 0 at the level of an economy (EU as a whole), we have all started to translate our targets in relation to PCF, so it is common to link directly the concept of sustainability to the PCF and reduce it to a number.

Even if this is not completely wrong, sustainability is a wider concept that goes beyond emissions. Just having a look at the 17 SDG (sustainable Development Goals) one can understand that sustainability is about emissions, but also, about the use of natural resources, compatibility with living beings, use of energy and waste management, to mention a few. And the truth is that energy consumption for example, has a huge contribution in the PCF calculated for RM and products.

Chemical companies are not exempt from contributing to the sustainability goals and it is necessary to start work now. And if we think of chemical products, it is necessary to go to the beginning which is development phase. The Group FUCHS has created a framework that allows to create sustainable products from the beginning and with a 360° scope. This is what this paper is about: a framework that helps to develop sustainable lubricants.

2. Main aspects to take into consideration

When developing a new product, there are many things happening at the very beginning such as defining the performance of the product, selecting the materials to use and how to mix them or what will be the final destination of the product after use. With all of this in mind we can select a few points:

- Origin of raw materials (RM)
- Compatibility of RM with living beings and impact in the environment.
- PCF and biodegradability.
- Manufacturing process.
- Product consumption in use.
- Energy efficiency in use.
- Life cycle of the product.

3.

3.1 Raw Materials

When developing new products, it is important to consider every aspect of a RM with regard to sustainability. It is necessary to find renewable raw materials or recycled. Vegetable oils or re-refined oils are good examples of this. The different origin of the RM will have an impact in several characteristics of the material, such as PCF, biodegradability or hazards. Also interesting to check is the possibility of using certified RM (ECOLABEL, Blue Angel, OECD B01, RTSPO...)

These characteristics of the selected RM will have a direct influence on the equivalent characteristics of the finished product. In some particular segments of the market and for specific customers, it is important to have biodegradable, recyclable or certified products. Additionally, every day we have a growing demand of lower PCF products.

3.2 Manufacturing process

Since the calculation of PCF is very important in the concept of sustainability, it is important to optimize all aspects related to a product to reduce the footprint and one of the most impacting is energy. It is necessary to look for ways to prepare the product trying to stir the minimum time with the best possible result. Changes in the blending units can lead to more efficient mixing. The selection of RM that do not need to be heated for mixing is also impacting in the energy efficiency of the manufacturing process. A product that is blended at room temperature, will always be more sustainable than a product that needs heating, even if it is only heating at 40°C.

The manufacturing process includes washing steps of the blender, so the possibility to organize the production in a way that does not imply water (or solvent!!) consumption, which generates a new waste, is a high impact also in the sustainability of the product. Re-using the washing water or oil into the production of other products is also a contribution to sustainability as a resource recovery and less waste generation.

3.3 In use aspects

The focus of users of lubricants regarding the use phase is usually performance and compatibility with workers.

Performance is often just valued in terms of “works/ doesn’t work” and there is much more to see beyond that. It is important to measure if the product is providing more efficiency in terms of energy consumption (for example, if the product provides better lubrication it may be possible to reduce the operation cycle and thus electricity consumption) It can also happen that the product allows longer tool (or components) life which impacts the economic cost of the global operation.

And, last but not least, more sustainable products may be designed to work at lower concentrations or with extended life. This would impact the product consumption reducing residues at the end of the cycle.

3.4 End of life

In the development phase of a product, it is mandatory to think about the end of life of the product. The ideal situation is when it is possible to use the product in any other way: as RM for a new product, or as an intermediate product that needs some adjustment to be used for something else.

4. Conclusions

As we have seen, sustainability is not only a PCF calculation and comparison. The concept is much wider and when having it present at the very moment of starting a development, there are many aspects that can be improved.

It is necessary to have a 360° approach towards sustainability because the targets are ambitious and the solutions are not easy neither cheap. So, creativity will be a key to achieve what we need to preserve our planet.

**LUBR19 ID 113 Tailor-made Automation for Oil and Coolant Condition Monitoring Laboratories:
Modular, Customer-Centric Solutions from Sample Intake to Analysis**

Race for Clean Oil – Filter Efficiency Tests

Why Filtration Has Become a Competitive Advantage and Strategic Reliability Decision

By Steffen D. Nyman

Technical Knowledge Ambassador

C.C.JENSEN

In today's industrial landscape, performance is no longer measured by output alone. Operators are under simultaneous pressure to extend asset life, reduce total cost of ownership, improve sustainability, and avoid the operational disruption that comes with unplanned downtime. In that environment, oil cleanliness is not simply a maintenance metric. It is a business-critical lever for reliability, efficiency, and long-term equipment performance.

That shift in perspective matters. Lubricating oil does far more than reduce friction. It cools, protects, transfers energy, and supports the precision operation of bearings, gears, valves, and other critical machine elements. But oil can only perform those functions when contamination is kept under control. The difference between high-performing systems and underperforming ones often comes down to how seriously filtration is treated across the equipment lifecycle.

Contamination is Inevitable. Poor Control is Not.

From the moment a machine enters service, contaminants begin to build in the oil. Some are generated internally through normal wear. Others enter from the environment through poor breathers, seals, and maintenance activity. Water can accumulate through condensation or leakage, while oxidation and thermal stress create degradation by-products such as varnish and sludge.

Complicating matters further, industrial equipment rarely operates in a steady state. Load changes, temperature swings, pressure fluctuations, and start-stop cycles can all disturb previously trapped debris and reintroduce particles into circulation. Contamination, in other words, is not a static condition to be corrected once. It is a continuously moving target that demands a deliberate control strategy.

This is why leading operators increasingly view filtration not as a consumable expense, but as a frontline reliability technology.

Why Cleanliness Performance Translates into Machine Performance

The most damaging contaminants are often the ones least visible. Fine particles, especially those below 10 microns, are small enough to get caught in tight clearances in bearings, gears, and hydraulic components. Once there, they behave like an abrasive compound—accelerating wear and steadily eroding machine health.

The consequences are cumulative: declining efficiency, higher vibration levels, earlier component failure and thus shorter maintenance intervals. Clean oil slows down that progression significantly, helping preserve precision surfaces and maintain the performance that the equipment was designed to deliver.

Just as important, contamination accelerates oil degradation. As lubricants oxidize and lose their protective properties, replacement intervals shorten and operating costs rise. Cleaner oil slows that decline, extending lubricant life while reducing service frequency, waste and thus CO₂.

Reliability Depends on More Than Removal Efficiency

Reliability is not defined solely by whether a filter can capture contaminants. It is defined by whether the combination of filters can remove them fast enough to prevent oil cleanliness levels from drifting outside acceptable limits.

In real applications, contamination rarely rises in a straight line. It comes in spikes during start-ups, load changes, and transient operating events. If filtration cannot recover quickly enough between those spikes, the average oil contamination level will increase over time, and the probability of failure increases with it.

Effective filtration is therefore about resilience as much as capture rate. The goal is to sustain control of contamination under real-world operating conditions, not just nominal laboratory performance.

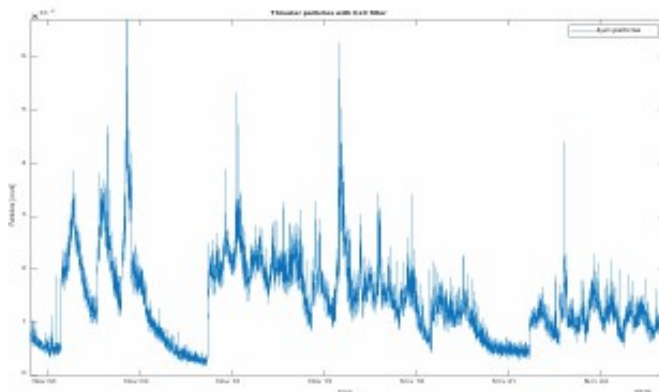


Illustration 1, particle counts measured by online particle counter (4-micron and larger)

The graph in illustration 1 shows 4-micron particle count in a gear oil during operation with changing speed and load. Here the oil filters can keep up, which is visual as low particle count in-between the higher peaks. Average count is between 10,000 and 30,000 particles per 100 ml, equal to ISO code 14-15 for ≥ 4 -micron (ISO 4406).

The Real Economics of Oil Cleanliness

When oil cleanliness is poor, the cost shows up everywhere: in premature wear, shorter oil life, more frequent maintenance, earlier replacement of expensive components and unplanned downtime. Put together, these effects increase total cost of ownership far beyond the visible price of filters or lubricants. By contrast, an effective oil filtration strategy reduces service demands, stabilizes machine condition and extends uptime.

This is where many organizations miscalculate. Filtration is too often evaluated as a standalone consumable cost rather than as a performance investment. In practice, systems with higher dirt-holding capacity and stronger contaminant control may cost more upfront, but when they can keep up with the contamination rate, they deliver lower lifecycle costs by preventing damage before it begins.

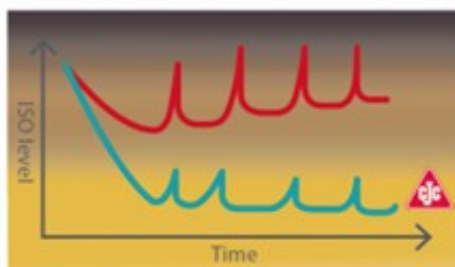


Illustration 2, Oil filters which cannot keep up vs. filters that can

If the oil filters cannot keep up then the average system cleanliness will continue to increase over time, which will result in high operation costs and risk of machine breakdown - shown in illustration 2 as the red curve. In contrary a filtration which can keep up, will give a low average contamination level in the oil (low ISO code), indicated by the green curve marked CJC.

Oil Filter Tests

Most users of oil filters are not familiar with different test methods and their limitations, nor how oil filters actually perform during their entire in-service life.

The standard oil filter tests are developed for pleated filter media (inline pressure filters) and the most used test, called the Multi-pass test (ISO 16889), has some limitations which include coarse test dust (MTD) and short testing time (max 3 hours). It is not ideal to evaluate the performance of an oil filter during its entire life. C.C.JENSEN has developed a test variant especially made for offline depth filters, which is based on the Multi-pass test but uses finer test dust (UFTD), lower ingress rate per hour and runs for 72 hours. This test variant is more accurate for evaluating performance during the entire oil filter life.

Why a Combined Filtration Strategy Wins

No single filtration method addresses every contamination challenge. In many applications, the strongest approach combines an air breather, reducing contamination in the head space, inline oil filters that provide full-flow protection during operation and an offline oil filter (kidney-loop) that continuously clean the oil at a finer level.

Because offline filtration operates independently of the main circuit, it does not experience pressure pulses, but enables continuous, deeper cleaning without interrupting production. That makes it especially effective for removing fine particles, water, and degradation products (varnish) that would otherwise remain suspended in the oil.

Most offline oil filters offer large capacity for contamination, since differential pressure is not as important as it is for full-flow inline oil filters.

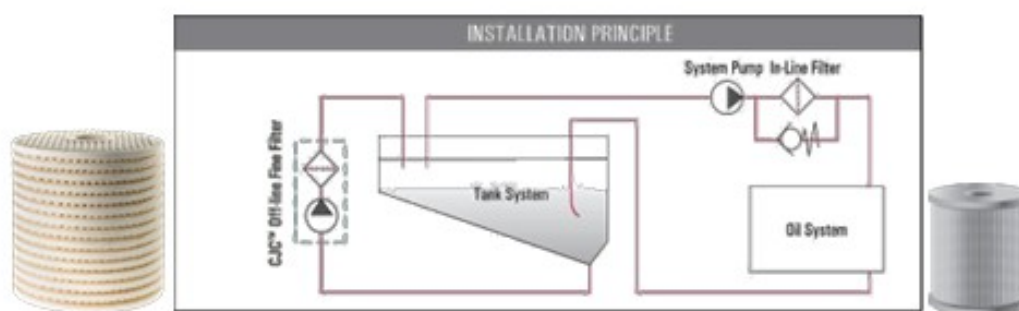


Illustration 3, Installation of inline and offline oil filters (kidney loop)

Depth Filtration and the Shift Toward Smarter Contaminant Control

Among the technologies gaining attention, depth filtration stands out for its ability to capture contaminants throughout the full thickness of the media rather than mainly on the surface. This changes both how filters load and how long they can maintain effective performance. This approach offers several advantages, including high dirt-holding capacity, stable filtration performance over time, and for some filter materials even removal of multiple contamination types, including water and varnish. For operators, the value is practical: cleaner oil, longer service life, more stable filtration performance, and better overall machine efficiency.

Sustainability and Reliability Are Now the Same Conversation

Clean oil does more than protect equipment. It also supports environmental performance by extending lubricant life, reducing waste streams, and lowering the energy losses associated with contaminated systems. For operations facing pressure to meet emissions, carbon footprint and resource-efficiency targets, these are no longer secondary benefits.

The broader lesson is clear: the most sustainable machine is often the one that runs reliably for longer, consumes fewer resources, and avoids unnecessary replacement of oil and components. Filtration sits directly at that intersection.

From Maintenance Practice to Boardroom Priority

For years, oil cleanliness was treated primarily as a maintenance issue. Today, that view is too narrow. In industries where uptime, energy efficiency, and asset utilization define competitiveness, filtration has become a strategic enabler with measurable operational and financial impact.

As manufacturers and asset owners work to reduce emissions, control costs, and increase resilience, oil cleanliness stands out as one of the clearest opportunities to improve all three at once.

Conclusion: Filtration Deserves a Bigger Role in Reliability Strategy

Machines will always generate contamination, and operating environments will always introduce new threats to lubricant health. The strategic question is no longer whether contamination exists, but how effectively it is being managed.

The organizations that treat oil cleanliness as a core part of machine design and reliability strategy are better positioned to protect equipment, stabilize performance, and reduce lifecycle costs. In an era defined by efficiency, uptime, and sustainability, filtration is no longer optional support infrastructure. It is part of the competitive architecture of industrial operations.

Clean oil is not just good practice. It is a signal of disciplined engineering, intelligent asset management, and operational leadership.

References:

Test done by Morten Henneberg, Innovation & Validation, C.C.JENSEN

Multi-pass test, ISO 16889

ISO 4406

Achieving superlubricity on hydrogenated diamond-like carbon coating under electrified sliding conditions with aqueous glycerol lubrication

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Abstract:

In this study, the tribological performance of a H-DLC versus steel contact pair lubricated with aqueous glycerol was systematically investigated under controlled electric potentials. The results reveal that when the applied voltage is maintained at or below 1 V, the system achieves a stable superlubricity regime, with coefficient of friction on the order of 10^{-3} and negligible wear of the H-DLC coating. This behaviour is attributed to effective surface passivation by hydroxyl-terminated species, which form a low-shear interfacial layer through repulsive interactions, suppressing adhesion and preventing direct asperity contact. Structural and chemical analyses confirm that the H-DLC coating retains its sp^3 -dominated bonding configuration within this voltage range, indicating the absence of electric-field-induced graphitisation. However, under higher voltages, severe surface damage and lubrication failure dominate the sliding response. These findings define a safe operational voltage threshold for superlubricity.

1. Introduction

Electrified mechanical system such as electric vehicles, generators, power transmission and railway components operated under increasingly demanding tribological conditions. In such applications, electrical currents and voltages can accelerate surface degradation through dielectric breakdown, tribo-corrosion and electrical discharge phenomena [1, 2]. Therefore, the development of tribological systems capable of maintaining ultra low friction under electrified conditions is of significant technological interest. Hydrogenated diamond-like carbon (H-DLC) coatings are promising materials due to their high chemical stability, hardness, excellent wear resistance and electrical insulating properties [2]. At the same time, aqueous glycerol-based lubricants have emerged as environmentally friendly alternatives capable of delivering exceptionally low friction [3]. Although both H-DLC coatings and aqueous glycerol have independently behaviour under electrified sliding conditions remains largely unexplored [3].

The present study investigates the superlubricity behaviour of H-DLC coatings against the steel ball under lubricated with aqueous glycerol under externally applied electrical current. Particular consideration was given to identify the voltage threshold at which superlubricity can be sustained and to elucidate the mechanism responsible for its degradation under increasing electrical loading.

2. Material and method

H-DLC coating were deposited on the mirror polished 100Cr6 steel substrates using plasma-assisted chemical vapour deposition. Friction experiments were performed using a reciprocating ball-on-disc tribometer on H-DLC coated disc sliding against a steel ball. The contact was lubricated with aqueous glycerol prepared using a 70:30 glycerol-to-water ratio. Electrified sliding experiments were conducted under applied voltages ranging from 0.1 to 1.4 V at a normal load of 3.5 N with a sliding speed of 0.1 m/s for a duration of 75 min. The friction behavior was continuously monitored.

(3) Results and discussion

Fig. 1 shows the friction behaviour of the steel/H-DLC tribosystem lubricated with aqueous glycerol under non-electrified and electrified sliding conditions. As shown in Fig. 1(a), aqueous glycerol enabled stable superlubricity with a friction coefficient below 0.01, whereas dry and water-lubricated contacts exhibited significantly higher friction. Fig. 1(b) demonstrates that superlubricity was maintained at applied voltages up to 1 V, with the lowest friction coefficient of approximately 0.007 observed at 0.6 V. However, increasing the voltage above 1 V resulted in a progressive increase in friction, indicating the loss of the superlubricity regime. Furthermore, the start-stop test in Fig. 1(c) confirms the robustness of the low-friction state up to 1.1 V. Beyond this threshold, friction increased rapidly, with the highest

values observed at 1.4 V, suggesting degradation of the lubricating interface and H-DLC coating. These results identify 1 V as the critical voltage threshold for sustaining stable superlubricity under the investigated conditions. The observed superlubricity is attributed to the formation of a hydroxyl-rich passivated interface generated through the interaction of aqueous glycerol, water molecules and the sliding surfaces. These surface species suppress adhesive interactions and facilitate low-shear sliding. Once the applied voltage exceeds the critical threshold, structural degradation of the coating disrupts this passivated interface, ultimately resulting in lubrication failure.

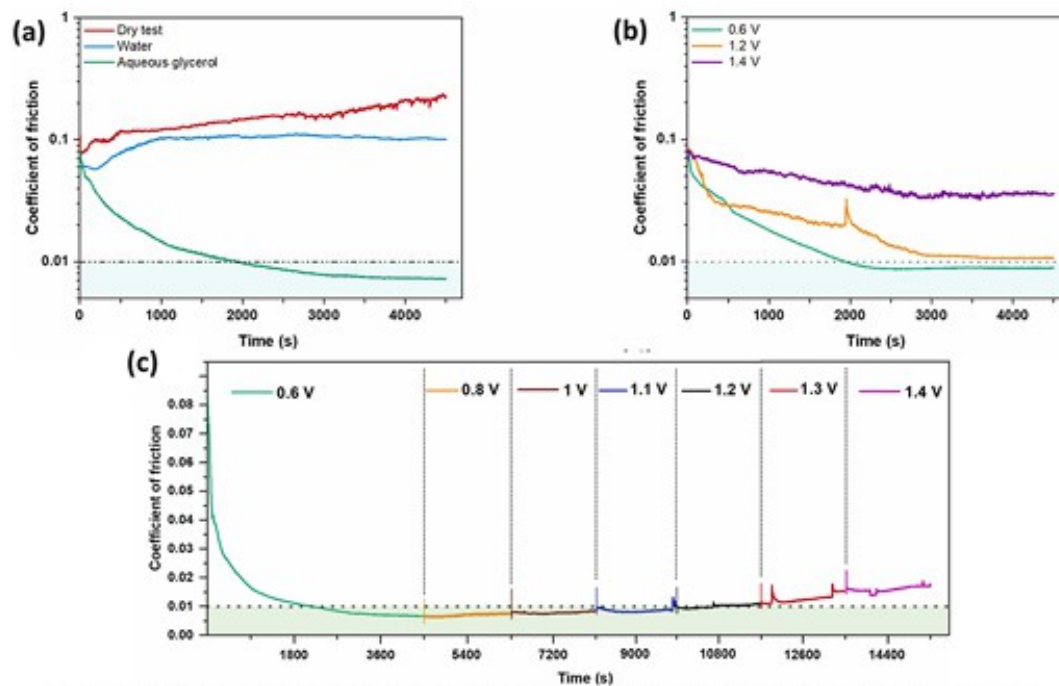


Fig.1 COF of friction of H-DLC coating (a) under dry and lubricated conditions without electrified sliding (b) with three different voltages, and (c) start-stop test with different voltages [3].

(4) Conclusions

- Stable macroscale superlubricity was achieved using H-DLC coatings with aqueous glycerol lubrication under electrified sliding conditions.
- Ultra-low friction (COF: 0.007–0.009) was maintained below 1 V with negligible wear.
- Long-duration and start–stop tests confirmed robust and stable superlubricity behavior.
- Raman and XPS analyses showed that the H-DLC coating retained its structural integrity below 1 V.
- Increasing voltage above 1 V induced graphitization ($sp^3 \rightarrow sp^2$ transformation) and coating degradation.

Acknowledgement

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How potato peels converted into synthetic esters leads to base oils with improved performance and significantly lowered carbon footprint

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Abstract

Hexanoic acid produced from agri-food residues offers a sustainable and scalable feedstock for polyol ester lubricants. Pentaerythritol-based C6 esters were synthesized and characterized, yielding properties consistent with commercial low viscosity standards for EV/HEV, wind turbine, and data centre cooling applications. With low viscosity, low temperature performance and good dielectric properties, hexanoic acid-derived polyol ester lubricants demonstrate excellent potential in low viscosity applications with a significantly reduced carbon footprint.

Lower viscosity lubricants have become a focus in emerging and fast-growing applications such as EV/HEV powertrains, wind turbines and data centre cooling, where low viscosity is widely recognized to better enable thermal management across various operating conditions [1]. In EV/HEV powertrains where the e-motor speed can reach 20,000 rpm, lower viscosity lubrication can prevent excessive friction and churning losses [2]. Lower viscosity lubrication is also seen as a potential solution to standstill corrosion in wind turbines [3], while in immersion cooling, it supports high heat transfer rates and high pumping rates, reducing operational costs [4].

Polyol esters (POEs) have attractive tribological characteristics and have long been used as lubricants in applications such as refrigeration systems, engine oils, gearbox oils and hydraulic fluids. The fatty acids used in POE lubricants are typically a mixture of chain lengths, whereby the composition can be changed to optimize properties of the lubricant, such as viscosity, for different operating conditions. Typical chain lengths used in POE lubricants range between C5-C18, and the shorter C5-C9 fatty acids are particularly suited for designing lower viscosity lubricants. Among these, hexanoic acid (C6) remains underutilized due to its natural scarcity (0.1-0.6% in coconut and palm kernel oil only), despite a molecular structure indicating desirable properties such as low viscosity, low temperature performance and good dielectric properties. Fermentation of agri-food residues offers a route to producing hexanoic acid in large, stable and regionally distributed supply. This introduces a new source of 40-80% lower carbon footprint base oil (Figure 1A) and opens opportunities for using C6 fatty acids in developing polyol esters for low viscosity applications.

To demonstrate the utility of C6-derived POEs, pentaerythritol-based POEs were synthesized using C5, C6 and C7 fatty acids. Each ester was synthesized using direct esterification, yielding predominantly fully esterified pentaerythritol esters (PE-C5, PE-C6, PE-C7). The products were distilled to a purity of around 98%. Thereafter, the physicochemical properties of the esters were measured and compared with commercialized standards for HEV, wind turbine and data center cooling applications. Considering the sensitivity of small-scale synthesis and processing, measurement of various properties of C5, C6 and C7-derived pentaerythritol esters provided an indication of the range of performance possible for PE-C6 (Figure 1). Physicochemical characterization of PE-C6 yielded: Kinematic viscosity at 40°C (KV40) of 15–20 mm²/s, kinematic viscosity at 100°C (KV100) of 3–5 mm²/s, viscosity index (VI) of 110–140, pour point of –36 to –21 °C, flash point of 204.5–213 °C, thermal conductivity of 0.10–0.17 W/m·°C, dielectric dissipation factor of 0.009–0.029, and relative permittivity of 3.29–3.57.

Based on the measurements of synthesized pentaerythritol esters, PE-C6 properties fall within the range of commercially available low viscosity formulations for the referenced applications (Table 1). For HEV and wind turbine applications, KV100 of PE-C6 falls within the range of performance of the commercial standards, indicating comparable performance at average operating temperatures in these applications. With respect to VI and pour point of PE-C6 in these two applications, further developments are required – e.g. through additive packages or blending strategies, or modifying the polyol structure - to ensure performance

and stability over a wider range of temperatures. For data center cooling, the KV40 and pour point values are well within range of the commercial standard. With lower viscosity compared to the standard, a PE-C6 could enable faster pumping rates and better heat transfer. Favorable thermal and dielectric properties further support the suitability of PE-C6 as a base oil component in low viscosity formulations across all three domains.

This work demonstrates that a polyol ester derived from hexanoic acid delivers properties consistent with commercially available standards in various low viscosity applications. This approach enables palm- and fossil-free lubricant base oils with a significantly reduced carbon footprint without compromising technical performance.

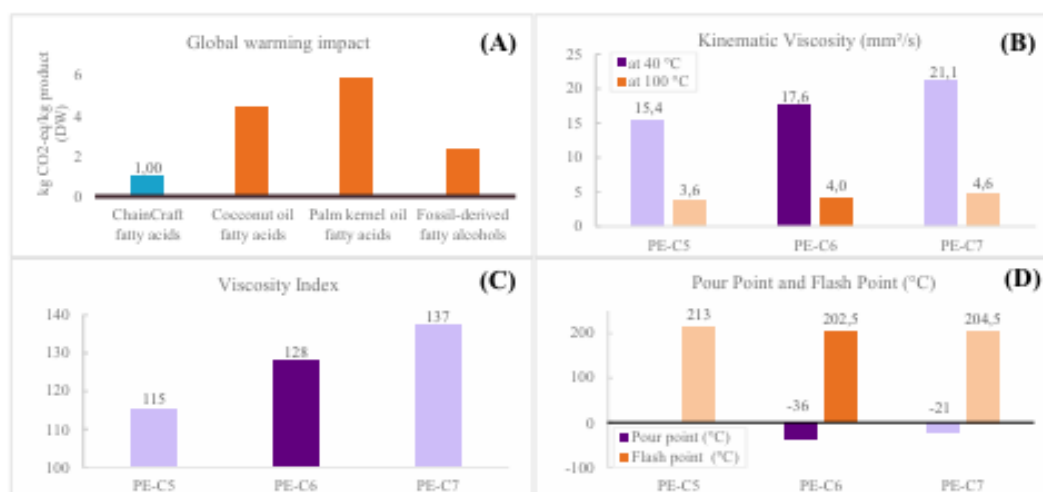


Figure 1: (A) Global warming impact calculated using a cradle-to-gate simulation of ChainCraft's fermentation process using potato juice as feedstock (B) Kinematic viscosity at 40°C and 100°C; (C) Viscosity index; (D) Pour point and flash point. The pour point of PE-C5 could not be determined.

Table 1: Comparison of PE-C6 properties as a base oil component with commercial lubricant formulations in various applications. Flash points were not included as all esters synthesized had flash points above operating temperatures relevant to the standards provided below.

Parameters	Unit	PE-C6	HEV	Wind turbines	Data centers
			Commercial standard 1	Commercial standard 2	Commercial standard 3
KV40	mm ² /s	17,5	n.a.	15	22,6
KV100	mm ² /s	4,1	3,6	3,9	n.a.
VI	-	128	144	164	n.a.
Pour point	°C	-36	-57	-57	-40

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Phosphate Ester – is Fill for Life Possible?

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Degradation and Regeneration of Ester Based Fluids

The need for power is constantly increasing, along with requirements for precision, reliability, longer lifecycles and lower consumption. On top of that, the demand for stability in the electric grid has increased vastly in the last 50 years.

All of these factors have forced manufactures to optimize the turbine control systems, the so-called Electro Hydraulic Control (EHC) system which governs the steam supply in steam turbines and air supply in gas turbines.

There are basically two ways to improve the response time of the control system:

1. High hydraulic pressure and very precise valves
2. High flow rates and large valves



Illu. 1, EHC fluid before and after conditioning

The first solution operates at higher pressures and makes use of relatively low flow rates and small fluid volumes. An example could be 1600 psi (110 bar) and 400 gallon of fluid (1,500 liter).

The second option incorporates larger valves and higher flow rates. While this requires larger fluid volumes, the system operates at lower pressure and uses less sensitive valves, e.g. 2000 gal of fluid (7,500 liter) and 600 psi (40 bar).

Due to the potential fire hazard associated with fluid leaking onto a hot surface e.g. a steam pipe, the EHC system fluid need to be fire-resistant or at least fire-retardant. EHC fluids could be based on synthetic oils, glycols or esters. Often the type of EHC fluid will be dictated by the insurance company.

For many EHC systems today, esters are the only fluids approved, so this paper will focus on phosphate ester fluids.

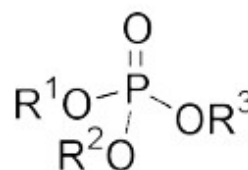
Phosphate ester is generated from an acid and an alcohol or a phenol group.

The three organic components (Rⁿ) determine the chemical and physical properties of the fluid.

The most commonly used ester for EHC fluid is based on Tri-Aryl phosphate ester, while new types are Trixylyl free (TXP-free) since it is better for the environment and easier to handle.

Phosphate ester has a high self-ignition temperature above 1,000°F (540°C) and the ability to self-extinguish. Known brands include Fyrquel, Pyrogard, EcoSafe, etc.

The making of ester is called esterification and produces water as by-product. For phosphate ester:



The problem

Unfortunately, the esterification process is reversible if the ester-based fluid comes in contact with water. This is referred to as hydrolysis:



The higher the water content and temperature, the faster the ester will break down by hydrolysis. The resulting acid built up (increasing AN value) will rapidly degrade the fluid and decrease the viscosity and resistivity. This will cause acid corrosion of sensitive servo-valves and other system components.

Consequences of EHC system fluid degradation and contamination

- Acid, gel and sludge/varnish formation
- Valve sticking or blocking
- Reduced lubricity and film strength
- Corrosion, erosion and abrasion wear
- Reduced fluid resistivity
- Soot generation (entrained air)
- Short fluid life

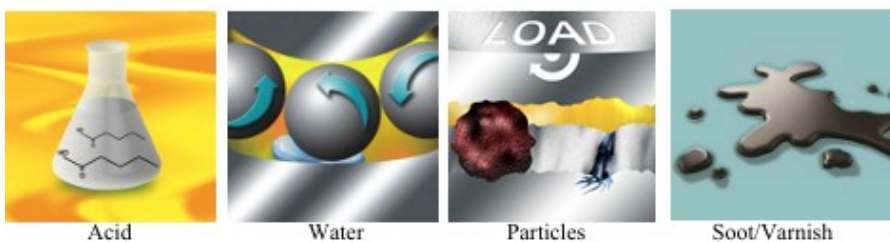
The result is poor EHC system reliability and reduced turbine availability.

The reliability of the EHC system is vital for the operation of the turbine, so avoiding failures with proper maintenance is absolutely essential. Ester based fluids are also quite costly to replace (6 – 10 Euro per liter or \$30 – \$50 per gal).

Water and acidity are not the only contaminants which can degrade the EHC fluid and components. Since the dynamic oil film and fine clearances in servo-valves are less than 5 microns, even the finest silt particles and soot/varnish deposits from fluid degradation can hinder proper operation. Fine particles get trapped in clearances between the valve plunger and housing. This abrasive wear is known as seizing or grinding, and can result in wear rates that are a thousand times greater than anticipated by the valve manufacturer.

Therefore, it only makes sense to use very fine filtration (3-5 micron) for maintaining the EHC fluid.

Four types of contamination



While most oil types generate sticky varnish when degrading over time, the oxidation and degradation products of phosphate ester resembles more of a soot like by-product together with increasing acidity.

It is recommended to maintain the phosphate ester and keep it within the following specifications (illustration 2)

Recommendations

Fluid analysis/test	Max. performance limit	Comments
Viscosity	+/- 10% of new fluid	Degradation by hydrolysis will <u>decrease</u> viscosity
Acidity (AN)	0.25 mg KOH/g	Water and hydrolysis will <u>increase</u> AN vastly
Water	750 ppm	For best accuracy use Karl Fischer titration shortly after sampling, as water changes chemically in ester, making it difficult to measure correctly after a few days
Particle count	ISO 16/14/11	Sensitive servo-valves require fine filtration (3 – 5 micron)
Mineral oil content	30 ml/l	Mineral oil impairs the fire-resistance
MPC membrane patch	MPC $\Delta E = 30$	MPC shows soot, varnish and sludge. Ultra Centrifuge and RULER tests can also be used
Resistivity	Minimum 50 M Ω m or 5 Giga-Ohm-cm	Low resistivity combined with high chlorine content (>50 ppm) is known to cause electro-kinetic wear of servo-valves
Air release	10 minutes	A poor air release will result in even faster soot built up (micro-dieseling effect)

Illustration 2, recommendations for phosphate ester EHC fluid

Most turbine manufactures understand these issues and have incorporated a fluid conditioning unit into the EHC system. This EHC conditioning unit often includes an acid reducing system followed by filters with fine filtration rates. Frequent oil analysis can verify that the system is up to the task of keeping the acid number, the resistivity and particle count etc. at the recommended levels (see table above).

Many acid scrubbing systems still use Fuller's Earth since its ability to reduce acid content is well known and it is also the cheapest to use. However, Fuller's Earth will form metal soap deposits and is known to reduce the fluids' ability to release air.

When the fluid's air release property is reduced, more air will be entrained in the fluid. This will result in adiabatic compression of the air bubbles and soot built up, referred to as micro-dieseling. Soot has a huge effect on degradation of the fluid and therefore the useful life. Unfortunately, soot is so fine that it will not show as an increase in particle count when looking at 4, 6 and 14 micron levels.

The best way to detect degradation and micro-dieseling in phosphate ester is with a membrane patch colorimetric test (MPC) that uses a 0.45 micron patch to show the black carbon deposits. MPC will also show sludge/varnish.

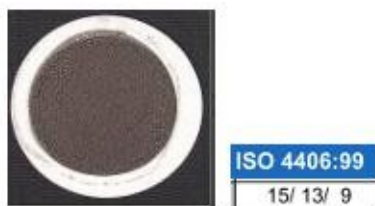


Illustration 3, Photo of MPC patch showing soot from micro-dieseling in EHC system

Here the MPC ΔE value is 79, while fluid cleanliness according to ISO 4406 is 15/13/9, clearly indicating that the particle counter cannot see the soot particles.

How to control micro-dieseling:

- Avoid use of constant volume pumps with pressure reduction valve - use frequency controlled pumps instead
- Use fluid with good air release properties and test it every 3 months
- Beware of suction line leaks
- Optimize the system and tank design:
 - Install return lines as far away from pump suction line as possible
 - Return lines need to be installed below the oil level to avoid splashing
 - Minimize turbulence in the return lines and use a diffuser in the tank
 - Keep the air in the head space dry and clean
 - Protect the suction line by baffles and perforated plates/wire screens to improve the air release in the tank (see drawing below from Noria Corporation)

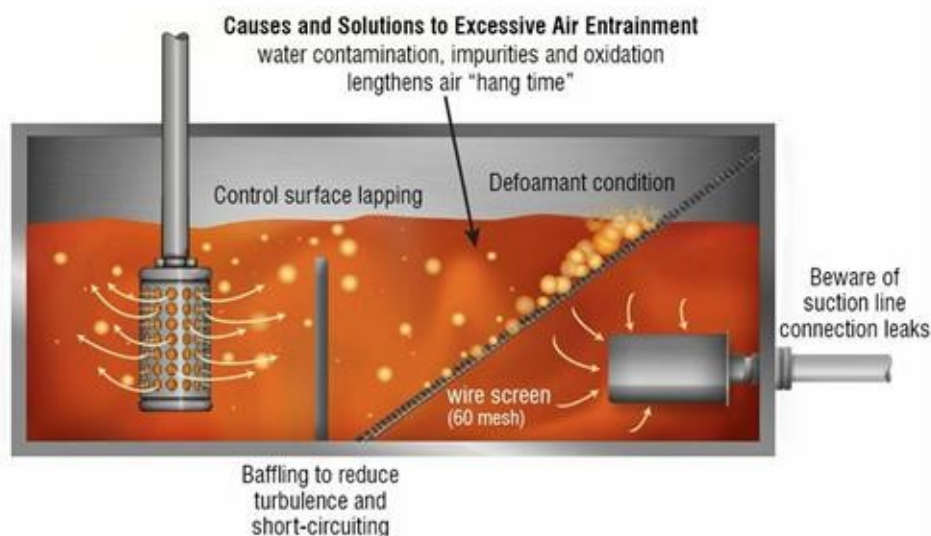


Illustration 4, Avoid entrained air. Source: Noria Corporation

The solution

Water removal

Since phosphate ester fluid is hygroscopic and has a very high saturation point during normal operation temperature (phosphate ester ~ 4,000 ppm or 0.4% water), humidity is very rarely found as free water and emulsions in EHC systems. Water contamination in a typical hydraulic system utilizing mineral based oil will often experience free water separated at the bottom of the tank. This is because water has a density higher than mineral oil, and the saturation point for mineral oil is quite low compared to that of phosphate ester.

While water is difficult to remove from phosphate ester, EHC fluids, it can be done. Cases will follow in this paper. The best way is to avoid or limit water entering the EHC system in the first place. This can be done by using desiccant breathers, bladders or purging dry air into the tank head space.

EHC conditioning units including acid reduction

A high acid number is often the condemning factor and reason for replacing ester fluid. In some power plants, the EHC fluid seems to last for decades with the acidity remaining around 0.2 mg KOH/g while other plants struggle to keep the acidity level below 0.5 mg KOH/g. Although fluid life is influenced by many factors, a well trained maintenance personnel who are familiar with phosphate esters and best practice fluid storage, handling and sampling procedures can significantly increase the fluid life.

As mentioned earlier, the acid reduction system contains some sort of acid absorption media. This can be Fuller's Earth, activated alumina beads or ion exchange resins. Acid absorption media based on active ion exchange resins are more effective in lowering the acid number than Fuller's Earth and activated alumina, especially on older, degraded phosphate ester with elevated acid numbers (AN above 0.5). Furthermore, ion exchange resins do not leave metal soaps in the fluid nor do they harm the air release. The ion exchange resins do release some moisture, but when used in combination with some kind of water removal method and fine filtration (3-micron), such a unit can maintain the EHC fluid properties and even restore the resistivity.

There are EHC conditioning units available in the market which can remove all four contaminant; acidity, particles, soot/varnish and water with one compact unit. If sized and maintained correctly an EHC conditioning unit should be able to keep acidity low and the other parameters in check for many years.

Here follows two case studies, all with similar goals.

Case studies - overall goals

- Improve EHC system reliability
- Increase phosphate ester life, by removing water, acids and degradation products
- Extend component life, by avoiding acid corrosion and particle wear (abrasion)

Approach

- Install offline ion exchange unit to reduce the acidity
- Install offline depth fine filter (3-micron) to remove metal soaps, soot/varnish and particles
- Install a method of water removal (absorption by molecular sieve beads)

Principle drawing of an offline oil filter installation (kidney-loop)

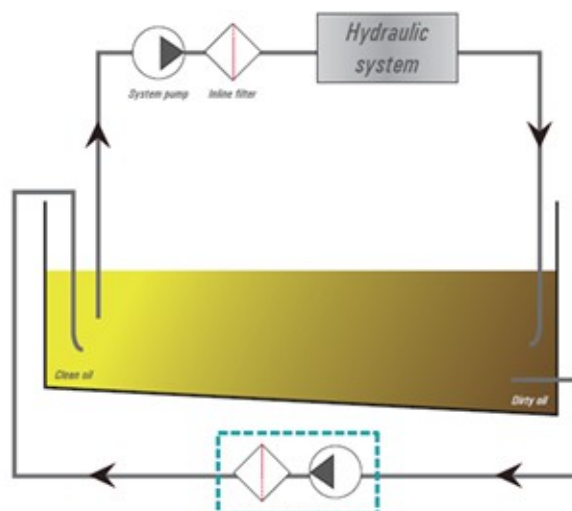


Illustration 5, EHC conditioning unit installed offline

Case 1, USA, EHC system on steam turbine

1,500 liter (400 gal) of Fyrquel EHC fluid was degraded and condemned to be replaced. The phosphate ester was out of spec on the following parameters:

Test	Sample Date July 27 th	Recommended limit
Acidity (AN)	0.77 mg KOH/g	0.25 mgKOH/g
Water	1,300 ppm	750 ppm
Particle Count	5 - 10 micron: 160,664	5 - 10 micron: 9,700
Resistivity	3 G-Ohm-cm	Min. 5 G-Ohm-cm

Illustration 6, Start-up

It was agreed to install a three-in-one EHC conditioning unit incorporating ion exchange resin beads for acidity reduction and 3-micron filtration to remove particles and sludge/varnish. Initially, the test did not incorporate water removal equipment. This was addressed with a molecular sieve insert after the acidity decreased.

After only 5 days in operation, the acidity was cut in half. The first ion exchange insert and filter were replaced after 1 month, resulting in reduced AN and particle count Sept. 1st. The acidity was now at a safe level, below 0.25 mgKOH/g.

Test	Sample Aug. 2 nd First ion exchange insert and filter	Sample Sept. 1 st Second ion exchange insert and filter
Acidity (AN)	0.4 mg KOH/g	0.21 mg KOH/g
Water	1,300 ppm	1,400 ppm
Particle Count	5 – 10 micron: 149,772	5 – 10 micron: 110,060
Resistivity	3 G-Ohm-cm	7 G-Ohm-cm

Illustration 7, First and second insert change

After an additional month of operation, a molecular sieve insert was added to the EHC unit and the water content was reduced by ~50%. After 6 months the sample showed that the EHC fluid was in great shape and back within recommended specifications: AN of 0.1, 800 ppm water, 7 G-Ohm-cm.

The particle count was still too high, but that will come down with continuous 3-micron offline filtration.

Test	Sample Oct. 3 rd Molecular sieve and filter	Sample Jan. 23 rd Third ion exchange insert and filter
Acidity (AN)	0.16 mg KOH/g	0.10 mg KOH/g
Water	700 ppm	800 ppm
Particle Count	5 – 10 micron: 192,136	5 – 10 micron: 60,308
Resistivity	5 G-Ohm-cm	7 G-Ohm-cm

Illustration 8, End of test period – phosphate ester as good as new

Conclusion case 1

This first case shows how effective the combination of ion exchange media and fine filtration works. The molecular sieve insert also did a fine job in lowering the water content in the hygroscopic phosphate ester fluid.

The compact EHC conditioning unit used here is suitable for EHC systems up to roughly 2,300 liter (600 gal). For larger volumes a second or third filter column can be added.

See photos of used inserts below.



Illustration 9, Used fine filter insert. Illu.10, Used ion exchange insert.

The photos in illustration 9-10 show the first used inserts being replaced after 1 month. The brown color on the 3-micron depth filter comes from particles and sludge/varnish removed from the fluid. The filter insert is fitted in series with a bag containing ion exchange resins (alternatively filled with molecular sieve beads). In the photo on the right, the ion exchange resin beads have expanded slightly due to saturation.

Case 2, Belgium, EHC system on large steam turbine

EHC system with 2,000 liter (530 gal) of Total Hydransafe. The phosphate ester was heavily degraded with the acidity at 0.9 mgKOH/g.

In July an offline four-in-one EHC conditioning unit was installed. The continuously operating unit utilized two bags containing ion exchange resins, two bags with molecular sieve beads and two depth media filter inserts (3-micron) in three separate filter housings in series.

After four weeks of operation, the acidity decreased from AN = 0.9 to AN = 0.29 and continued to decrease reaching the acidity level of 0.09 mgKOH/g after 6 months of operation, which is as good as new phosphate ester fluid.

The water level was reduced from above 1,000 ppm to 139 ppm in the same period of time.

H/Km olie:		69938 H	69938 H	69938 H	69938 H	?	69938 H	69938 H
H/Km totaal:		87932 H	87395 H	86764 H	86005 H	?	85083 H	84053 H
Bijvulling:	L	?	?	?	?	?	?	?
Toestand van de olie:								
Viscositeit bij 40°C	cSt	44.5	44.9	44.2	44.9	44.7	45.0	44.4
Viscositeit bij 100°C	cSt							
Viscositeitsindex	-							
AN	mgKOH/g	0.09	0.30	0.27	0.24	0.11	0.14	0.29
Water (KF)								
	ppm	139	240	344	335	231	692	905

Illustration 11. Oil samples over 6 months



*Illustration 12 – 13, shows the CJC PE conditioner unit, HDU 3*27/54 on a tank.
Second photo is the used bags containing saturated ion exchange resins.*

EHC fluid maintenance summary

So, can the EHC system be filled-for-life?

If properly maintained, the phosphate ester can last 15 – 20 years in operation, but it will need to be monitored and kept within specifications.

Best practice:

- It is important to set targets for contamination levels and measure them monthly/quarterly (viscosity, acidity, water content, particle counts, soot/sludge/varnish by MPC patch test, mineral oil content, resistivity, wear metals, etc.). See recommendations in illustration 2.
- Since ester degrades by hydrolysis, rapidly increasing acidity, water should be kept out of the system and below 750 ppm in the fluid
- Avoid ingress. The tank should have effective desiccant air breathers that remove both fine particles and moisture. Purging dry air into the tank head space is also a good solution to keep contaminants out
- Removal of water: Water can be removed from ester by molecular sieve beads. Maintaining low water level by purging dry air into the tank head space is also recommended.
- Acidity, particle and soot/varnish contamination can be maintained and reduced by installing an PE conditioning unit which includes acid reduction and fine depth media filtration (3 micron). While different acid absorption media can be used, ion exchange resins are the most effective, leaving no metal soap deposits behind nor impairing the air release property of the fluid. New TXP-free ester require special customized ion exchange resins.
- Entrained air due to poor air release, tank design or leaks on the suction side of the pump will result in micro-dieseling and soot built up. Membrane patch tests (MPC) will show severity and whether action needs to be taken to solve the problem
- Awareness training of maintenance/operation staff is key to success. Use best practices for storage, handling and make-up fluid as well as fluid sampling

Presentations about EHC fluid basics, degradation and conditioning are available on request.

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- Tank design, Noria Corporation

Tribology for Industry: Closing the Gap Between Knowledge, Application and Measurable Benefits

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Abstract

Tribology has demonstrated its value in reliability improvement and operational efficiency; however, a major gap still exists between tribological knowledge and its industrial perception. In many organizations, tribology is still viewed only as a maintenance activity rather than a strategic contributor to productivity and business performance.

This presentation discusses the importance of closing that gap through knowledge dissemination and measurable value demonstration. Drawing from professional experience in Latin America and Europe, and activities developed through the Asociación Argentina de Tribología (AAT), it explores how companies, universities, and technical associations can strengthen tribology culture within industry.

A practical case study from a 300 MW thermal power plant in Mexico will illustrate how a high-velocity flushing project generated significant production availability benefits, highlighting the importance of communicating tribology in operational and economic terms.

1. Introduction

Tribology has historically been associated with lubrication, wear reduction, and machine reliability. Although its technical importance is widely recognized among specialists, many industrial organizations still perceive it only as a maintenance-related activity rather than a strategic contributor to productivity, sustainability, safety, and business performance.

Throughout the author's professional experience in Latin America and Europe, it became evident that one of the main challenges for tribology is not only technical implementation, but also effective communication of its real industrial value.

2. Development

An important influence in the author's professional development was Miguel González Bonnin, founder of the company where the author started his career. Beyond building a successful organization, he actively promoted tribology dissemination throughout Latin America by organizing technical symposiums and encouraging collaboration between industry and academia between 2002-2004. The author first heard the name Peter Jost [1] from Don Miguel González Bonnin.

Inspired by this vision, the author became actively involved in initiatives focused on tribology dissemination, particularly through the Asociación Argentina de Tribología (AAT), which integrates universities, research institutes, and industrial companies. Through conferences, technical presentations, virtual activities, and university engagement, the association seeks to strengthen tribology culture and attract new professionals to the field.

The presentation also highlights the importance of collaboration and knowledge sharing between institutions, companies, and technical communities. Industrial value increases when best practices are shared and translated into measurable operational and economic benefits.

One of the greatest challenges remains the communication of value. While technical specialists often focus on lubrication performance and reliability indicators, industrial organizations increasingly require measurable impacts related to production, safety, environmental performance, and operational continuity.



Fig. 1. Miguel González Bonnin (center) with two international speakers during the STLE Mexico Symposium, 2004

3. Case Study

A practical example discussed in this presentation involves a high-velocity flushing project performed during a scheduled shutdown at a 300 MW thermal power plant in Mexico.

The project was initially proposed after oil analysis identified contamination and lubricant degradation in the turbine lubrication system. The original objective was to improve oil cleanliness and reduce startup reliability risks, using procedure based on ASTM D-6439-99 [2].

During the flushing process, daily ISO cleanliness reports were presented to the maintenance team. However, discussions with the production manager revealed an unexpected operational benefit. In previous shutdowns, startup procedures required several additional days to manually clean startup protection meshes due to contamination released into the system. Following the flushing process, those delays were eliminated.

This experience demonstrated that the true value of tribology was not only associated with reliability improvement, but also with significant gains in production availability and operational continuity. It also revealed the importance of communicating tribology using the language of production and business performance.

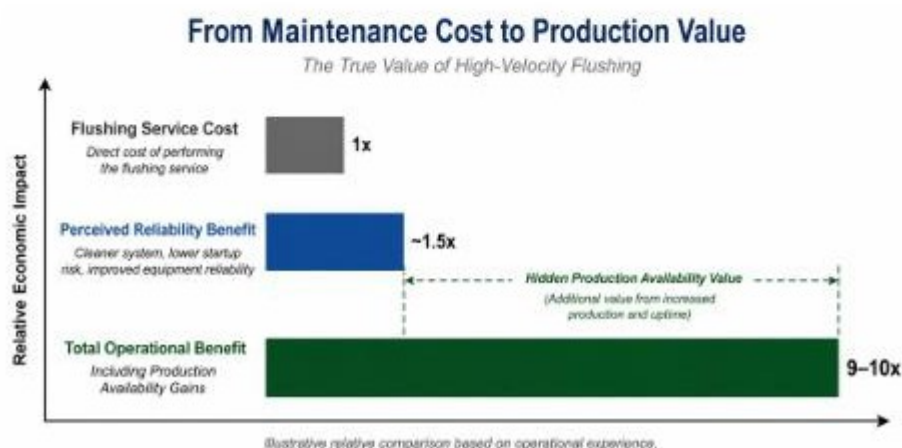


Fig 2 Total Operational Benefit of Tribology best Practice

4. Actions to close the gap

Closing the gap between tribological knowledge and industrial perception requires active dissemination and stronger communication efforts across multiple organizational levels.

First, it is essential to initiate high-level discussions with industrial management to communicate tribology not only as a technical discipline, but as a strategic contributor to productivity, sustainability, reliability, safety, and operational efficiency. Tribology must be connected to measurable business indicators that are meaningful for decision-makers.

Second, universities play a key role in developing future professionals. Greater interaction with undergraduate and postgraduate engineering programs is necessary to introduce tribology concepts earlier in professional development and increase awareness of its industrial importance.

Finally, active participation in tribology and lubrication associations is fundamental. Companies, universities, and technical professionals should collaborate by sharing knowledge, best practices, and success stories beyond normal commercial competition. The collective dissemination of technical knowledge ultimately strengthens the entire industry and creates greater long-term value opportunities for all participants.

5. Conclusions

Tribology possesses enormous potential to improve industrial productivity, reliability, sustainability, and operational performance. However, many of its benefits remain insufficiently communicated across organizations.

Closing the gap between tribological knowledge and industrial perception requires stronger dissemination efforts, interdisciplinary communication, and measurable value demonstration. Universities, technical associations, and industry leaders all play a fundamental role in promoting this cultural transformation.

Tribology must evolve from being perceived as a purely technical discipline into a strategic industrial language connected to production, reliability, sustainability, safety, environmental impact, and business value.

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OOST Methodology: A Systems-Oriented Optimization of Interconnected Tribological Systems to Enhance Centrifugal Pump Reliability

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Abstract: This work presents the OOST methodology as a systems-based approach to improving centrifugal pump reliability through the identification and interconnection of tribological subsystems. Bearings, sealing systems, shaft contact zones and fluid-metal interfaces are analyzed under systems thinking. Failure and wear patterns across these elements are treated as distributed indicators of systemic instability. Field results demonstrate reliability improvements through structural interventions, including lubrication optimization, sealing adjustments and hydraulic surface modifications.

1. Introduction

Centrifugal pump reliability is commonly addressed through isolated interventions on bearings, seals or hydraulic components. However, recurring failures indicate that degradation is rarely attributable to a single component, but rather to interactions between multiple tribological interfaces operating under coupled mechanical, thermal and hydraulic conditions.

From a systems perspective, behavior is governed by interconnections and feedback structure rather than isolated elements [1]. In pumps, bearing condition affects shaft stability, shaft dynamics influence sealing performance, leakage promotes contamination, and hydraulic degradation modifies vibration and loads. OOST is formulated as a systems-oriented methodology to interpret and act on these interactions.

2. Tribosystems Architecture in a Centrifugal Pump

A centrifugal pump can be described as an interconnected tribological system composed of four subsystems: bearings, sealing system, shaft contact zones and wetted hydraulic surfaces (impeller, volute, wear rings). These interact through vibration, temperature, contamination, leakage and hydraulic forces. Bearings operate under rolling contact and depend on lubrication, cleanliness and thermal control. Sealing systems function under distinct regimes: packing under mixed lubrication with controlled leakage, and mechanical seals under a micrometric fluid film sensitive to vibration, pressure and temperature. Shaft-packing interaction introduces additional wear mechanisms under inadequate lubrication or solids ingress. Wetted surfaces govern erosion, abrasion, corrosion and cavitation, directly affecting hydraulic performance and dynamic loading. Field troubleshooting confirms this interconnected behavior. Mechanical seal failures are frequently linked to equipment condition, operation, fluid characteristics and maintenance practices, with typical drivers including runout, vibration, cavitation, flashing and poor lubrication.

3. System Dynamics and Feedback Structure

Pump degradation is governed by reinforcing feedback loops. A critical loop is leakage-contamination-wear-instability: leakage enables contaminant ingress, accelerating wear and lubricant degradation; wear increases vibration and shaft instability; instability further increases leakage.

Mechanical seal damage patterns (scoring, chipping, heat checking) often reflect these systemic conditions, but OOST extends diagnosis beyond the seal. The methodology evaluates distributed tribological observables:

- Bearings: overheating, contamination, fatigue, corrosion, wear
- Mechanical seal: leakage, seal faces fracture and wear
- Shaft (packing zone): wear, fretting
- Hydraulic surfaces: erosion, corrosion, cavitation

These patterns are treated as outputs of a coupled system rather than isolated failures.

System behavior is further explained through stocks, flows and delays [1]. Wear, contamination and thermal load accumulate over time; particle ingress, heat generation and material loss act as flows; and delays exist between initial degradation and observable failure. This explains why component replacement alone often results in recurrence.

4. OOST Methodology

OOST improves reliability by acting on system structure. The methodology comprises:

1. System boundary definition
2. Tribological regime characterization
3. Mapping of interdependencies and feedback loops
4. Evaluation of distributed tribological observables
5. Intervention at leverage points

Key leverage points include contamination control, lubrication strategy, sealing configuration, shaft stabilization and hydraulic surface condition. In line with systems thinking, targeted structural interventions generate disproportionate improvements in system behavior [1].

5. Industrial Application and Field Results

Field application confirms that sustainable improvements arise from structural interventions rather than component replacement. In packed pumps, optimized leakage control reduced water consumption and contamination transfer. In vibration-driven failures, correlation of seal, bearing and shaft damage enabled identification of underlying causes such as misalignment or hydraulic instability.

Interventions on wetted surfaces further demonstrated systemic impact. Reduction of roughness and recirculation improved hydraulic stability and reduced dynamic loading. Literature supports this effect: smoother coated surfaces have been shown to improve pump efficiency by up to ~9% and reduce power consumption, while increased roughness is associated with performance losses and cavitation intensification [5–7].

Within OOST, coatings act not only as corrosion protection but as structural modifications to the hydraulic tribosystem, influencing flow behavior, turbulence and load transmission across the system.

6. Conclusions

Centrifugal pumps behave as interconnected tribological systems where bearings, seals, shaft contact zones and hydraulic surfaces interact through feedback mechanisms involving leakage, contamination, vibration and wear.

OOST provides a practical framework to interpret these interactions using distributed tribological observables and to intervene at leverage points affecting global system behavior. By integrating tribology with systems thinking, the methodology enables more accurate diagnosis and more durable reliability improvements, moving beyond component-level maintenance toward systemic optimization.

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Assessment of lubricant performance in hydrogen-assisted dual-fuel internal combustion engines

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Abstract:

There is a growing trend in the use of hydrogen as an alternative or supplementary fuel to the traditional fossil fuel-driven internal combustion engines (ICE). An important aim is to use hydrogen fuel to aid the achievement of net-zero carbon emission targets. Hydrogen is widely accessible, plentiful and may decrease human society's long-term intense dependence on fossil fuels [1]. In particular, there are implications for tribological performance of ICE, and particularly the performance of lubricants. The study by Rahmani et al [2], among others, has highlighted some of the tribological issues. However, in-field studies of lubricants subjected to combustion of hydrogen have been rather rare. This paper intends to address this gap in knowledge through investigation of in-field use of dual fuel hydrogen-assisted ICEs.

Keywords: hydrogen, internal combustion engine, friction, X-ray photoelectron spectroscopy.

Introduction:

Hydrogen is an eco-friendly option as a fuel for automotive sector, and using it for road vehicles will be environmentally friendly with zero tailpipe emissions, dealing with the new agenda of the World Health Organization to reduce the emissions from the automotive sector [1]. Introducing hydrogen into engines can lead to a large amount of nitrogen oxides being produced (NO_x), which has regulated limits in most nations. The conventional method to reduce it is with catalytic converters and by adding more air to the mixture [3].

Due to the high burn rate and diffusivity when compared to diesel, and the range of combustible concentrations, it can be more straightforward to achieve ideal combustion conditions with hydrogen, because of its properties. This allows for increased power output and decreased fuel consumption when compared to diesel [4].

Lubricant samples have been collected periodically from two diesel and two diesel-hydrogen dual fuel refuse trucks in Aberdeen, UK. These samples have been subjected to rheological assessment as well as a comprehensive comparative program of pin-on-disc tribometry and surface evaluation using X-ray photoelectron spectroscopy to determine both bulk lubrication performance as well as ability of the sampled used lubricants in formation of protective tribo-films.

Methodology:

For the pin-on-disk wear test, two specimens are required. One, a pin with a radiused tip, is positioned perpendicular to the other, usually a flat circular disk. A ball, rigidly held, is often used as a pin specimen. The test machine causes either the disk specimen or the pin specimen to revolve about the disk centre. In either case, the sliding path is a circle on the disk surface. The pin specimen is pressed against the disk at a specified load usually by means of an arm or lever and attached weights. The amount of wear is determined by measuring appropriate linear dimensions of both specimens before and after the test, or by weighing both specimens before and after the test [5].

Results & discussion:

Sliding Speed mm/s	Diesel engine oil - CoF	H2/diesel engine oil - CoF
100	0.127	0.124
600	0.118	0.113

Table 1: Coefficient of friction for the samples on different speeds

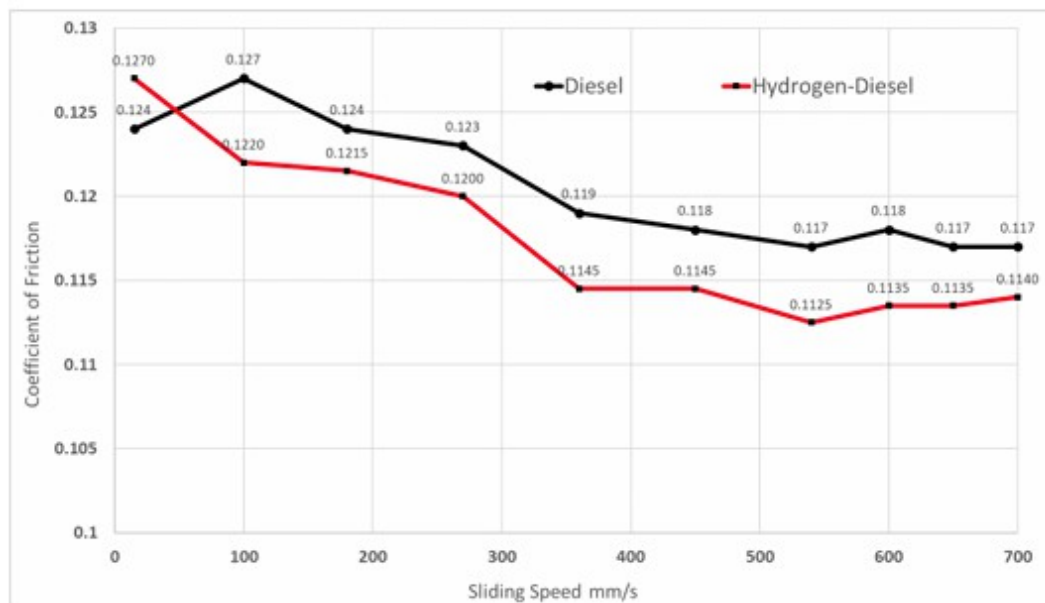


Figure 1: Comparison between CoF for the oil samples

In figure 1, we can see the results of pin-on-disk tests clearly stating that the diesel ICEs that are running with 20% hydrogen has lower CoF than the ones with diesel only, due to the water existence, as a by-product of hydrogen combustion.

The difference is not huge because the diesel engines we are testing are only using 20% hydrogen fuel on high torque only. So, all the time, we have diesel only, and at higher torques, 20% hydrogen is added to the mixture in the combustion chamber.

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Tribotronic System for Piston Ring Lubrication

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Abstract

Friction in the piston–cylinder assembly contributes up to 50% of total internal combustion engine friction, negatively affecting fuel efficiency and emissions. This study presents a novel tribotronic lubrication system that replaces the oil control ring and actively regulates oil delivery using oil film thickness as feedback. A floating liner test rig was developed to measure piston–liner friction and oil film thickness simultaneously. Experimental results demonstrated substantial friction reductions of up to 71.6% across different lubricant grades. The proposed system enables dynamic cylinder lubrication control, offering potential reductions in wear, fuel consumption, and carbon emissions across automotive, stationary, and marine engine applications.

1. Introduction

The integration of tribological components, such as gears, seals, and bearings, with advanced sensors, actuators, and intelligence technologies has resulted in revolutionary Tribotronic devices. These systems can dynamically adjust their functioning in response to various environmental and operational factors, offering significant potential advantages across a range of applications. One of the most promising benefits of Tribotronic devices is enhanced performance. They can optimise their operations to suit specific conditions, thereby maximising efficiency and output. Furthermore, their built-in intelligence provides real-time data on their performance and condition, enabling proactive maintenance and troubleshooting. Another advantage is their ability to autonomously adapt to changing circumstances, leading to smoother operation and improved reliability. This adaptability not only enhances performance but also contributes to extended equipment lifespan by minimising wear and tear. Moreover, Tribotronic devices offer the added advantage of reduced friction, resulting in lower energy consumption and operational costs. By dynamically adjusting friction levels, they mitigate power loss, thereby enhancing energy efficiency and sustainability.

2. System Configuration

Figure 1 illustrates the overall system layout. The cylinder liner is fitted with sensors that measure the oil film thickness, and these sensors are linked to an amplifier and the data acquisition system. Oil temperature is measured using a thermocouple, which is connected to an amplifier chip before sending the signal to the data acquisition system. Friction force is measured by Kistler force transducers, which are connected to the PXI chassis. The crank index and crank speed sensors are also connected to the PXI chassis to support data recording. Oil supply is accurately regulated by a syringe pump operated through a Nema 17 stepper motor, which is controlled by an Arduino Uno. The Arduino Uno is connected to a laptop for setting operating parameters, while the Arduino Mega is linked to the laptop for real-time monitoring and data acquisition, as well as for controlling oil delivery using the Tribotronic system algorithm.

3. Test Setup

The experiment followed a carefully controlled procedure using only two piston rings: a compression ring and a scraper ring. First, the cylinder liner was thoroughly cleaned with a solvent and then dried using highly absorbent tissue paper. Compressed air was then applied to the liner to ensure it was completely dry. This cleaning process was repeated several times to remove any remaining oil from previous tests and to ensure that the liner was in a clean initial condition.

The piston was positioned at the bottom dead centre, and the engine speed was fixed at 25 rpm. The oil syringe was filled with the required quantity of oil and placed at its starting position. Once the engine was

started, data collection began using the PXI chassis data acquisition system and continued for 120 seconds. This test duration was considered adequate to evaluate the system's effectiveness in reducing frictional force losses.

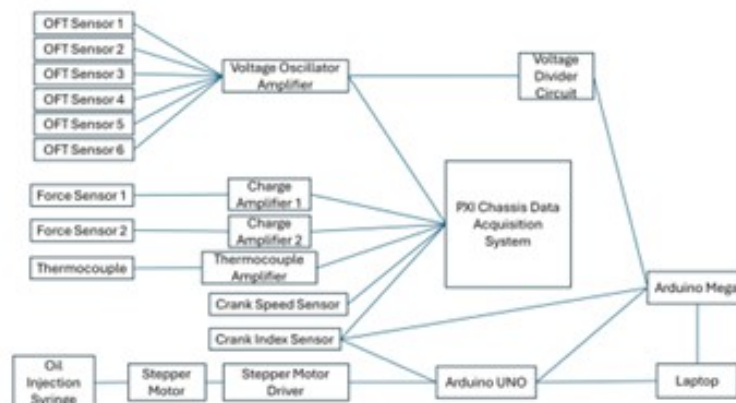


Figure 1: Block Diagram of Tribotronic Test Rig

4. Results

Figure 2 presents the instantaneous friction force alongside the automatic oil injection events during the first 40 seconds of the 120-second test. The orange pulses indicate the moments when oil was injected. The results demonstrate that the Tribotronic system gradually supplied oil in order to reduce and stabilise the friction force.

After 13 injection pulses, the oil film thickness reached the required level, as shown in Figure X. Although the recorded signal seems to show a decrease in oil film thickness, this was due to the sensor initially detecting air instead of oil, as air has a different dielectric constant. This response is reflected in the step change observed in the oil film thickness signal. Once enough oil reached the sensor position, the signal began to represent the actual oil film thickness. Therefore, the initially higher readings were associated with the presence of air rather than a thicker oil film.

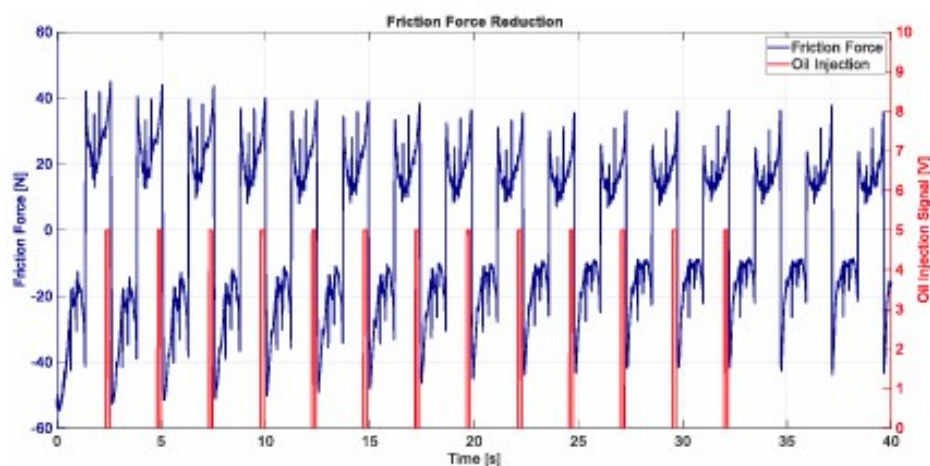


Figure 2: Instantaneous Friction Force

5. Conclusions

In summary, this paper presented a tribotronic system for a floating-liner engine that includes an oil injection with a feedback control system that is capable of adjusting the levels of the oil on the cylinder liner to minimise the friction force.

TRIBO 16 ID Low-Friction Diamond-Like Carbon Coatings for Tapered Roller Bearings: Design, Characterization and Tribological Performance

Controlled Synergistic Transition of Friction Mechanism in Ceramics with Lubricant system based on 2D nanostructures WSe₂ as a Tribological Trigger

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Abstract Two-dimensional tungsten diselenide (WSe₂) nanostructures synthesized at IPM NASU were applied as low-concentration oil additives and as solid-lubricant tribofilms for ceramic and metal–ceramic tribopairs. Tribological performance was evaluated using Ball-on-Flat and Four-Ball tests under extreme and dynamic loading conditions. The introduction of only 0.1–2 wt.% WSe₂ induces a pronounced nonlinear threshold effect, transforming adhesive friction into a stable mild-wear regime and reducing wear by several times. The protective action persists even after removal of the initially applied tribofilm, indicating a self-healing effect. WSe₂ nanostructures suppress adhesive junction formation, promote low-shear tribofilm development, and stabilize sliding. These results demonstrate the high potential of WSe₂ 2D nanostructures for advanced ceramic and hybrid tribosystems.

1. Introduction

Ceramic and metal–ceramic tribosystems are increasingly used in high-performance applications due to their high hardness, thermal stability, and chemical resistance. However, under extreme or dynamic loading conditions, these materials frequently suffer from adhesive friction, unstable sliding, and accelerated wear, which significantly limits their operational reliability. Conventional liquid lubricants and solid coatings often fail to ensure stable friction regimes in ceramic tribocontacts, especially when surface adaptation mechanisms are suppressed.

Recent advances in two-dimensional (2D) nanomaterials have opened new opportunities for controlling friction mechanisms at the nanoscale. Among them, tungsten diselenide (WSe₂) exhibits a lamellar structure with low shear strength, high thermal stability, and strong affinity to ceramic surfaces. When introduced either as a lubricant additive or as a surface-embedded tribofilm, 2D WSe₂ nanostructures can act as an active tribological trigger, inducing a controlled transition from adhesive friction to a stable mild-wear regime.

The present work focuses on elucidating the synergistic and threshold-type effects governing this transition in ceramic and metal–ceramic tribopairs lubricated with WSe₂-based systems. Particular emphasis is placed on dynamic loading conditions, long-term protection, and the emergence of self-healing behavior enabled by embedded 2D nanostructures.

2. Results and Discussion

Tribological tests were performed using Ball-on-Flat and Four-Ball configurations on SPS-consolidated Si₃N₄ + ZrN/TiN ceramic and metal–ceramic specimens under constant and oscillating normal loads. Tungsten diselenide (WSe₂) 2D nanostructures were introduced either as low-concentration additives to the lubricating oil or as solid-lubricant tribofilms on the contact surfaces.

In reference conditions, unmodified tribopairs exhibited unstable friction and pronounced adhesive wear. The introduction of WSe₂ at concentrations of only 0.1–2 wt.% resulted in a sharp reduction of friction and wear and induced a transition to a stable mild-wear regime. This transition shows a pronounced nonlinear threshold character and is especially evident under dynamic loading conditions, where conventional lubrication mechanisms are typically ineffective.

Measured friction coefficients decreased by several times compared to the reference system, while wear rates were reduced by factors of 3–7, depending on the test configuration and loading mode. SEM observations of wear tracks revealed smoother surfaces with suppressed adhesive junctions and reduced debris formation in WSe₂-modified systems.

A key result is the long-lasting protective effect of WSe₂ nanostructures. Stable low-friction behavior persisted even after the initially applied tribofilm was worn away, indicating the presence of embedded 2D nanostructures in the near-surface region of the tribopairs. This effect was reproducible across repeated tests. Fig 1.

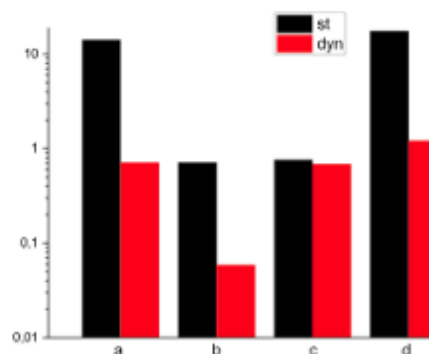


Fig. 1. Linear wear of ceramic components: **a** – reference Si_3N_4 without WSe_2 ; **b** – with grafted WSe_2 layer; **c** – grafted layer after washing with polar solvents (acetone, ethanol); **d** – grafted layer after repolishing. Dependence of wear [I] (μm) on mechanochemical treatment time (min) for ball specimens with diameters Ø13 mm and Ø6 mm under quasi-static (St) and dynamic (Dyn) loading modes.

As shown in Fig. 2, triboplateing of 2D- WSe_2 nanostructures onto ceramic ball surfaces by mechanochemical milling results in reduced wear compared to untreated balls when an optimal processing time is applied. The wear of the friction pair strongly depends on the counterbody diameter: balls with Ø13 mm exhibit 2–4 times higher wear than those with Ø6 mm, irrespective of the loading mode. Dynamic loading decreases wear for both diameters, but the effect is most pronounced for Ø6 mm, where wear remains low and stable (≈ 0.4 μm). For Ø13 mm, minimum wear is achieved at short treatment times (20–30 min), after which wear increases. These results indicate that smaller counterbody diameter and dynamic loading promote the formation and stabilization of a low-shear WSe_2 tribolayer, suppressing adhesive interactions and ensuring superior wear resistance.

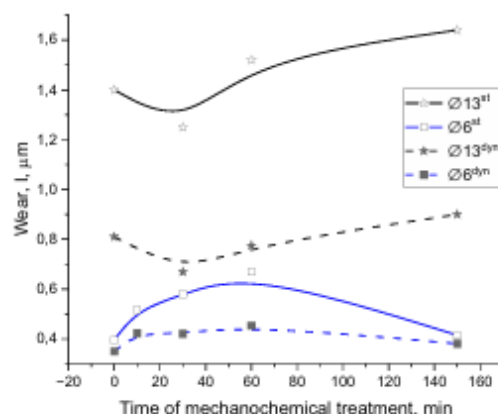


Fig. 2. Dependence of wear [I] (μm) on mechanochemical treatment time (min) for ball specimens with diameters Ø13 mm and Ø6 mm under quasi-static (St) and dynamic (Dyn) loading modes

5. Conclusions

The obtained results indicate that WSe_2 2D nanostructures act as an active tribological trigger. During sliding, aligned nanoplatelets promote the formation of a low-shear tribofilm, suppress adhesive interactions, and enable continuous regeneration of the lubricating layer through particle reintegration. This mechanism provides a self-healing effect and stabilizes friction under extreme and dynamic operating conditions.

Acknowledgments:

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Minimum energy sliding equilibrium model for redundant kinematic mechanism

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Abstract

Many mechanical systems exhibit kinematic redundancy, where identical global motion can arise from different local sliding configurations. In friction-dominated components, it is complicated to predict that sliding velocities and associated power losses. Axial piston pumps present a representative case, as the slippers interacting with the swashplate have unconstrained rotational degrees of freedom, leading to unknown local kinematics. This paper proposes a kinematic equilibrium model based on a minimum energy loss principle to determine the operating condition of the slippers without imposing constraints. Sliding velocities are formulated consistently with the global kinematics, friction forces are evaluated, and total power loss is minimized numerically. The approach provides physically consistent estimates of sliding patterns and friction losses, improving efficiency prediction in axial piston pumps.

1. Introduction

Redundant kinematic conditions are common in mechanical systems involving rolling or sliding contacts, such as rolling bearings, friction-driven transmissions, and hydraulic machines [1]. In such systems, identical global kinematics can be achieved through multiple local motion configurations, leading to different sliding velocities and frictional power losses. Traditional modelling approaches solve this redundancy by constraining degrees of freedom, computing reaction forces, and integrating friction losses accordingly. However, these assumptions do not necessarily correspond to the actual equilibrium state of the system and may lead to inaccurate loss predictions. Axial piston pumps are a representative example of this problem [2,3]. The slippers slide on the swashplate and are free to rotate relative to the pistons, resulting in multiple kinematically feasible configurations under the same operating condition.

2. Methodology

The model focuses on a single slipper–swashplate interface, where the slipper is allowed to rotate freely about its axis, while global kinematics are imposed by the pump rotational speed and swashplate geometry. External loads, including hydraulic pressure forces and inertial effects, are considered, and frictional forces arise at the contact interfaces (Figure 1a). To address kinematic redundancy, all sliding velocity contributions at the contact interface are formulated consistently with the global motion (Figure 1b).

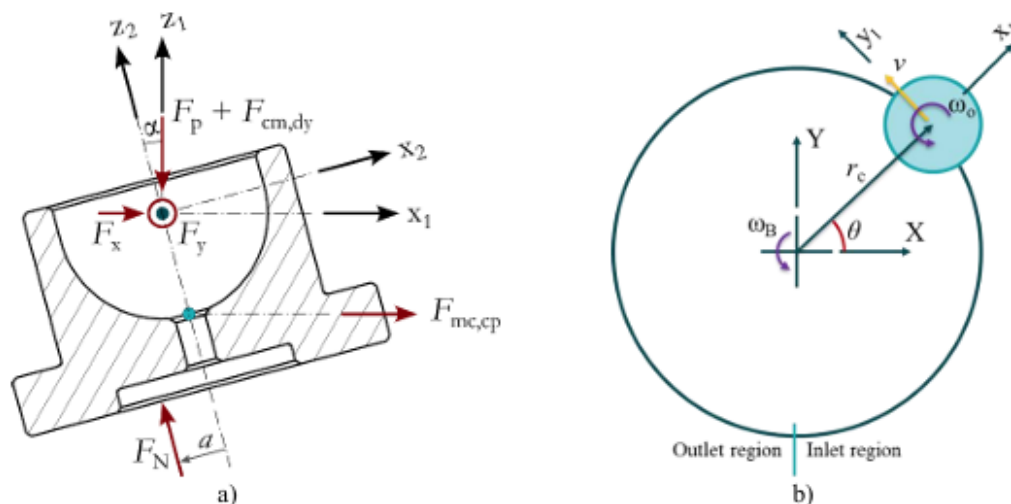


Figure 1: a) loads and reaction forces acting over the slipper of the axial piston pump; b) kinematic calculation region of an axial piston pump.

The local sliding velocity at any point (x,y) on the slipper surface is expressed as

$$v_s(X,Y) = \vec{r}_c \times \vec{\omega}_B + \vec{r}_s(x_1,y_1) \times \vec{\omega}_o \quad (1)$$

Where r_c is the position vector of the slipper centre, ω_B is the angular velocity imposed by the global motion, r_s is the local position vector on the slipper surface, and ω_o is the unknown slipper spin velocity. The total frictional power loss is computed by integrating the local dissipation over the contact surface A :

$$P_{loss} = \iint_A \tau \cdot v_s \cdot dA \quad (2)$$

where τ is the frictional shear stress. The kinematic equilibrium of the slipper is assumed to correspond to the condition that minimizes the total power loss. A numerical optimization algorithm is therefore used to determine the slipper spin velocity ω_o that leads to minimum energy dissipation while satisfying the global kinematic constraints.

3. Results and discussion

The proposed method was applied to a representative axial piston pump operating condition. Figure 2a shows the loads acting on the slipper in an entire revolution, considering the inlet and pump regions on the pump. Figure 2b shows the equilibrium rotational speed at each position on a entire revolution. Figure 2c shows the resulting frictional power loss distribution. The results show a well-defined minimum in total power loss, indicating a unique energetic equilibrium despite the kinematic redundancy.

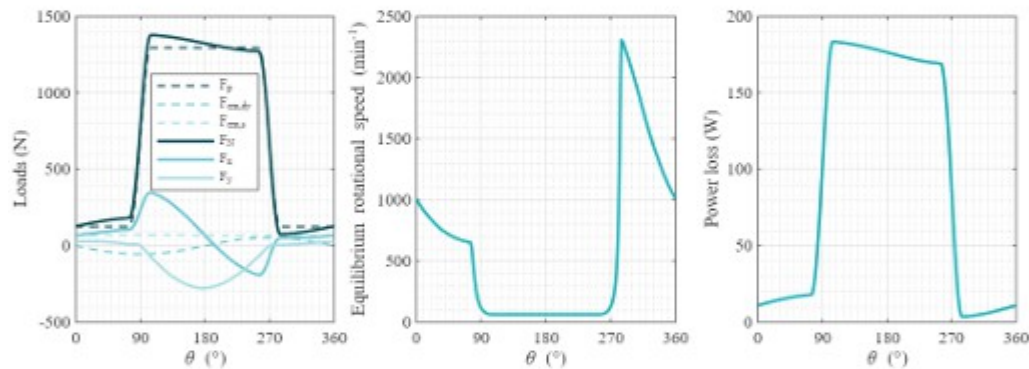


Figure 2: a) Loads and reactions act on the slipper on a single revolution; b) equilibrium rotational speed; c) power loss result of the slipper losses.

5. Conclusions

This work presents a minimum energy-based approach to determine kinematic equilibrium in redundant mechanical systems. The method is applied to axial piston pumps, where slipper rotation is not mechanically constrained. Instead of imposing a predefined kinematic condition, the model allows the slipper to rotate freely and identifies an equilibrium state that minimizes total frictional power loss.

The results indicate that the system naturally tends toward a minimum energy configuration within the redundant kinematic space. This approach provides a more realistic estimation of sliding velocities and friction losses and can improve efficiency predictions and design optimization of axial piston pumps and similar tribological systems.

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Torque loss in an angular contact ball bearing

Equations for Predicting the Minimum Oil Film Thickness in Reciprocating Hydrodynamic Line Contacts

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Abstract

In hydrodynamically lubricated reciprocating line contacts, it is known that the oil film thickness is not zero at the reversal points. Calculation of the minimum oil film thickness, and the position at which it occurs, usually requires a numerical solution of the Reynolds' equation that includes "squeeze" effects. Such a model has been developed, and many simulations have been carried out in which the amplitude, slider width, slider radius of curvature, viscosity, oscillation frequency, and applied load have been varied over a wide range. Useful approximate equations for both the maximum oil film thickness in the contact and the minimum oil film thickness (and its angular position) have been found and are reported here.

1. Introduction

Reciprocating contacts are commonplace in tribology. Examples include piston rings/valve trains in engines, oscillatory rolling element bearings, and reciprocating test rigs found in tribology laboratories. For hydrodynamic line contacts, it has been reported [1] that the oil film thickness in such a reciprocating contact is proportional to the square root of $\eta U/w$, where η is lubricant viscosity (Pa.s), U is the relative sliding speed of the surfaces (m/s) and w is the load per unit length (N/m) acting on the contact. For elastohydrodynamic line contacts, the central oil film thickness is proportional to $(\eta U)^{0.7}$. These simple equations would predict zero oil film thickness at the reversal positions.

In fact, it is known that the oil film thickness close to reversal positions is not zero, due to the presence of the "squeeze" term in the Reynolds' equation. There is no simple, widespread, equation currently available to tribologists that can be used to estimate the minimum oil film thickness in a reciprocating hydrodynamically lubricated line contact. The purpose of this paper is to propose just such an equation.

2. Numerical Solution of Hydrodynamic Line Contact, Including "Squeeze" Effects

A fast, robust, numerical Reynolds equation solver has been developed and implemented in Python. This has been used to calculate the oil film thickness variation in a hydrodynamic line contact, including squeeze effects. Typical results are shown in Figure 1 below. For the simulation that includes "squeeze" effects (the red line), the key parameters are h_{min} (m), h_{max} (m) and the angle Δ (°). The angle Δ is the shift in the position of the minimum oil film thickness position from the nearest reversal point. If "squeeze" effects are not included, then h_{min} and Δ are both zero.

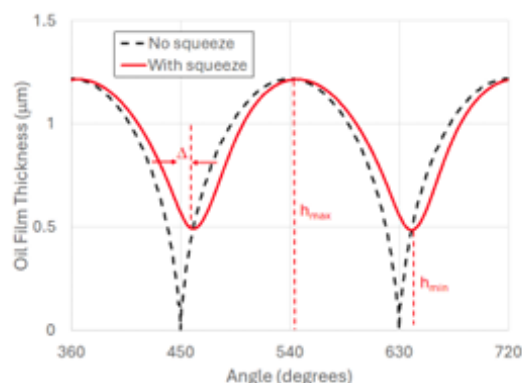


Figure 1: Calculated oil film thickness (μm) value versus angle ($^\circ$) for a reciprocating hydrodynamic line contact, with and without "squeeze" effects

The angle, shown in the horizontal axis of Figure 1, is simply equal to ωt , where t is time (in seconds) and ω (s^{-1}) is the rotational frequency of the reciprocating motion. The simulations assumed a symmetric, parabolic slider, and parameters: amplitude = 5 mm, frequency = 30 Hz, slider width = 0.5 mm, viscosity = 10 mPa.s, load per unit length = 100 N/m and slider radius of curvature = 0.026 m.

Many numerical simulations were performed, and the values of h_{min} , h_{max} and Δ were recorded for a wide variation of amplitudes, frequencies, slider widths, viscosities, loads and slider radii of curvature.

Using a combination of data analysis and data fitting, the following equations were found for h_{max} , h_{min} , and angle Δ . These equations were validated against experimentally measured oil film thickness data [2].

$$\frac{h_{max}}{b} = 0.2524 C_{max} \left(\frac{r}{r_o} \right) \sqrt{\frac{\eta \omega A}{P_{back} b}}$$

$$\frac{h_{min}}{b} = 0.22 C_{min} \left(\frac{r}{r_{sq}} \right) \left(\frac{A}{b} \right)^{0.25} \sqrt{\frac{\eta \omega}{P_{back}}}$$

$$\Delta \approx 35.0 \left(\frac{h_{min}}{h_{max}} \right) \left(\frac{b}{A} \right)^{0.25} + 51.1 \left(\frac{h_{min}}{h_{max}} \right)^2 \left(\frac{b}{A} \right)^{0.5}$$

Where, in the above equations, $C_{max}(r/r_o)$ and $C_{min}(r/r_{sq})$ are functions which allow for the oil film thickness variation with slider radius of curvature (and $C_{max}(r/r_o) = 1$ when $r = r_o$, and $C_{min}(r/r_{sq}) = 1$ if $r = r_{sq}$). Also, in the above equations, the angle Δ is in degrees.

Predictions from above equations have been compared with experimentally measured oil film thickness results [2], and reasonable agreement between the model and experiment has been found, which provides validation for this approach.

In addition, interesting insights have been found as to how the oil film asymmetry in reciprocating contacts (the difference in oil film thickness when the slider moves in different directions) is influenced by the parameter (A/b) .

5. Conclusions

Simple equations have been derived for h_{max} , h_{min} , and Δ , which give good agreement with full numerical simulations of the Reynolds' equation (including "squeeze" effects) and which have been found to be in reasonable agreement with experimental data.

In addition, interesting insights have been found as to the importance of the parameter (A/b) in determining both oil film thickness asymmetry in reciprocating contacts, and in determining the ratio of h_{min} to h_{max} (which surprisingly doesn't depend directly on η , U or w).

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Triboelectric wind turbine for Mars exploration

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The aim of this work is to design and develop an efficient Triboelectric Generator (TEG) integrated into a robust turbine demonstrator that can efficiently operate under Mars environmental conditions. A combination of low friction and high inherent triboelectric charge density materials have been integrated into the TEG architecture operating under a freestanding mode. The generator is compounded by a stator based on Al+PTFE and a rotor that involves a self-lubricating H-DLC coating specifically design for vacuum tribology. The system was evaluated under Earth and Mars atmospheric conditions, providing valuable outputs in terms of power generation and wear (lifetime). Moreover, the turbine mechanical elements such as blades, sealings, and vessel were designed, simulated, manufactured, assembled, and tested to achieve the correct operation based on Mars's environmental requirements.

Blade Health Monitoring of Turbo Propulsion Systems: Novel Modal-Based BTT and BTC Simulator with Experimental Validation

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Abstract

Blade failures are a serious form of turbine malfunction, and a means to detect signs of imminent failure through health monitoring would be valuable. Blade Tip Timing (BTT) is a non-contact method that uses casing-mounted probes to measure blade tip time of arrival (ToA), so it can be compared to expected ToA (EToA) to detect anomalous blade vibration [1]. Although BTT offers advantages such as simultaneous blade monitoring, durability, and potentially low cost, sensors and algorithms require extensive validation. This research develops a modal-based BTT and Blade Tip Clearance (BTC) simulation with crack simulation capabilities and validates data from it through controlled experiments on blade specimens. 5 mm deep cracks were placed at the root and found to produce an average reduction in natural frequency of 2.4%. The experimental results showed good agreement with ANSYS simulations, and a rotating rig is being developed to extend validation under more realistic operating conditions.

1. Introduction

Blade failures account for a significant proportion of turbine malfunctions, necessitating advanced health monitoring systems (BHM) [1]. BTT is a promising non-contact technology that employs stationary probes mounted on the engine casing to detect blade tip ToA during rotation. By comparing the ToA with the EToA, calculated as a function of blade tip radius, rotational speed, and circumferential position, BTT systems utilise advanced algorithms to convert this time displacement into measurable blade vibration. This potentially offers significant advantages to the BHM strategy, including simultaneous monitoring of all blades, longevity, and reduced cost compared with traditional measurement systems [2].

2. BTT Simulation

Developing robust BTT algorithms requires validation against controlled experimental data. Direct physical testing with actual turbines is costly, time-consuming, and offers limited parameter variation with limited reproducibility. BTT simulation addresses these challenges by providing controlled virtual data, thereby avoiding physical testing during initial algorithm development [3]. However, simulator accuracy depends on experimental validation to ensure predictions reflect realistic blade behaviour.

This research develops a modal-based BTT and BTC simulation model enhanced with novel crack capabilities, validated through systematic experimental testing. The BTT model employs a multi-software framework in which each tool performs a specialised role. SolidWorks was used to create accurate 3D models of a test blisk geometry, and ANSYS was used to perform finite element analysis to extract modal properties such as natural frequencies and mode shapes. MATLAB was then used for data processing, enabling communication among system components and computing blade tip displacements. Simulink was also used to solve the governing differential equations and simulate blade dynamic behaviour. Figure 1 presents details of the resonant behaviour, with the peaks in both plots representing the first and second blade modes. The BTT displacement increases sharply at the first peaks, and the tip clearance shows a corresponding strong deviation, indicating a dominant modal response matching with the first mode of the blisk at 532Hz. The second peak is smaller at 860Hz due to weaker modal participation at higher modes in continuous systems like rotating blades.

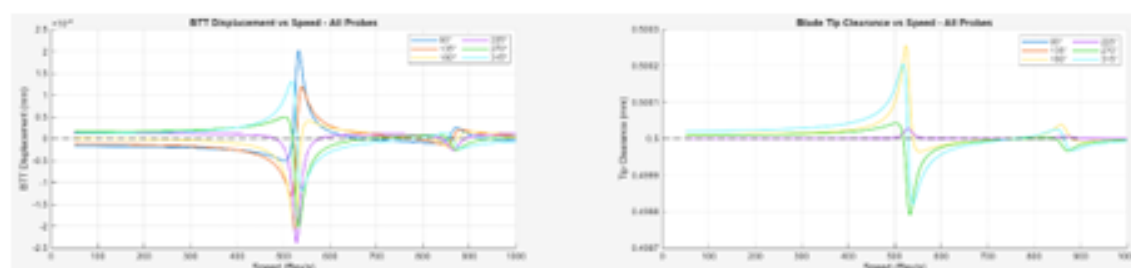


Fig.1: BTT and BTC displacement (mm) graphs against Speed (Rev/s)

3. Experimental Validation

Experimental validation utilised blade specimens and systematic testing to establish baseline datasets and validate ANSYS simulator predictions. Cut slots were introduced to simulate fatigue impact- cracks. Experiments and ANSYS simulations revealed measurable natural-frequency reductions: 5mm deep triangular slots resulted in an average reduction in frequency of 1.4%, while line cracks showed a 2.3% reduction in resonant frequency. Validation across multiple specimens demonstrated a correlation between experimental measurements and ANSYS simulations, as indicated in Figure 2. In these tests, an impact hammer and an accelerometer were used to measure resonant frequencies on the blades, which were also simulated using ANSYS Harmonic Response. The results from experiments and simulations fell within 6% of each other.

Figure 3 illustrates a rotating apparatus which is being developed using identical blade specimens, extending validation to realistic turbomachinery conditions. The equipment includes a multi-probe optical sensor array that will enable non-contact measurement during rotation, providing a simple operational environment while maintaining control over damage configuration. An electromagnetic blade excitation system will be deployed to introduce forces onto the blades to simulate real-world engine-order conditions in a controlled setting, such as mechanical wakes and non-uniform airflow.

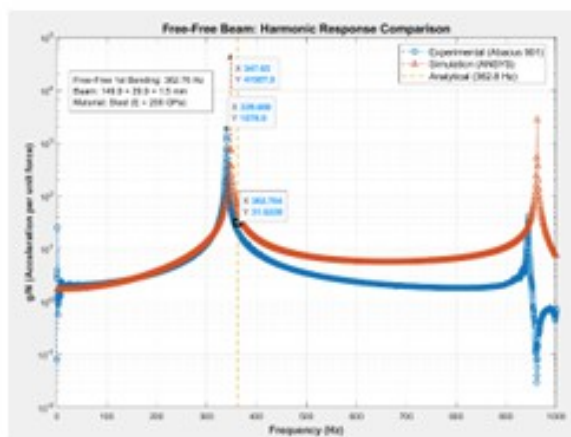


Fig.2: Harmonic response comparison graph

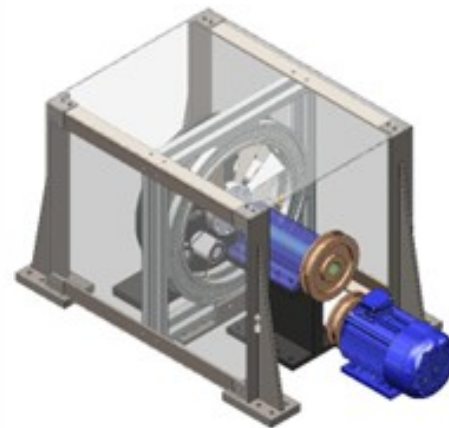


Fig.3: Experimental Rig CAD

5. Conclusions

BTT is a promising method of moving towards operational online blade health monitoring in turbines, with advantages compared to traditional methods. However, realising its full potential for crack and damage detection requires significant further development in terms of algorithm robustness, uncertainty quantification, and validation under realistic operating conditions. The work presented here contributes to this goal by establishing an integrated framework that combines a modal-based BTT and BTC simulation with experimental validation at both static and the planned dynamic levels. The framework will enable systematic evaluation of BTT-based blade health monitoring strategies under idealised conditions for simple in-service turbomachinery. This will support the development of comprehensive blade fault identification methodologies and contribute to future condition-based maintenance and life extension strategies for critical rotating components.

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Optical scatterometry-enabled phase-space representation for functional characterisation of tribological contacts

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In Persson contact mechanics, a rough surface is described by the height distribution $P(h)$ and the power spectral density $C(q)$, whose moments depend on the band-limit through a scale parameter ζ . Slope estimates from numerically differentiated profiles inflate uncertainty and limit cross-instrument comparability. We propose a phase-space density $\rho(h, h', \zeta)$ that combines profile-based topography with optical angular-resolved scattering (ARS), giving gradient-free access to $h'_{\text{rms}}(\zeta)$. The combination yields an experimentally accessible state variable for tribological contact monitoring, bridging to a thermodynamic description of surface states.

1. Introduction

In tribological systems, the topography of a contacting body is described as a solid-state property that is covered by the lubricant film in the hydrodynamic regime, so that the load is not carried by the roughness peaks [1]. In the boundary and mixed lubrication regimes, during tribological run-in, the load peaks at the contact points cause shearing of the non-load-bearing material, while unloaded portions of the surface remain untouched. This process is understood as geometric run-in, and the vertical material distribution, expressed as the bearing area curve, is used to characterize the contact properties. This model neglects both the geometry of the contact regions and their multiscale character. The most established continuum-mechanical framework is Persson's spectral contact mechanics, which provides the physical interpretation of the statistical description of rough surfaces as a Gaussian random process and has been refined into a diffusion-equation formulation [2]. However, the Surface Topography Challenge has revealed the metrological difficulty of this approach: even within identical measurement principles, experimentally determined surface spectra vary by several orders of magnitude [3]. We therefore propose a new measurement methodology that generalizes Persson's approach and, by combining topographic and spectral methods, renders the multiscale model metrologically accessible [4].

2. From height to slope: the metrological asymmetry of spectral roughness descriptors

Spectral parameters derived from topographically sampled data carry exceptionally large metrological uncertainties. Fig. 1 illustrates this on a simulated Gaussian profile: while height-based descriptors such as the bearing curve remain robust across measurement principles, the spectral and slope-based descriptors diverge by several orders of magnitude depending on instrument noise and filtering. While models assume the tip radius as the bandwidth limitation, in practice the instrument characteristic dominates the spectrum

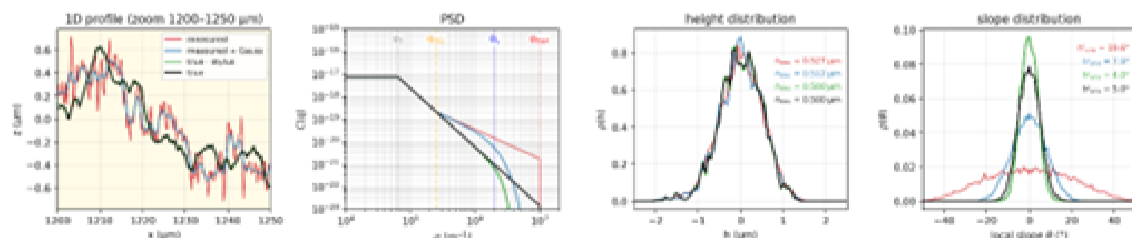


Fig. 1. Persson bandwidth picture of a rough Gaussian surface, $\zeta = q/q_0$, $q_{\text{max}} \approx 160$. True profile (black), stylus envelope morphologically band-limited at q_{bp} (green), measured profile with $1/f$ noise above q_{ACL} (red), Gauss-filtered measurement at $q_s = 2\pi/l_s$ (blue). h_{rms} remains invariant across all representations, while h'_{rms} diverges by a factor of five.

in the high-frequency range [5]. Slopes obtained by numerical differentiation of height data therefore amplify short-wavelength content and measurement noise, and their uncertainty depends strongly on lateral sampling, filtering, and instrument-specific artefacts. Since the diffusing pressure distribution in Persson's framework is governed by the scale variable ζ and dominated by the mean square slope $\langle (\nabla h)^2 \rangle$ as the second

moment of the slope distribution $\rho(h')$, the predictions of these models elude experimental verification through topographic measurement alone.

3. Angular-resolved scattering as gradient-free access to the slope distribution

Angular-resolved scattering (ARS) light measurement provides a fundamentally different access to the slope content of a rough surface. A focused beam illuminates the surface, and each microfacet of inclination θ reflects the incident light at twice the local slope angle, $\phi = 2\theta$. The angular intensity distribution $I(\phi)$ recorded on the detector array therefore represents, after coordinate transformation, the slope distribution $\rho(h')$ itself, directly and without numerical differentiation. The variance of this distribution, the Aq-parameter standardized in VDA 2009[6], corresponds to the second spectral moment $\langle(\nabla h)^2\rangle$ over the instrument's effective bandwidth $k_0(\zeta) \dots k_1(\zeta)$ and is traceable through a BRDF-based calibration chain to the SI unit of length [7]. ARS thus delivers $h'_{rms}(\zeta)$ that governs Persson's pressure diffusion as a direct measurement, while the height distribution $P(h)$ remains the domain of profile-based topography.

4. Phase-space fusion as a thermodynamical state of the surface

Topographic profilometry yields a robust height distribution $\rho(h)$, while ARS provides direct access to the slope distribution $\rho(h')$. Both can be combined into a joint density $\rho(h, h', \zeta)$ that captures the height and slope of every surface element on a single scale-dependent plane under appropriate constraints. The multiscale character of solid matter, ranging from grain structure through crystallites and atomic lattice to quantum-mechanical bond elasticity, restricts the spectral content of the surface to functional frequency bands. As shown in [8], this material-imposed band structure enforces a correlation between $\rho(h)$ and $\rho(h')$ and defines a scale-dependent quasi-Wigner distribution $\rho(h, h', \zeta)$. A maximum-entropy variation under the constraints of $h_{rms}(\zeta)$ and $h'_{rms}(\zeta)$ yields a Lagrange multiplier that maps the topography onto the elastic energy stored in the contact under load, providing an experimentally accessible phase-space state of the surface [8].

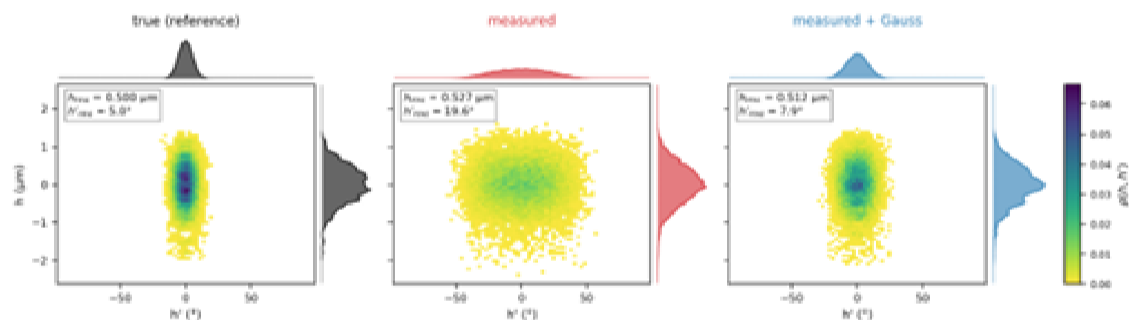


Fig. 2. Phase-space density $\rho(h, h')$ for the same Gaussian surface in three topographic representations, normalised to the true reference. $\rho(h)$ (top) is nearly invariant, while $\rho(h')$ (right) and $\rho(h, h')$ diverge by a factor of four. Direct ARS measurement of $\rho(h')$ is required to recover the correct phase-space state.

5. Conclusion & Outlook

The Lagrange multiplier from section 4 acts as the intensive variable conjugate to the elastic energy stored in the loaded contact, in analogy to inverse temperature. The maximum-entropy variation thereby promotes $\rho(h, h', \zeta)$ to a thermodynamic ensemble of surface states with a partition function over the multiscale frequency bands of the solid. Tribological run-in then appears as a relaxation of the surface ensemble towards lower free energy, accessible through the combined topography and ARS measurement of $\rho(h, h', \zeta)$.

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Advanced Tribological Testing Machines developed at TEKNIKER

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Abstract

The paper describes the advanced tribological machines developed, and constructed by TEKNIKER, to reproduce the failure mechanisms of the tribological systems and select materials, coatings and lubricants, under different environments and extreme working conditions (eg. Ultrahigh vacuum, thermal fatigue, tribocorrosion, drag friction induced by fouling, seals component testing, etc). Tribological machines have also been developed to realize triboremediation, that means decontamination by tribolytical reaction with simultaneous activation of reactants, transforming mechanical energy into chemical energy.

Keywords: Tribological machines, ultra-high vacuum, thermal fatigue, tribocorrosion, drag friction, seal testing, triboremediation

1. Introduction

TEKNIKER has developed tribological test benches and tribological studies for a wide variety of applications. The tribological characterization tools are used for material selection of the tribosystem (e.g., type of materials, surface treatments, lubricants). This knowledge makes it possible to simulate at laboratory a still wider list of tribological systems to implement materials solutions into energy and resource efficient products and processes, to reduce carbon footprint. [1] In this paper, it is also highlighted the development of a tribological testing machine, that consists of a triboreactor to realize triboremediation of waste.

2. Methodology

The key aspect of the tribological machines is to reproduce the failure mechanisms (pitting, scuffing, abrasion, adhesion, thermal fatigue, tribocorrosion, etc.) of a wide range of materials (seals, textiles, steels, cast iron, light alloys, ceramic, composites), and tribological systems (mechanical components, biomaterials, tribolubrication), and environments (vacuum, ultrahigh vacuum, low or high temperature, and corrosive).

In the case of the triboremediation, in the triboreactor, the science-based generation of nascent surfaces, under high pressures, and high shear forces provides the required activation energy for the dissociation of the C-Cl bond in PCBs, cell breakage and disintegration of pathogens [2], organofluoride waste (PFAS, fluoropolymers).[3]

3. Results

The following tribological testing machines have been developed by TEKNIKER:

- **Ball on Rod**, point contact rolling fatigue
- **Cylinder on Cylinder**, line contact rolling fatigue
- **Bearing tests** (radial and axial), to measure torque and wear.
- **Drag friction test**, for different applications (e.g., paints for ships, friction losses in heat exchangers)
- **Ultrahigh vacuum machine for tribological testing** with online mass spectra detection.
- **Outgassing measurement** of lubricants, polymers and coatings under vacuum conditions
- **Tribocorrosimeters** under oscillatory and rotatory conditions, to calculate mechanical wear, corrosive (chemical) wear, and their synergy.
- **Thermal fatigue test bench**, to simulate fatigue cracks combining cycles at high and low temperature

- **Gravelometer** to test the stone-chip (abrasives, screws) resistance to impact of coatings
- **Dynamometer test** for disc brakes wear and thermal fatigue studies.
- **Clutch dynamometer** test, to measure torque and wear
- **Seals bench test** to study seals tribological properties, under rotatory and oscillatory conditions, and different environments
- **Mirror tester:** to study abrasion resistance of solar mirrors (like car washer tester).
- **Triboremedy** Triboreactor to study the transformation of mechanical energy into chemical energy.

For example, TEKNIKER developed an **Ultrahigh vacuum tribometer for material testing** with online mass spectra detection. The main advantage of the system is that it allows *in operando* observation of the reactions occurring during the test.

An analysis of the results from the tests, supported by further surface analysis, allows us to better understand the dynamic of the tribolayer formation.

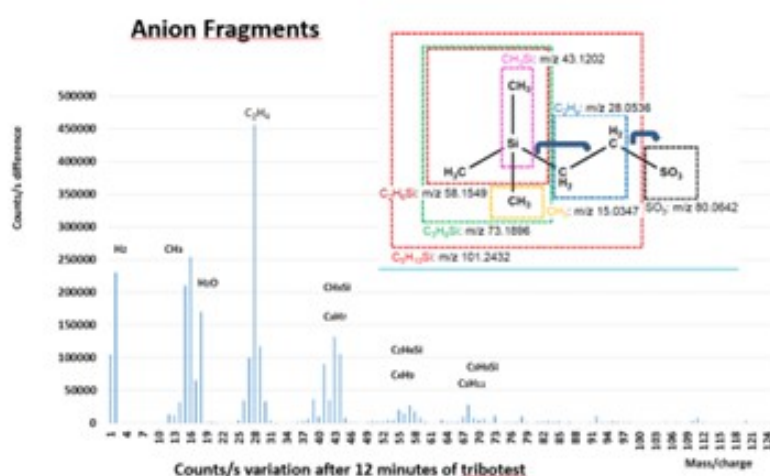


Fig. 1.- Anion fragments detected during tribotesting.

For triboREMEDY and TriFluorium projects instead, the objective was to transform mechanical energy into chemical energy, and to promote the degradation of persistent organic pollutants. For this reason, the effort was focused on developing a system that could operate in a wide range of environmental conditions and that could be operated safely to avoid the exposure of the user to the gases that could have been produced. Finally, for triboREMEDY was also developed a system that by using shear stress could eliminate the microorganisms present in water.

4. Conclusions

A huge range of new testing equipment and protocols have been developed to simulate failure mechanisms in tailored working environments. This knowledge makes it possible to study at laboratory, a wide list of tribological systems and develop new standards. The portfolio of testing machines has been enlarged to develop tribological testing machines to realize triboremediation, for decontamination of substances of concern.

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KN9 Carlos Miguel Mota GALP ENERGY

From Lubrication Practice to Data Driven Asset Insight: A Digital Approach to Lubrication Excellence and Condition Monitoring

COND13 ID Transforming Lubrication into Operational Intelligence

COND 14 ID 87 Standardization of Particle Detection and Counting in Lubricants: Concepts, Landscape, and Future Outlook

A Lightweight Algorithm to Verify Sensor Health in Wind-Turbine Lubrication-Oil Monitoring

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Abstract

Accurate monitoring of particle and bubble content in wind-turbine lubrication oil is crucial for assessing component wear and detecting emerging faults. Following recent monitoring trends, such monitoring can be performed remotely using oil particle monitoring sensors. Nevertheless, due to varied reasons sensors might provide incorrect measurements. This work presents an algorithmic approach that verifies the sensor readings used for this monitoring task and detects patterns indicative of abnormal operation. By identifying these deviations early, supports proactive maintenance decisions and helps maintain the accuracy of turbine health evaluations. The procedure is lightweight, ensuring low computational cost and suitability for real-time monitoring environments. The algorithm has been tested extensively on a wide range of real operational datasets from deployed wind turbines, demonstrating reliable performance across varying operating conditions and sensor units.

1. Introduction

Monitoring wind-turbine components through lubrication oil analysis is essential for predictive maintenance. Particles and bubbles in the oil indicate mechanical wear and emerging faults. Remote sensors now allow continuous monitoring, but readings can be affected by noise, drift, or inaccuracies, potentially compromising maintenance decisions. This work presents an efficient algorithmic framework that validates sensor outputs and detects patterns of abnormal operation. Tested on extensive real-world datasets, the method enables early detection of deviations, supporting proactive maintenance and improving sensors health assessment reliability.

2. Literature Review

The quality and reliability of wind turbine sensors have been studied to ensure safe and efficient operation. For example, Aljanaideh et al. (2025) propose a data-driven fault detection method for mechanical and operational sensors, including wind speed anemometers, rotor and generator speed sensors, blade pitch sensors, and nacelle accelerometers, using transmissibility operators to detect deviations without requiring system inputs [1]. This study extends the scope to sensors designed to detect bubbles and wear particles in wind turbine oil.

3. Method

3.1. Data The study uses data collected from 61 turbines distributed across four wind farms, comprising approximately 200,000 samples in total. Each dataset includes multiple measurements characterizing the condition of turbine oil. Specifically, the datasets contain ISO cleanliness values ($ISO \geq 4, 6, 14$), particle counts in several size ranges (particles $> 21 \mu m$, $> 38 \mu m$, $> 70 \mu m$), total particle count, and total bubble count. The ISO values indicate the cleanliness level of the oil according to the ISO 4406 standard, where higher values correspond to higher particle contamination and therefore a greater likelihood of wear. Measurements are taken at 10-minute intervals. In addition, an expert has assigned a binary label to each turbine data sample indicating sensor installation correctness.

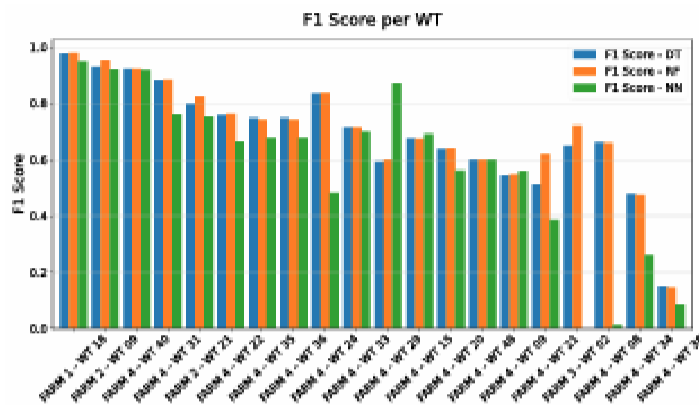
3.2. Preprocessing To prepare the data for analysis, a sliding window approach with a window size of 20 samples is applied. Within each window, both the mean and variance of the recorded variables are calculated. This preprocessing step smooths short-term fluctuations in sensor readings, mitigates the influence of transient noise, and captures the local dynamics of particle and bubble levels. By including variance in addition to mean, the method also preserves information about short-term variability, which can be indicative of emerging anomalies. The sliding window ensures that these statistics are computed continuously across the dataset, providing a stable and informative input for subsequent detection algorithms.

3.3. Models Three classification models were evaluated: Decision Tree (DT), Random Forest (RF), and Neural Network (NN). The Decision Tree was configured with a maximum depth of 7 and balanced class weights to handle class imbalance. The Random Forest consisted of 25 trees, each with a maximum depth of 7, using square-root feature selection at each split and balanced class weights. The Neural Network was implemented as a Multilayer Perceptron with a single hidden layer of 8 neurons, ReLU activation and Adam optimizer. All models were trained using 10 random seeds to improve robustness and reduce variability due to initialization.

3.4. Validation scheme The dataset is split at turbine level into 41 training turbines and 20 test turbines, ensuring that all data from a given turbine is contained entirely within either the training or test set to avoid data leakage.

Both sets include turbines from all four wind farms to ensure a balanced distribution of operational and environmental conditions across training and testing data. The F1-score is adopted as the primary evaluation metric due to the imbalanced nature of the dataset, where normal operating conditions significantly outnumber faulty ones. The positive class corresponds to abnormal sensor behavior, which is rarer than normal operation. We also measure computational efficiency by reporting training time and single-sample inference latency for each model, as the goal is to obtain a lightweight and efficient algorithm suitable to be embedded on the sensor.

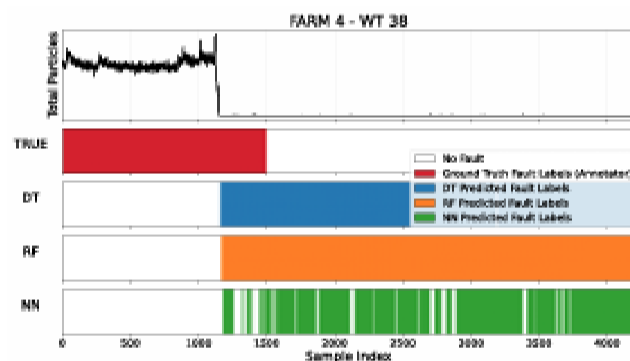
4. Results



The graphs presented here report the F1-score computed from the predictions of each model for every wind turbine in the test set. The F1-score is computed per turbine to evaluate model performance across different turbine types, environments, and individual units. Additionally, we report the training time and inference (test-time) per sample for each model: DT — training: 0.410056 s, test: 3.0×10^{-8} s; RF — training: 2.159456 s, test: 3.7×10^{-7} s; NN — training: 11.354078 s, test: 1.7×10^{-7} s.

The results show that Decision Tree (DT) and Random Forest (RF) outperform the Neural Network (NN), which is overly complex for the dataset and less effective. The NN also has higher training costs, making it less suitable for lightweight applications. In contrast, tree-based models achieve a better balance between performance, efficiency, and alignment with expert annotations.

Overall, the average F1-score across all turbines in the test set is approximately 0.7 for DT and RF, although performance varies across turbines. In several cases, the models show systematic disagreement with expert labels. For example, in the worst-performing turbine, the model predictions are observed to be approximately the inverse of the annotated labels. This behavior indicates a potential inconsistency in the labeling process rather than a pure model deficiency. Specifically, the segments classified as “not working sensor” by the model coincide with intervals in which the particle-related signal remains constant at zero, whereas the annotator indicates that the sensor is functioning properly during these periods. These observations suggest that the proposed models may also serve as a consistency check on human annotations. Systematic divergences between model predictions and labels could highlight cases where expert labeling is overly generalized or potentially inaccurate.



5. Conclusions

This work presented a lightweight, real-time framework for validating oil particles and bubble sensor readings in wind turbine lubrication systems, demonstrating that tree-based models achieve strong performance with minimal computational cost compared to more complex neural approaches. Experimental results on real operational datasets demonstrate strong agreement with expert annotations, while also revealing potential inconsistencies in the annotation process. This suggests that the approach is a promising solution for sensor data quality validation in condition monitoring systems.

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Goodbye “Ghost Particles”: Improving Particle Counting Accuracy with the ASTM D7647 Dilution Method

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Abstract

ASTM D7647 is the ASTM-recommended dilution method for particle counting of in-service lubricants by light extinction. Although the method was specifically designed to eliminate counting errors caused by water and “soft” particles such as varnish and additive precipitates, the diluent list in Annex A1 (Table A1.1) admits both water-masking solvents (75 % toluene / 25 % isopropanol, dipropylene glycol n-propyl ether) and non-water-masking solvents (kerosene, Stoddard solvent, lamp oil). This investigation evaluated seven diluent options on eight lubricants spanning mineral, PAO, PAG and ester chemistries (126 individual analyses). Counts on a varnish-laden turbine oil rose from a 71,996 particles/mL undiluted reference to 142,505 (kerosene, 1:1) and 223,460 (Stoddard solvent - Varsol, 1:2) — increasing further with dilution. On an MTD calibration fluid spiked with 1 % water, the same non-water-masking diluents returned counts of 165,885–250,312 particles/mL versus a dry reference of 10,758. Across the eight samples, solvent choice alone moved the reported >4 µm(c) ISO 4406 cleanliness code by up to 12 codes — a factor of more than 4,000 in particle concentration on the same fluid. We propose limiting the D7647 diluent list to a Toluene/IPA mixture (75:25 or 90:10) and DPnB, and present evidence that 90 % toluene / 10 % isopropanol is the best overall performer when used at 1:2 sample-to-diluent dilution.

Keywords: particle counting, ASTM D7647, water masking, soft particles, varnish, dilution, ghost particles, ISO 4406, in-service lubricants.

1. Introduction

Solid particulate contamination is the dominant cause of mechanical wear and failure in lubricated and hydraulic systems. Particle counting by automatic optical particle counters (APCs) operating on the light-extinction principle has been the standard tool for monitoring this contamination for more than three decades. APCs detect a particle when its passage through a laser-illuminated sensing zone produces a transient drop in transmitted light intensity; the magnitude of the drop is converted to an equivalent particle size using a calibration curve derived from ISO 11171 [1].

This optical principle is non-discriminating. Anything that occludes the beam — a solid particle, an air bubble, a water droplet, an inhomogeneous region of soft varnish or sludge — is recorded as a particle. Water and soft contaminants therefore produce “ghost particles”: optical events that do not correspond to wear-relevant solids and that artificially inflate the reported cleanliness code, sometimes by orders of magnitude.

ASTM D7647, “Standard Test Method for Automatic Particle Counting of Lubricating and Hydraulic Fluids Using Dilution Techniques to Eliminate the Contribution of Water and Interfering Soft Particles by Light Extinction” [2], was introduced in 2010 specifically to address this problem. Its title is unambiguous: a dilution method whose purpose is to eliminate the contribution of water and soft particles. In practice, however, the method as written is non-specific about how that elimination is achieved. Annex A1 (Table A1.1) of the current revision, D7647-24, lists six allowable diluents — only two of which (75 % toluene / 25 % isopropanol, hereafter “75/25 T/IPA”, and dipropylene glycol n-propyl ether, hereafter “DPnB”) are classified as “water-masking” in the standard’s own definition (§ 3.2.8.1) [2]. Of the remaining four — kerosene, lamp oil, Stoddard solvent and 67:33 lamp oil:DPnB — the first three have no recognised ability to dissolve water at any level and, as the data presented here will show, also fail to keep many soft contaminants in solution after dilution.

The consequence is well documented. The temporary precision statement in Section 14 of D7647-24 reports reproducibility limits that are several times wider than the analogous limits for ISO 11500 on clean reference fluids. Round-robin and interlaboratory study (ILS) results have repeatedly shown unacceptably broad scatter, with the same sample drawing both the cleanest and the dirtiest result of any laboratory in a

given study — a pattern that becomes intelligible once it is recognised that participating laboratories have been free to choose any solvent in Table A1.1.

This paper revisits a 2023 investigation in which seven candidate diluents (six listed in Table A1.1 plus one new candidate — 90 % toluene / 10 % isopropanol, hereafter “90/10 T/IPA”) were evaluated on a panel of eight lubricants representing the principal in-service oil chemistries seen in industrial laboratories, plus a calibration fluid (MTD CAL) spiked with 1 % and 2 % distilled water. The dataset comprises 126 individual particle-counter analyses. The paper has three goals: (i) to quantify, on common samples, the magnitude of the “ghost particle” error introduced by non-water-masking diluents; (ii) to compare the two water-masking diluents already in Table A1.1 against a 90/10 T/IPA blend that has not previously appeared in the standard; and (iii) to support a forthcoming D02.96.05 ballot to remove non-water-masking diluents from D7647 and to add 90/10 T/IPA as a permitted alternative.

2. The ASTM D7647 method and the diluent table

D7647 is built around four sequential operations: agitation, dilution with a Table A1.1 diluent at typically 1:1 sample:diluent (mass basis, ~50 % undiluted fraction), agitation and degassing of the diluted sample, and triplicate counting through a sensor calibrated to ISO 11171. The dilution step has two purposes. The first is to bring the viscosity of high-viscosity gear and compressor oils down into the operating envelope of the APC (~1–10 cSt at the sensor inlet). The second — and the one that justifies the method’s existence — is to dissolve free or emulsified water and to dissolve soft contaminants such as varnish, oxidation product and additive precipitates so they no longer occlude the beam.

The standard is explicit that only two of the six listed diluents — 75/25 T/IPA and DPnB — are water-masking (§ 3.2.8.1, [2]). It is silent on whether soft particles dissolve in the non-water-masking solvents. The temporary precision statement (§ 14.1) is based only on diluents marked with an asterisk in Table A1.1, which are lamp oil and DPnB; the published precision is therefore not representative of the toluene/IPA blends used by many in-service laboratories. This combination — a permissive diluent list, an inconsistent precision basis, and an interlaboratory study population that mixes water-masking and non-water-masking solvents — is the structural cause of the ILS scatter reported by Subcommittee D02.96.05.

3. Materials and methods

3.1 Lubricant samples

Eight lubricants and a calibration fluid were selected to span the principal base-stock chemistries and viscosity grades encountered in industrial in-service oil analysis. The panel deliberately mixes used oils (where soft particle contamination is realistic) and fresh oils (where the count from a competent dilution should approach the count obtained on the undiluted sample). Sample details are summarised in Table 1.

Sample	Viscosity grade	Status	Base stock	Description
Mobil DTE 846	ISO 46	Used	Group II mineral	Turbine oil with high level of varnish contamination
Erving Synthetic Compressor	ISO 46	Fresh	Group IV PAO	PAO compressor oil
Mobil DTE 10 EXCEL 46	ISO 46	Fresh	Mineral / PAG	High-performance anti-wear hydraulic oil
Mobil Gear 600XP220	ISO 220	Fresh	Mineral	EP industrial gear oil
Mobil SHC Gear 320	ISO 320	Fresh	PAO	Synthetic industrial gear oil
PetroCanada ATF D3M	ISO 46	Fresh	Mineral	C4 automatic transmission fluid
IR SSR Compressor (Ultra Coolant)	50 cSt @ 40 °C	Used	PAG / ester	Polyglycol/ester compressor coolant
PC Purity FG PAG Gear Oil	ISO 460	Used	PAG	Food-grade synthetic gear oil
MTD calibration fluid (± 1 %, 2 % H ₂ O)	ISO 15	Spiked	Mineral	ISO 11171 calibration fluid, used for the water-masking test

Table 1. Lubricant panel used in this investigation.

3.2 Diluents

Seven diluents were evaluated. Five appear in D7647-24 Table A1.1; one (90/10 T/IPA) is a new candidate; one (100 % butyl glycol) was tested as a possible cost-reduced alternative to DPnB. Toluene, isopropyl alcohol (IPA), butyl glycol, DPnB and K1 kerosene were obtained from Caledon Laboratory Chemicals or Sigma-Aldrich; Stoddard solvent (Varsol) was obtained at retail. All diluents were filtered through 0.45 μm polycarbonate membranes before use, with the contribution of the filtered diluent confirmed to be less than 12.5 % of the total counts in the diluted sample, as required by D7647-24 § 8.2 [2]. Diluent compositions are listed in Table 2.

Diluent (volumetric)	In D7647-24 Table A1.1?	Water-masking?	Rationale for inclusion
100 % butyl glycol (ethylene glycol n-butyl ether)	No	Partial	Cheaper alternative to DPnB
75 % toluene / 25 % IPA	Yes (water-masking)	Yes	Listed water-masking diluent
100 % DPnB (dipropylene glycol n-propyl ether)	Yes (water-masking)	Yes	Listed water-masking diluent
100 % kerosene (K1)	Yes	No	Listed non-water-masking diluent
100 % Stoddard solvent (Varsol)	Yes	No	Listed non-water-masking diluent
90 % toluene / 10 % IPA	No	Partial	Reduced-IPA candidate; less aggressive
67 % kerosene / 33 % DPnB	Equivalent to 67 % lamp oil / 33 % DPnB in A1.1	Partial (DPnB-driven)	Original ILS diluent for D7647:2010

Table 2. Diluents evaluated. “Water-masking” status is per D7647-24 § 3.2.8.1 [2].

3.3 Sample preparation and instrumentation

All counts were obtained on a single CINRG Systems APC22M auto-diluting particle counter equipped with a Klotz 45/50 sensor calibrated to ISO 11171. The instrument has a coincidence threshold of 25,000 particles/mL. Samples were homogenised by mechanical agitation followed by ultrasonic degassing (60 s, 40 kHz) and were transferred into 30 mL MC79 medicine cups. Sample volume was determined automatically from sample-height measurements with an accuracy of ± 0.3 mL at the 15 mL working volume. Each sample was diluted at two nominal sample-to-diluent ratios — 1:1 (undiluted fraction ≈ 0.5) and 1:2 (undiluted fraction ≈ 0.3) — with the actual undiluted fraction calculated gravimetrically and recorded for each measurement. Diluted samples were stirred for 60 s and counted within 90 s of agitation, in accordance with D7647-24 § 4.7 [2].

Each diluted sample was sampled at 30 mL/min through three sequential 7 mL counts on a single 23 mL syringe fill, with the first 2 mL dispensed to waste and only the central 5 mL of each 7 mL count quantified. Reported particle concentrations are the mean of the three 5 mL counts. ISO 4406 codes were calculated independently for each of the three counts and an average code reported. The dataset comprises 126 individual analyses across the eight samples, two dilution ratios and seven diluents, plus undiluted references where viscosity permitted. The complete dataset is available in the supplementary spreadsheet.

4. Results and discussion

4.1 Soft particle interferences: the Mobil DTE 846 used turbine oil

Mobil DTE 846 was sampled from a 24 MW turbine after several thousand hours of service. Visual inspection showed the colour and faint cloudiness associated with varnish formation; FT-IR confirmed elevated oxidation in the 1740 cm^{-1} region. Counts on the undiluted reference were 71,996 particles/mL $> 4 \mu\text{m(c)}$, corresponding to ISO 23/23/19. Counts on each diluted sample are presented in Table 3 and Fig. 1.

Diluent	U fraction	>4 $\mu\text{m(c)}$ per mL	>6 $\mu\text{m(c)}$ per mL	ISO 4406 code	Verdict
Undiluted reference	1.00	71,996	52,788	23/23/19	ref
75/25 T/IPA (1:1)	0.46	121	52	14/13/10	good
75/25 T/IPA (1:2)	0.31	129	54	14/13/10	good
90/10 T/IPA (1:1)	0.52	180	68	15/13/10	good
90/10 T/IPA (1:2)	0.30	76	27	13/12/9	good
DPnB (1:1)	0.49	141	60	14/13/11	good
DPnB (1:2)	0.32	79	35	13/12/10	good
67/33 K/DPnB (1:1)	0.49	1,081	334	17/16/13	marginal
67/33 K/DPnB (1:2)	0.32	120	43	14/13/10	good
Butyl glycol (1:1)	0.48	99	31	14/12/9	good
Butyl glycol (1:2)	0.31	162	67	15/13/11	good
Kerosene (1:1)	0.46	142,505	80,286	24/24/18	ghost
Kerosene (1:2)	0.29	193,128	74,317	25/23/16	ghost
Stoddard solvent (Varsol) (1:1)	0.49	138,949	89,120	24/24/19	ghost
Stoddard solvent (Varsol) (1:2)	0.28	223,460	118,433	25/24/18	ghost

Table 3. >4 $\mu\text{m(c)}$ and >6 $\mu\text{m(c)}$ counts on Mobil DTE 846 used turbine oil for each diluent and dilution ratio. Green = approaches the true count of dissolved varnish; red = ghost particles; yellow = marginal. The undiluted reference is shaded grey.

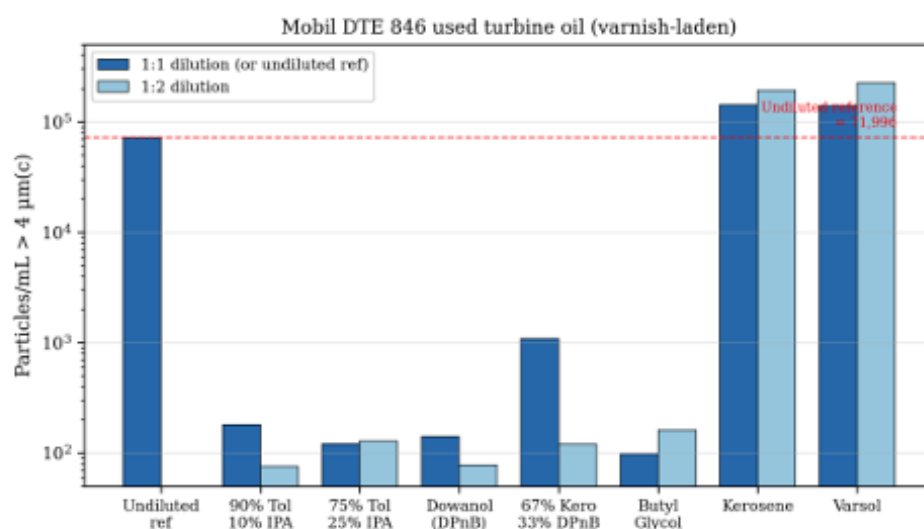


Fig. 1. >4 $\mu\text{m(c)}$ particle concentration in Mobil DTE 846 used turbine oil by diluent (log scale). The dashed horizontal line is the undiluted reference. Bars exceeding the reference indicate that the dilution step has created "ghost particles" rather than removing them.

Three behaviours are visible. The water-masking diluents (75/25 T/IPA, 90/10 T/IPA, DPnB) and butyl glycol all return counts in the range 76–180 particles/mL >4 $\mu\text{m(c)}$. This is the count that survives once the varnish has been fully dissolved into the diluted matrix; it is approximately 400–1,000 $\times$ lower than the undiluted reference, which is consistent with the qualitative observation that the bulk of the >4 $\mu\text{m(c)}$ signal in the undiluted sample is varnish, not solid wear debris. The 67/33 K/DPnB blend returns 1,081 particles/mL at 1:1 but recovers to 120 at 1:2, indicating that the kerosene fraction approaches its solubility limit for this varnish at high sample loadings.

Kerosene and Stoddard solvent (Varsol) behave fundamentally differently. At a 1:1 dilution, both produce counts that are approximately 2 $\times$ the undiluted reference; at 1:2 dilution, both produce counts that are 2–3 $\times$ the 1:1 result. Diluting the sample further makes the count rise. The only mechanism that can produce

this signature is the precipitation of varnish from the diluted phase as the kerosene/Stoddard solvent (Varsol) fraction increases — the ghost particle problem the standard was created to eliminate. The reported ISO codes confirm the magnitude of the error: 25/24/18 for Stoddard solvent (Varsol) at 1:2, against 13/12/9 for 90/10 T/IPA at 1:2 — a 12-code disagreement on the same sample. Each ISO 4406 code represents a factor of two in particle concentration, so the same fluid is being characterised as more than four orders of magnitude apart in cleanliness depending only on which solvent the laboratory chose to use.

4.2 Water masking: the MTD calibration fluid spike test

To isolate the water-masking question from the soft-particle question, MTD calibration fluid was spiked with 1 % and 2 % distilled water by mass and analysed against a dry MTD reference (Table 4 and Fig. 2). The dry reference returned 10,758 particles/mL $>4 \mu\text{m(c)}$ (ISO 21/19/16). The undiluted MTD + 1 % H_2O sample returned 37,319 particles/mL with all six ISO codes saturated at 22 across all sizes, the unmistakable signature of a water haze.

Diluent	Sample	U fraction	$>4 \mu\text{m(c)}$ per mL	ISO 4406 code
None (dry reference)	MTD dry	1.00	10,758	21/19/16
None (water reference)	MTD + 1 % H_2O	1.00	37,319	22/22/22
75/25 T/IPA (1:1)	MTD + 1 % H_2O	0.44	10,877	21/19/16
75/25 T/IPA (1:2)	MTD + 1 % H_2O	0.34	11,117	21/19/15
75/25 T/IPA (1:1)	MTD + 2 % H_2O	0.43	10,393	21/19/16
75/25 T/IPA (1:2)	MTD + 2 % H_2O	0.30	10,845	21/19/15
DPnB (1:1)	MTD + 1 % H_2O	0.43	11,451	21/19/16
DPnB (1:2)	MTD + 1 % H_2O	0.28	11,773	21/19/16
DPnB (1:1)	MTD + 2 % H_2O	0.49	10,440	21/19/17
DPnB (1:2)	MTD + 2 % H_2O	0.28	9,578	20/19/17
90/10 T/IPA (1:1)	MTD + 1 % H_2O	0.41	23,623	22/21/21
90/10 T/IPA (1:2)	MTD + 1 % H_2O	0.27	8,881	20/19/16
90/10 T/IPA (1:1)	MTD + 2 % H_2O	0.46	103,864	24/24/23
90/10 T/IPA (1:2)	MTD + 2 % H_2O	0.27	36,516	22/21/21
Butyl glycol (1:1)	MTD + 1 % H_2O	0.44	14,561	21/20/16
Butyl glycol (1:2)	MTD + 2 % H_2O	0.32	15,369	21/20/16
67/33 K/DPnB (1:1)	MTD + 1 % H_2O	0.51	23,646	22/21/21
67/33 K/DPnB (1:2)	MTD + 1 % H_2O	0.28	11,186	21/20/18
Kerosene (1:1)	MTD + 1 % H_2O	0.46	170,500	25/25/24
Kerosene (1:2)	MTD + 1 % H_2O	0.31	250,312	25/25/25
Stoddard solvent (Varsol) (1:1)	MTD + 1 % H_2O	0.47	165,885	25/24/24

Table 4. $>4 \mu\text{m(c)}$ counts and ISO 4406 codes on MTD calibration fluid with 0 %, 1 % and 2 % water spike, by diluent and dilution ratio.

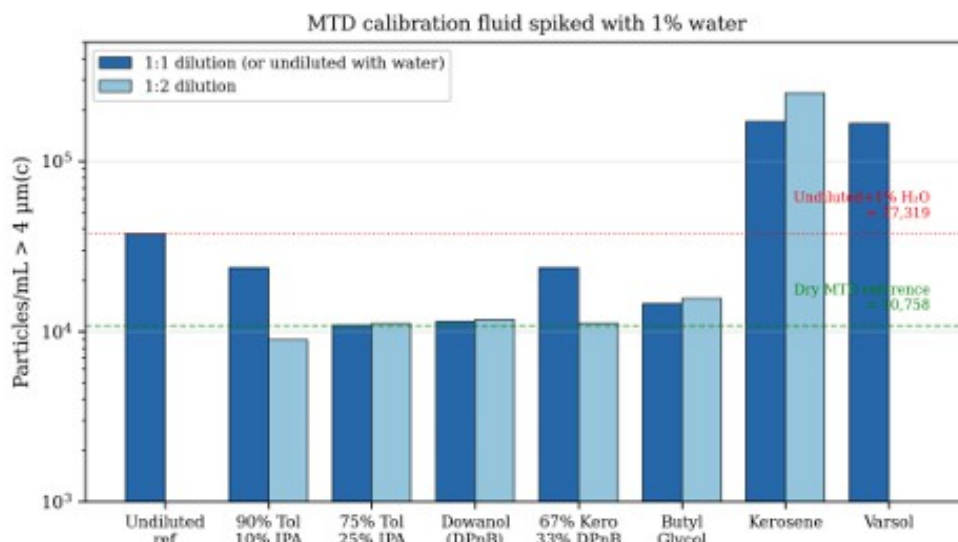


Fig. 2. $>4 \mu\text{m(c)}$ counts on MTD calibration fluid spiked with 1 % water (log scale). Green dashed line: dry MTD reference. Red dotted line: undiluted MTD + 1 % water. A diluent that masks water should pull the count from the red line down to the green line; a diluent that does not mask water leaves the count at the red line or higher.

The 75/25 T/IPA blend masks 1 % and 2 % water at both 1:1 and 1:2 dilutions, returning counts within 5 % of the dry reference and ISO codes identical to the dry reference. DPnB matches this performance at 1 % water and is one half-code worse at 2 % water. These two diluents are correctly identified as water-masking by D7647-24 § 3.2.8.1.

Kerosene and Stoddard solvent (Varsol) return counts an order of magnitude higher than the undiluted spiked sample, which is the expected behaviour: not only do they fail to dissolve the water haze, the additional non-polar solvent further reduces the IPA-equivalent activity of the diluted phase and encourages additional water droplet formation as the solvent evaporates from the syringe. ISO codes saturate at 25/25/24 (kerosene 1:1) and reach 25/25/25 at 1:2 — the maximum reportable value across all three sizes. These results confirm that kerosene and Stoddard solvent (Varsol) have no role in any sample where water contamination is even a possibility, and that the standard's practice of permitting an operator to choose them at the bench is unwise.

The 90/10 T/IPA blend, with its reduced IPA fraction, masks 1 % water successfully only at 1:2 dilution (ISO 20/19/16, count 8,881 — within 18 % of the dry reference). At 1:1 dilution it masks an effective 0.5 % water but fails at 1 %. At 2 % water it fails at both dilutions. This is consistent with the expected polar-solvent stoichiometry: at a 1:2 dilution the diluted sample contains ≈ 6.7 % IPA, of which ≈ 1 % is available to dissolve the water phase — sufficient for typical in-service oils, which rarely accumulate more than 0.5–1 % free water before being flagged for action. Operators using 90/10 T/IPA as a routine diluent must therefore use a 1:2 sample-to-diluent ratio whenever water is suspected and must fall back to 75/25 T/IPA for samples with very high water (>1 %) loading.

4.3 Cross-sample performance and the magnitude of the ILS problem

Fig. 3 summarises the $>4 \mu\text{m(c)}$ count returned by each diluent on each sample, normalised so that the lowest count for that sample = 1 $\times$. Reading the figure horizontally shows that 90/10 T/IPA is the lowest-counting diluent on six of the seven oil samples in which it could be measured, and is within 1.5 $\times$ of the lowest on the seventh (the IR SSR PAG/ester compressor coolant). 75/25 T/IPA is consistently within 1.5 $\times$ of 90/10 T/IPA. DPnB is generally close behind, with two notable insolubility failures (Mobil SHC Gear 320 and PC Purity FG PAG, where neither DPnB alone nor butyl glycol could keep the sample in solution).

Reading the figure vertically tells the ILS story. The same sample, the same particle counter, the same operator, the same calibration fluid — only the choice of diluent varies — and the reported count moves by 100 $\times$ to 4,000 $\times$. The corresponding ISO 4406 code at $4 \mu\text{m(c)}$ varies by 3 codes (Mobil DTE 10 EXCEL 46, the cleanest sample) up to 12 codes (Mobil DTE 846, the varnish-laden used turbine oil). For reference, the temporary D7647-24 reproducibility limit for the $4 \mu\text{m(c)}$ channel is approximately 1.5 ISO codes [2]; the diluent-driven disagreement we observe is between 2 $\times$ and 8 $\times$ the published reproducibility, and it is a systematic bias rather than random scatter.

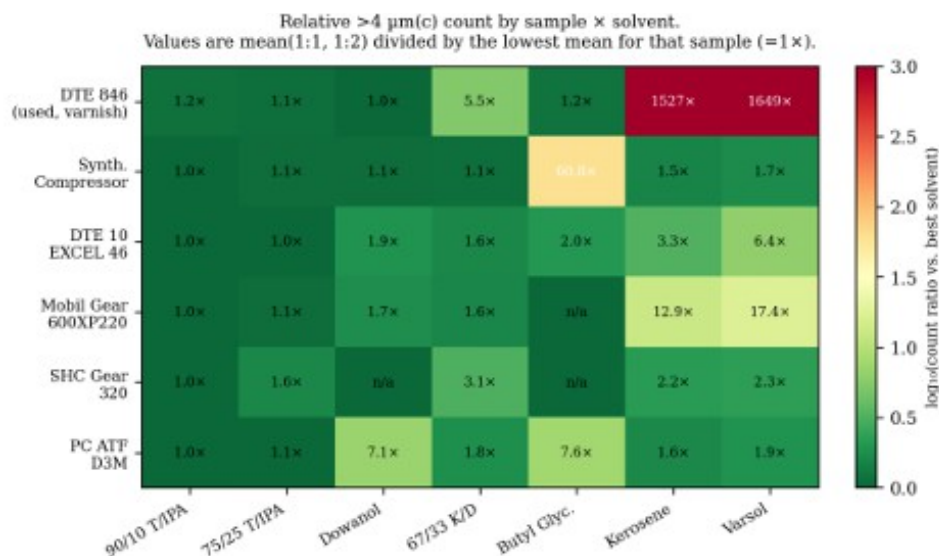


Fig. 3. Relative $>4 \mu\text{m(c)}$ count for each (sample, diluent) cell, normalised so the lowest mean count for that sample $= 1\times$. Cell colour and label show the multiplicative penalty paid by choosing each diluent. The dynamic range is approximately 4,000 $\times$.

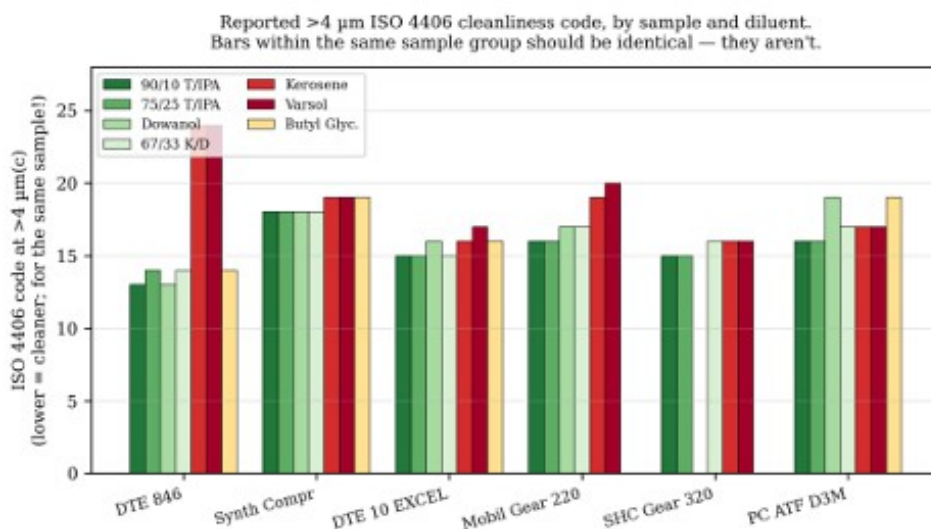


Fig. 4. Reported ISO 4406 cleanliness code at $>4 \mu\text{m(c)}$ for each sample, by diluent. Bars within the same sample group should be identical; the visible spread is the systematic between-laboratory bias that has caused D7647 round-robin scatter.

4.4 Effect of dilution ratio

With a competent water-masking diluent, the difference between 1:1 and 1:2 dilution is minor for most samples. On Mobil DTE 846 the 1:1 and 1:2 counts with 75/25 T/IPA differ by only 7 % (121 vs 129); with 90/10 T/IPA the 1:2 count is approximately half the 1:1 count (76 vs 180), reflecting more complete varnish dissolution at the higher dilution. The exception is the highly viscous PAO Mobil SHC Gear 320, where a 1:1 dilution leaves enough undissolved sample to scatter at high count rates (8,121 particles/mL with 75/25 T/IPA) while a 1:2 dilution returns the expected clean value (237 particles/mL, ISO 15/13/8). This is consistent with the standard's recommendation in § 9.6 that very viscous oils benefit from a higher dilution.

With kerosene or Stoddard solvent (Varsol), the dilution-ratio effect runs in the wrong direction — 1:2 returns a higher count than 1:1 — because the soft particle precipitation increases as the kerosene fraction increases. This sign reversal is itself diagnostic: a competent dilution should produce monotonically lower

counts as the dilution increases, until the sample is dilute enough that diluent counts dominate. Any laboratory observing the opposite trend should treat the diluent as compromised for that sample chemistry.

4.5 Final ranking and implications for the standard

Table 5 summarises the diluent ranking for each sample, separately for soft-particle removal and for water masking. The ranking confirms three points:

Sample	First	Second	Third
Mobil DTE 846 (used, varnish-laden)	90/10 T/IPA	DPnB	75/25 T/IPA
Erving Synthetic Compressor	90/10 T/IPA	75/25 T/IPA	DPnB
Mobil DTE 10 EXCEL 46	90/10 T/IPA	75/25 T/IPA	67/33 K/DPnB
Mobil Gear 600XP220	90/10 T/IPA	75/25 T/IPA	67/33 K/DPnB
Mobil SHC Gear 320	90/10 T/IPA	75/25 T/IPA	Kerosene*
PetroCanada ATF D3M	90/10 T/IPA	75/25 T/IPA	Kerosene*
IR SSR Compressor Ultra Coolant	Kerosene	90/10 T/IPA	Varsol
PC Purity FG PAG Gear Oil	90/10 T/IPA	75/25 T/IPA	DPnB
MTD CAL + 1–2 % H ₂ O (water masking)	75/25 T/IPA	DPnB	Butyl glycol

Table 5. Diluent ranking for each sample. Solvent performance was rated on the combined performance of the 1:1 and 1:2 dilutions. * indicates a third-place ranking for kerosene only because samples with no soft-particle or water issues are insensitive to diluent choice.

First, 90/10 T/IPA is the highest-performing single diluent across the eight oil samples, with seven first-place rankings out of eight. Second, 75/25 T/IPA is the safest diluent for samples with even slightly suspect water status. Third, kerosene and Stoddard solvent (Varsol) have no overall first-place finishes on any oil where soft particles are present and have catastrophic failures on water-bearing samples; their only positive results are on samples (such as the IR SSR Ultra Coolant) where they happen to dissolve a problematic ester additive that confounds the more polar diluents. We recognise that these single edge-cases were the original argument for keeping the non-water-masking diluents in Table A1.1; the Ultra Coolant data in our panel show that the polar diluents 75/25 T/IPA and 90/10 T/IPA are within a factor of 1.4× of kerosene on this sample and remain acceptable.

On this evidence we propose three changes to D7647 in the next revision cycle. (1) Remove kerosene, lamp oil and Stoddard solvent from the permitted-diluent list in Table A1.1, except as a clearly-flagged option for samples where water can be conclusively excluded and where soft particle interference is verified to be absent. (2) Add 90 % toluene / 10 % isopropanol as a permitted water-masking diluent, with a note that it must be used at a 1:2 sample-to-diluent ratio when free water exceeds 0.5 %. (3) Update the precision statement in § 14 so that it is based on the water-masking diluents only, which would substantially tighten both the repeatability and the reproducibility limits.

These changes also address a long-standing question in the user community: whether the visual assessment of a diluted sample as “clear” is adequate to declare the dilution successful. The 1:1 Mobil DTE 846 / kerosene sample appeared clear by eye and yet returned counts twice the undiluted reference. Visual inspection is a necessary but not sufficient check, and the optical particle counter itself is the most sensitive indicator of incomplete dissolution — specifically through the dilution-ratio sign test described in § 4.4 above.

5. Conclusions

ASTM D7647-24 has the right title, the right principle, and a diluent list that undermines both. By permitting non-water-masking solvents (kerosene, Stoddard solvent, lamp oil) alongside water-masking solvents (75/25 T/IPA, DPnB), the standard allows two laboratories to follow the same procedure on the same sample and arrive at ISO 4406 codes that differ by up to 12 codes — more than four orders of magnitude in particle concentration. This is the structural cause of the reproducibility scatter that has dogged D7647 since its publication.

The data presented here, drawn from 126 individual analyses across eight in-service lubricants and a calibration fluid, supports four specific conclusions:

- 1. Kerosene, Stoddard solvent (Varsol) and lamp oil generate ghost particles** in samples containing varnish, oxidation product or other soft contaminants. The ghost-particle signal scales upward with dilution ratio, the opposite of a competent dilution.
- 2. Kerosene, Stoddard solvent (Varsol) and lamp oil have no water-masking ability.** On a 1 % water spike they return counts more than 15× the dry reference. They cannot be used safely on any in-service sample whose water status is unknown.
- 3. A blend of 90 % toluene and 10 % isopropanol is the highest-performing single diluent** across the eight oil samples tested, ranking first on seven of eight, and is recommended as a new addition to Table A1.1. Its water-masking ability is reduced relative to 75/25 T/IPA but remains adequate for the 0.5–1 % free-water levels typical of in-service samples when the sample is diluted at 1:2.
- 4. 75 % toluene / 25 % isopropanol remains the safest diluent for high-water samples** and should remain in the standard. DPnB is acceptable but suffers solubility failures on PAO and PAG-rich samples. Butyl Ether was included in the evaluation as being similar to DPnB but considerably less expensive, however it showed inferior performance with some samples and cannot be considered as a direct substitute.

Restricting D7647 to water-masking diluents would tighten the published precision statement, restore the standard's consistency with its title, and remove the most common single source of laboratory disagreement on in-service oil cleanliness reporting. We recommend that Subcommittee D02.96.05 ballot these changes in the next revision cycle.

Acknowledgements

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Collaborative Robotics and AI-Driven Computer Vision for the Automation of Rotating Disc Electrode (RDE) Atomic Emission Spectrometry in Lubricant Analysis

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Abstract: This paper presents the ASSIST project, an automation framework for the Spectroil 100 Rotating Disc Electrode (RDE) spectrometer based on a 6-axis collaborative robotic system. By integrating an AI-driven Computer Vision subsystem and a dedicated calibration interface, the system achieves sub-millimetric positioning accuracy and real-time consumable verification. The robotic system manages the sequential installation of disc electrodes, rod electrodes, and oil cuvettes through optimized "Macro-Movement" libraries. The primary outcome is a significant decrease in manual labor, with an improved repeatability and reduced operator exposure to potentially harsh working conditions. Validation trials conducted in industrial environments confirm the robustness of the approach. Furthermore, the system preserves the intrinsic environmental advantages of RDE spectroscopy, with direct sample analysis without chemical solvents or argon gas, representing a sustainable "green" alternative to Inductively Coupled Plasma-based techniques.

1. Introduction

In the field of condition monitoring and predictive maintenance, the ASTM-D6595 method [1] remains the primary choice for screening wear metals and contaminants in lubricants. While newer technologies like Inductively Coupled Plasma (ICP) are popular, they require extensive infrastructure, including specialized gases and chemical diluents. In contrast, RDE spectrometry provides rapid analysis with minimal sample preparation but is traditionally limited by manual operation, requiring skilled personnel. ASSIST preserves the "green" benefits of RDE, which requires no argon or solvents, while introducing the automation efficiency typically found in ICP systems.

The ASSIST system addresses these limitations by transforming a conventional Spectroil 100 RDE spectrometer into an automated analytical platform (Figure 1). By integrating collaborative robotics (Industry 4.0 robotic arm) and intelligent sensing, the system manages batches of up to 40 oil samples without human intervention.

This transition addresses the challenges of mechanical tolerances in legacy hardware while significantly improving reproducibility and operational safety.



Fig.1 – Assist autosampler overview

2. Engineering the ASSIST Architecture

The core of this automation is a **6-axis anthropomorphic robotic arm** (UFACTORY xArm 6), characterized by a 5 kg payload and an impressive repeatability of ± 0.1 mm. This level of precision is essential because the Spectroil 100 was not originally designed for automated operation and presents relatively loose mechanical tolerance. To address this challenge, the robot is programmed to replicate the fine motor skills of a human operator, performing tasks such as: loading fresh electrodes, positioning oil cuvettes, and carefully removing waste after analysis. To manage these complexities, the system utilizes a dual-computing strategy where a Linux node handles the high-level AI and motion, while a Windows unit manages the spectrometer's native software.

3. Structural Precision: The Supporting Frame

Achieving sub-millimetric accuracy requires more than just a smart robot; it requires a mechanically stable reference structure. The ASSIST system is enclosed within a stiff aluminum framework composed of structural beams and protective metal panels. This "sensorized" rigid case ensures that the spatial relationship between the robot and the spectrometer remains constant, even if components need to be disassembled for maintenance. Calibration is supported by dedicated APIs and reference pins allow the system to compensate for manual assembly tolerances, ensuring that the robot can grab electrodes and move oil-filled cuvettes without the risk of spills or mechanical collisions.

5. Advanced Robotics and Fluid Motion

The use of a 6-axis arm enables high dexterity, allowing complex manipulation tasks to be executed efficiently. Through the development of "**Macro-Movement**" libraries, the robot does not simply move in jerky, discrete steps; instead, it performs optimized, continuous sequences. This approach enables smooth execution of critical operations, such as electrode insertion and gap positioning, reducing mechanical stress and variability. Every movement has been stress-tested on dedicated benches to ensure that the robot's real-world performance matches its technical specifications, prioritizing both speed and the integrity of the delicate spectrometer components.

6. Optimized Workspace: Racks, Bins, and 3D Printing

The workspace layout is a result of careful 3D modeling and simulation to minimize cycle time and prevent contamination. Custom racks for electrodes and oil samples have been manufactured using **3D-printed resin**, avoiding metallic contamination that could interfere with spectrometric measurements. This choice ensures that no stray metallic particles can interfere with the lubricant's results. Furthermore, the system incorporates a structured waste management approach through three distinct bins: one for used rod electrodes (which can be sharpened and reused), one for oily disc electrodes, and one for contaminated consumables (burned oil and plastic holders). This separation contributes to maintaining a clean and "green" laboratory environment.

7. Sensory Awareness and Real-Time Monitoring

ASSIST is "aware" of its environment through a dense network of sensors. Magnetic sensors verify that the removable 10-sample rack lines are correctly seated, while visual sensors confirm that each slot actually contains an oil sample before the robot attempts to grab it. Capacity sensors monitor the "stock" of electrodes, ensuring the robot doesn't start a batch without enough electrodes. Even the spectrometer door and waste bins are monitored to prevent overflows or mechanical interference, creating a fully "closed-loop" system that can pause itself if a mismatch is detected.

8. AI-Driven Vision and Infrared Monitoring

A key component of the system is the AI-driven Computer Vision subsystem based on an Infrared (IR) camera, mounted outside the combustion chamber. Using Artificial Intelligence, the system generates comparative masks to verify that the analytical cell is clear before loading new consumables. Most importantly, the camera verifies the electrode gap distance required by ASTM-D6595, providing a digital fail-safe that human operators once had to check by eye.

9. Safety, Compliance, and the Human Element

While the robot does the heavy lifting job, human safety remains the priority. The entire system is enclosed in polycarbonate protective panels with interlocked sliding doors. If a door is opened during a run, the system immediately enters a safety mode and pauses all motion. The safety screen avoids the

operator collision risks, reduce uncontrolled emissions of smoke, smell, noise, and to protect the oil samples from possible environmental contamination (dust). The system has successfully passed **CE compliance testing**, ensuring it meets international standards for industrial and laboratory safety.

10. Seamless Logic and User Interface

The ASSIST platform is controlled through a web-based interface designed to simplify interaction with the system. Operators can manage batches, view historical results, and monitor real-time telemetry from any connected device. The software architecture allows the robot to handle the sequential installation of electrodes and cuvettes while simultaneously communicating with a customized version of the Spectroil software via specialized APIs. This integration ensures that the standardization and daily checking protocols, traditionally the most tedious part of the day, are handled automatically.

11. Operational Workflow and Daily Routine

The daily workflow begins with system initialization and automatic verification procedure (daily check). The robot automatically warms up the instrument and runs standardization samples (0, 100, and 900 ppm) following Spectro-Sci procedures. Once the software confirms the results meet the required acceptability profiles, the operator is cleared to load the main analysis batch. The robot then takes over, managing the door, the electrodes, and the samples in a precise sequence. While the total cycle time per sample is slightly longer than a manual test to ensure safety, the "unattended" nature of the work is the true efficiency gain.

12. Field Validation: From Italy to Chile

The ASSIST system has undergone extensive validation in industrial environments. Currently, the system is a permanent fixture at the **Mecol Laboratory in Italy**, where it serves as part of the routine analytical line. This "stress test" involves processing thousands of samples to fine-tune the algorithms and movement paths. Simultaneously, a second unit is undergoing pilot trials at **Proteco Chile SpA in South America** [2]. In the Chilean mining and heavy industrial sectors, where high-volume oil analysis is critical for preventing catastrophic machine failure, the ability to automate RDE spectrometry in harsh, non-laboratory environments has proven indispensable.

13. Conclusions: A Sustainable Future

The ASSIST system significantly reduces manual intervention in RDE spectrometry (over 80%) of the manual labor associated with RDE spectrometry. By freeing technicians from repetitive tasks and exposure to noise, it allows them to focus on high-value data interpretation, improving repeatability and operator safety while maintaining the intrinsic advantages of the technique. Furthermore, as a "green" solution that avoids the heavy gas and chemical requirements of ICP, ASSIST represents a significant step forward in sustainable laboratory practices for the global lubricant condition monitoring industry.

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Inline Oil Condition Monitoring as a Tool to Detect Gear Pitting

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Keywords: Oil monitoring, Inline, Gears, Pitting

Abstract (Maximum length: 10 lines)

Oil Condition Monitoring (OCM) is increasingly used for real-time gearbox health assessment, overcoming delays of traditional oil analysis. This study investigates inline OCM for detecting gear pitting and its challenges. An accelerated test using an FZG gear rig combined inline oil sensors with a camera system to track gear pitting. Results showed that wear debris sensors successfully detected three wear stages: run-in, steady-state, and accelerated wear, aligning with theory. Nonetheless, not all wear debris were detected by sensors, as some of these remained in the gearbox. This could potentially limit accurate quantification of total wear. Besides, oil properties like viscosity and density did not indicate wear in this test. The study concludes that inline OCM can detect wear trends but has limitations in precision and interpretation. Future work should focus on more severe wear conditions and further investigating the correlation between sensor data and wear.

1. Introduction

Oil Condition Monitoring (OCM) is becoming widely used to assess gearbox health. It detects wear through debris analysis and evaluates lubricant condition by measuring properties like viscosity and density, which are crucial for gearbox lifespan. Traditional offline oil analysis, based on periodic sampling, provides detailed but delayed insights—often days or weeks old. To overcome this, research is shifting toward inline monitoring, which delivers real-time data and supports predictive maintenance. However, inline systems introduce challenges in interpreting sensor data, some key challenges include: (1) Viscosity measurement: Essential for load-carrying capacity but affected by temperature, air bubbles, and contamination. (2) Wear debris analysis: Helps detect gear wear but is complicated by unknown particle origins, recirculation (causing overestimation), and missed particles (causing underestimation). In this research, the capability of monitoring gear pitting using inline OCM - and the challenges associated with installing such a system - is explored.

2. Methodology

An accelerated pitting-lifetime test using a back-to-back gear tester (also known as FZG rig) was performed. This test rig was equipped with both an inline OCM system and a vision-based condition-monitoring (VCM) system [1], which was used to periodically capture images of the gear surfaces to establish a baseline of the gear health. **Figure 1** shows an overview of the test rig, lubrication system, different oil flows and the OCM system. A total of four oil sensors were installed. The selected sensors are the (1) Atten[2] S120 OilWear sensors for particle detection ($>4\mu\text{m}$), particle classification based on morphology and air bubble content. (2) Atten[2] OilHealth Probe Max for measuring oil degradation and water content. (3) Yakes YTS-61 to measure oil temperature, viscosity, density and the dielectric constant. (4) Yateks YFM-8, which can differentiate between ferromagnetic ($>40\mu\text{m}$) and non-ferromagnetic ($>150\mu\text{m}$) particles.

3. Results

During the tests the presence of micro- and macropitting was verified using the integrated camera system. Two routes were explored to detect this wear using the OCM: (1) By analysing the data using the wear debris sensors (S120 & YFM-8) or (2) by analysing the oil parameters which could potentially be influenced by wear debris being present (i.e., viscosity and dielectric constant). Both wear sensors were able to detect the evolution in wear as shown in Figure 2. Three regions can be seen: (1) run-in, (2) steady-state, and (3) accelerated wear. This evolution aligns with theoretical expectations on the wear generation. The sharp rise at the 30h mark for the YFM-8, could not be explained based on the qualitative assessment of images from the integrated camera system. Therefore, it is believed to be a measurement error, and should be considered

a false alarm in practice. Regardless, an increasing trend of damage accumulation, i.e. region (3) accelerated wear, could be observed in both sensors after this moment.

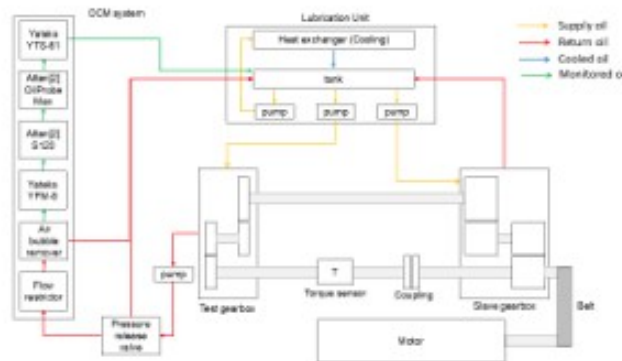


Figure 1: Schematic overview of the test rig, lubrication system and OCM system.

Within this dataset, it was not possible to detect the presence of wear by analysing oil parameters such as viscosity, density, or dielectric constant. Therefore, it is possible that wear alone does not have a significant influence on these oil parameters. However, a few remarks should be made. In more realistic conditions, wear is commonly a result of reduced oil performance; therefore, monitoring oil parameters remains valuable. Additionally, under more severe wear conditions, the oil could degrade at an accelerated rate, potentially leading to detectable changes in oil parameters and leading to increased wear, finally contributing to a vicious cycle that accelerates component (gear and oil) degradation.

Finally, after the test, during disassembly, it was noted that many wear particles were still present in the test gearbox. This indicates the importance of ensuring that wear debris does not become trapped in the system without passing by the sensor. Additionally, each time the test rig was restarted, a short spike in detected wear debris was observed by the sensors. Therefore, in future tests, the total worn area should be monitored, using the integrated camera system. This allows evolution of the wear trend to be compared between the camera and the OCM system. This would provide a better understanding of whether wear debris sensors should be used for trend analysis or if they allow quantitative wear analysis.

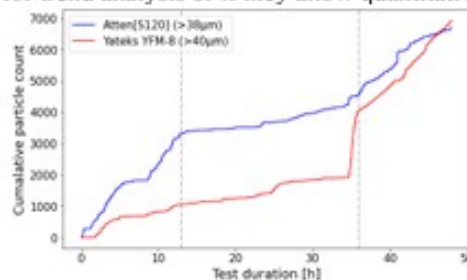


Figure 2: Cumulative wear debris detected for the YFM-8 and S120 wear sensors

4. Conclusions

An OCM system was installed on a back-to-back gear tester, and an accelerated pitting test was performed. The presence of micro- and macropitting was verified using an integrated camera system. Both wear debris sensors (S120 & YFM-8) could detect wear generated. Three wear stages could be detected: (1) run-in, (2) steady-state and (3) accelerated wear. Additionally, during these tests, no observable difference in the oil properties were found that could indicate wear being present in the gearbox. Finally, it was observed that some wear debris remained inside the gearbox itself, therefore not passing by the sensors. Future tests should be performed to investigate the influence of severe wear on oil properties, and additionally, using the integrated camera an investigation can be performed whether wear debris sensors can quantify the total worn amount.

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AI Agents in Condition Monitoring and Predictive Maintenance: Reshaping the Future of Asset Reliability

Jorge Alarcón | Bureau Veritas

Elías Alarcón | Synthexia Co-lab

Protests Against Machinery

Type	Problem
Petition to the House of Commons (England) 1794	The invention and use of the machine for carding wool... brings the most alarming reduction of manpower... will deprive the mass of artisans of their means of existence... a large number is already without work and without bread
Captain Swing Letters (agricultural workers) 1832	Threats against landlords for introducing threshing machines that eliminated winter work for day laborers
Local English Newspapers 1830	Reported Luddite riots destroying mechanical looms (1811-1816) and burning of threshing machines in the countryside

Key data on labor replacement population

There was **no long-term** mass unemployment.

Mechanization **did not** eliminate all employment; instead:

1. It migrated workers from rural areas to cities
2. It created new jobs in factories, railways, mining, and services
3. Agriculture: 65% of the English population (1801) → 8.6% (1901)



What is an AI agent?

Feature	What it means
Autonomy	Makes decisions and takes actions with minimal human oversight
Reasoning	Uses logic, knowledge, and context to analyze data and make informed decisions
Planning	Breaks down goals into smaller tasks and creates strategic plans to achieve them
Memory	Remembers across tasks and changing states, learning and adapting over time

I am a software program that **autonomously** performs tasks for a user or system by interacting with my environment and using AI to achieve predetermined goals.

I **independently** choose the best actions to reach my objectives.



LUBRICANTS, TRIBOLOGY
AND CONDITION MONITORING

Prediktiv Översikt – Case

- 4 PdM technicians
- 1800 rotating assets
- 6 predictive technologies

Level of Knowledge



Analyze the data and write the report

2 technicians

4 hours

35%



Of their time is spent uploading, analyzing data and issuing a report



LUBRICANTS, TRIBOLOGY
AND CONDITION MONITORING

Prediktiv Översikt – Case



“We’re smart enough to invent **A.I.** — yet dumb enough to need it... and so stupid we can’t even tell if we did the **right thing.**”

Jerry Seinfeld

? ANY QUESTION?

Jorge Alarcon | Elías Alarcón

New Patterns



2016

DeepMind crushed the best AlphaGo players.

2023

Human creativity skyrocketed, and even the worst professionals were now better than the champions of the pre-AI era.

COND 19 ID 86 Novel Online Sensor Approaches for Water Contamination Detection in Lubricating Oils

COND 20 ID 94 Continuous Optical Monitoring for Predictive Maintenance of Hydraulic Systems

Mapping Degradation Pathways in Turbine Oils Under Severe Thermal Stress

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Overview

Turbine oil degradation is rarely a single-mode failure, and the pathways that dominate at one temperature do not necessarily dominate at another. This study uses the Turbine Oil Performance Predictor (TOPP) to age seven commercial and reference fluids at 150 °C and benchmarks the results against companion data sets at 120 °C, 180 °C, and 195 °C. MPC, FTIR, RULER, RPVOT, and kinematic viscosity were measured at controlled aging intervals out to fifty days. At 120 °C the oils follow predictable, near-linear oxidation kinetics. At 150 °C and above the behaviour becomes sharply nonlinear, with a well-defined inflection point tied to antioxidant exhaustion beyond which oxidation, polymerisation, and base-stock breakdown all accelerate. The combined diagnostics reveal a consistent lead-and-lag relationship between chemical and physical markers that has direct implications for condition-monitoring strategy in modern gas-turbine fleets.

1. Introduction

Modern industrial gas turbines run hotter, longer, and on smaller fluid charges than they did a decade ago. Bulk reservoir temperatures of 80–90 °C are now routine, feeding bearings whose hot-spot temperatures sit well above that. The question reliability teams face is no longer whether the oil will degrade, but where on the degradation curve a given charge sits and how much useful life remains. Answering that requires a test platform that ages fluid under representative thermal stress and a diagnostic suite that captures both the chemistry and the physics.

The Turbine Oil Performance Predictor (TOPP) was developed for exactly this purpose. It exposes a fluid sample to controlled high-temperature oxidative stress in the presence of metal catalysts and trace water, simulating the thermal severity of a gas-turbine bearing return line. Pulling samples at successive aging intervals produces a time series that can be analysed with the standard tools of oil condition monitoring [1, 2]. Running the same protocol at four temperatures, as we do here, lets us separate kinetic effects from mechanistic ones.

2. Experimental approach

Seven turbine and circulating oils were aged in TOPP glassware at 150 °C for up to fifty days, with samples drawn at approximately 7, 16, 23, 29, 40, and 50 days. The same oils, where available, were also aged at 120 °C, 180 °C, and 195 °C using the same test configuration. The fluid set spanned a range of formulations, including high-performance Group II turbine oils, a Group IV synthetic, a GTL-based oil, and several modern low-varnish formulations, together with a Group III base stock dosed with a representative ashless additive system.

Each pulled sample was characterised by Membrane Patch Colorimetry (ASTM D7843), kinematic viscosity at 40 °C (ASTM D445), Rotating Pressure Vessel Oxidation Test (ASTM D2272), Linear Sweep Voltammetry of phenolic and aminic antioxidants (ASTM D6971), elemental analysis by ICP (ASTM D5185), and FTIR spectroscopy across the bands relevant to oxidation, nitration, water, and additive depletion. From the FTIR data we tracked an oxidation index based on the 1670–1800 cm⁻¹ carbonyl region, a thermal-degradation index, and the absolute C=O peak area.

3. Behaviour at 150 °C

The 150 °C data tell a remarkably consistent story across formulations. RULER moves first. Phenolic antioxidants drop to single-digit percentages of initial concentration within two weeks, and aminic antioxidants are exhausted shortly after. In the first turbine oil series, total antioxidant loss reached 17 percent at Day 7, 52 percent at Day 16, 83 percent at Day 23, and 100 percent at Day 29. RPVOT collapsed in parallel, falling from 1,480 minutes at Day 7 to 28 minutes at Day 29.

FTIR confirms that what looks like a quiet period in the bulk fluid is actually the antioxidant package doing its job. Through Day 23 the oxidation index, thermal-degradation index, and C=O peak area all rise modestly. Between Day 23 and Day 29, immediately after the antioxidants are exhausted, every FTIR marker jumps by an order of magnitude or more. Oxidation index goes from 2.61 to 22.83. C=O peak area

risers 1,900 percent. Thermal degradation index quadruples. By Day 40 the oxidation index has reached 68, a 7,200 percent increase over the virgin fluid.

Viscosity follows the FTIR signal with a measurable lag. Viscosity is essentially flat through Day 23, increases 31 percent by Day 29, and then climbs to nearly three times the virgin value by Day 50. MPC values are erratic in the early aging window, swinging between 14 and 57, before sludge formation prevents measurement entirely at Day 50. The fluid by then is no longer a fluid in any operational sense.

This lead-and-lag pattern is the central observation. Antioxidant depletion and varnish potential are the early-warning signals. Carbonyl growth confirms oxidation has gone autocatalytic. Viscosity rise is the late-stage receipt that the lubricant has already failed. Treating viscosity as a primary monitoring metric, as some of the industry still does, means catching the problem only after bearing surfaces have been exposed to weeks of unprotected fluid.

4. Cross-temperature comparison

Plotting the oxidation index against TOPP sample number for each temperature produces near-linear regressions with very different slopes. For one oil type, the slope is 0.137 at 120 °C, 0.150 at 180 °C, 0.453 at 195 °C, and 0.557 at 150 °C. The 150 °C slope sits above the 180 °C slope because by 180 °C the early samples have already been pushed past the antioxidant inflection, flattening the apparent rate. The lesson is that 150 °C captures the transition zone where the lubricant moves from controlled to uncontrolled oxidation more clearly than either lower or higher temperatures do.

Equating oxidation index across temperatures gives a useful translation table. A 150 °C aged sample reaches the same oxidation index as a 120 °C aged sample roughly ten times faster, consistent with the Arrhenius rule of thumb that every 10 °C doubles oxidation rate. The same exercise between 150 °C and 180 °C shows the higher temperature is only modestly faster in early aging, because the chemistry has shifted into the autocatalytic regime where antioxidant content, not temperature, is rate-limiting. Above the inflection, more heat does not buy proportionally more degradation.

Across the seven fluids the qualitative pattern was the same. The quantitative position of the inflection varied by formulation. The Group IV synthetic and the modern low-varnish formulations held their antioxidant systems longer at 150 °C than the conventional Group II oils. The Group III base stock with a representative additive package collapsed earliest, with RPVOT falling 96 percent between Day 0 and Day 14. Formulation matters most in the early-to-mid aging window. Once the antioxidants are gone, the differences narrow sharply.

5. Conclusions

Three findings carry directly into operating practice. First, antioxidant depletion measured by RULER is the most actionable early-warning signal in this data set, and it leads every other diagnostic by roughly two weeks of TOPP aging at 150 °C. Second, the inflection point at which a fluid moves from controlled to autocatalytic oxidation is sharp, repeatable across formulations, and visible in FTIR before it is visible in viscosity or MPC. Third, the Arrhenius scaling between 120 °C and 150 °C is well-behaved, but extrapolating above 150 °C should be done with caution because the rate-limiting chemistry changes once antioxidants are exhausted. For OEMs and operators specifying turbine oils for severe-duty or extended-interval service, the practical recommendation is to set replacement and intervention triggers on the leading indicators rather than the lagging ones, and to use multi-temperature TOPP data rather than single-point bench tests when benchmarking new formulations.

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COND 22 ID 53 From Crisis Management to Asset Management: 4 Real Cases Where Off-line Filtration Changed the Game

How to Safely Collect Representative, Reliable Oil Samples from Fleet and Industrial Hydraulic Systems.

Bernie Hall, Checkfluid Inc. (www.checkfluid.com)

Why collect hydraulic system oil samples (at minimum monthly to quarterly intervals)?

1. Safer equipment and people (workers and communities).
2. Reduced repair costs. Everything is more expensive, and components are not always readily available.
3. Optimized service. Reactive and time-only based preventative maintenance doesn't work anymore. PM and other services in 2026 should be time + predictive + proactive (condition-trending based).
4. Lifecycle management. You can learn a lot about each equipment from its oil analysis history, as long as the data is representative and reliable. Even identical equipment makes/models in identical applications can have completely different "personalities" and lifecycle costs.
5. Higher profit/ Lower cost per hour or unit of output. Reinvest in machines, employees, and growth.

Introduction:

Have you experienced oil analysis data that seems to jump up or down with no apparent reason? This data becomes confusing and impossible to trust, let alone trend. If so, you are not alone. This problem across the world is unfortunately still too common. *But don't blame your oil analysis laboratory!* Your partner laboratory and their equipment, software technology and technicians can only analyse, measure and report what they receive inside each sample jar. Every 60 mL to 90 mL oil sample must be representative of a hydraulic system that could be 200 Litres or 2,000 Litres, or even larger. In other words, that bottle of oil that fits in the palm of your hand must accurately represent the entire hydraulic system. The data in each sample gets analysed and reported, is the data you must rely on to help optimize costs and reduce premature failures and downtime on your machines worth thousands to millions of dollars. When it comes to collecting the samples, it is critical that your technicians and reliability engineers have the right hardware and procedures to get the job done right, every time.

Sample takers must have a way to safely and repeatably collect representative oil samples while the equipment and oil are at operating temperature, viscosity and conditions. Fortunately, in nearly all hydraulic systems (in both mobile fleet equipment and industrial plant applications), this is easy to achieve by correctly installing a permanent oil sampling valve on the return line of each hydraulic system.

1. Oil Sampling Port Location: Primary, secondary and tertiary sample points are discussed in the presentation slides but to sum it up: Identify the main return line on the hydraulic system; the main return line is downstream of all system components, but before/upstream of the return line filter and oil reservoir. Verify the return line pressure is between 5 psi and 100 psi maximum (this is typical in most hydraulic systems, regardless of the pressure on the output/supply side of the pump).

2. Oil Sampling Valve Selection: Select the correct oil sample valve type that is leak-proof against oil/liquid, air pressure, and ingress-proof against vacuum pressure. Oil sampling valves must seal 100% against both pressure and vacuum, which is especially important in hydraulic systems. Features that include a low pre-sample purge volume, easy to use, and have an automatic shutoff. Locate an existing accessory oil pressure port on the return line (direct port, or tee location), where the oil sample valve can be permanently installed to capture live flowing pressurized oil into the sample jar, prior to filtration and to being diluted in the reservoir. For brand new equipment, original equipment manufacturers will install a KP, LP or KST oil sampling valve as a standard, or can be ordered as a factory installed option.

3. Collect Your Samples: Follow proper sampling procedures to ensure cleanliness and integrity of the sample as it is being collected. For example, remove the cap on the sample bottle just before activating the valve, and replace it immediately after the sample is collected to the proper fill line on the bottle. It is important to leave sufficient headspace in the bottle for the laboratory to agitate before running the optimum tests. In addition to standard tests, for hydraulic systems it is imperative that ISO particle count for system cleanliness and Karl Fischer test for water be ran on every sample. Crackle Test, or even a test slate where Karl Fischer is triggered by Crackle, is insufficient for operation-critical fleet and industrial

equipment hydraulic systems. The extra cost to run these tests will yield false positively high, or false negatively low results if the sample is not representative. This can happen when taken from a reservoir where both particles and water shed to the bottom at varying rates and concentrations. Systems operating continuously, 24/7 or years between turnarounds should use a Membrane Patch Colourimetry and other test for varnish potential. These can be valuable as a spot test, specifically any system where lower cost, lower performance hydraulic oils are being used. Unless an active circulating sample is collected at operating temperature, the MPC score will be unrepresentatively low as previously solubilised/suspended varnish and attached (often abrasive) deposit molecules plate out rapidly upon entering and cooling in the reservoir.

Remember:

Representative, Reliable Hydraulic Samples Every Time = Reliable Data = Reliable Trending = Reliable Decision Making = Safe, Reliable, Long-Lasting Equipment.

Hydraulic Oil Sampling Valve Installation Examples:

Fig. 1 Fleet/Utility Truck. Pushbutton valve/pressure gauge tee installation on inlet side of hydraulic return line filter.
Fig. 2 Fleet/Forestry Skidder. Factory installed pushbutton valve on return line hydraulic/hydrostatic drive system.
Fig. 3 Fleet/4WD Farm Tractor. Factory installed KST probe valve on return line hydraulic/hydrostatic drive system.
Fig. 4 Fleet/Mining truck. Collecting a hydraulic sample. Pushbutton valve/ remote access sample centre.
Fig. 5 Industrial/Press. Return line filter inlet with adapter. Note: Select the direct install thread size whenever possible.
Fig. 6 Industrial/Press. Pushbutton valve installed on return line in a modified elbow.
Fig. 7 Fleet/Refuse Truck. Factory installed pushbutton valve with factory welded port on return line.
Fig. 8 Fleet/ Return line filter inlet port installation. Collecting a sample. Push to open and release to close.
Fig. 9 Fleet/Articulated Dump Truck. Factory installed KST probe valve on hydraulic return line/inlet elbow adapter.
Fig. 10 Industrial/Marine Crane. Pushbutton valve/inlet elbow adapter on hydraulic return line filter.
Fig. 11/12 Fleet/Bin Lorry. Pushbutton/pressure gauge tee installation on inlet side of return line filter.
Fig. 11/12 Fleet/Bin Lorry. Collecting a sample. Pushbutton valves shut off instantly and automatically after sampling.



Fig. 1



Fig. 2



Fig. 3



Fig. 4



Fig. 5



Fig. 6



Fig. 7



Fig. 8



Fig. 9



Fig. 10



Fig. 11/12

BOOK of POSTERS

Evaluating the Compatibility of ZrC and TiC Nanofluids as Electric Vehicle Transmission Fluids with Polymeric Elastomers

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Abstract

The present study investigates the compatibility of a PAO6 base oil with two optimized nanofluids containing 0.01 wt% of either titanium carbide (TiC) or zirconium carbide (ZrC) nanoparticles, in silicone, fluorocarbon (FKM), and ethylene propylene diene monomer (EPDM) rubbers. The elastomers were subjected to an aging process in the fluids at 140°C for 216 hours. The volume variation analysis revealed that FKM rubber displayed the highest dimensional stability (approx. 4% volume increase), while EPDM and silicone swelled by around 90% and 22%, respectively. Mechanical testing demonstrated that the 0.01 wt% ZrC nanofluid yielded the best performance, proving to be a highly promising ETF alternative with superior compatibility for FKM and silicone seals.

1. Introduction

The transition toward electromobility requires advanced thermal and lubrication solutions that do not compromise powertrain components. The development of new Electric Vehicles (EVs) necessitates new Electric Transmission Fluids (ETFs) that can provide superior lubrication and thermal management and are highly compatible with the various materials used in the system [1]. In electric motors, the lubricant is in direct contact with various materials, including copper winding, polymers, and elastomers, under high-speed and high-temperature conditions [2]. Polymeric elastomers, which are frequently utilized for the fabrication of seals and gaskets in electric vehicle (EV) powertrains, have been observed to undergo degradation when subjected to lubricants for extended periods [3]. Traditional lubricants may cause premature failure of these components through chemical degradation or excessive swelling. The present study investigates the compatibility of a base oil (PAO6) and two optimized nanolubricants formulated with either Titanium Carbide (TiC) or Zirconium Carbide (ZrC) nanoparticles (NPs), both at a concentration of 0.01 wt%, with different types of elastomers.

2. Methods

The optimized nanofluids containing an elastomer sample were exposed to an aging process for nine days (216 hours) at an elevated temperature of 140°C. Three different elastomers such as silicone, fluorocarbon (FKM), and ethylene propylene diene monomer (EPDM) rubbers were used. Their compatibility was assessed using tensile tests (elongation at break and tensile strength) and volume variation analysis. The volume change was calculated using Archimedes' principle, weighing the samples before and after the aging process. Comparing these metrics allowed for an accurate evaluation of material degradation after prolonged high-temperature exposure.

3. Results and conclusions

The outcomes of the volume variation tests showed that the EPDM rubber experienced significant swelling (around 90%) and silicone rubber swelled by approximately 22% in all fluids. The high swelling in EPDM, suggests a strong affinity between the non-polar PAO6 base oil and the EPDM polymer chain, which could lead to a loss of sealing integrity in practical applications. In contrast, the FKM rubber demonstrated the highest dimensional stability, undergoing only a minimal volume increase of around 4% when exposed to the nanolubricants, which is crucial for maintaining sealing capacity (Fig. 1).

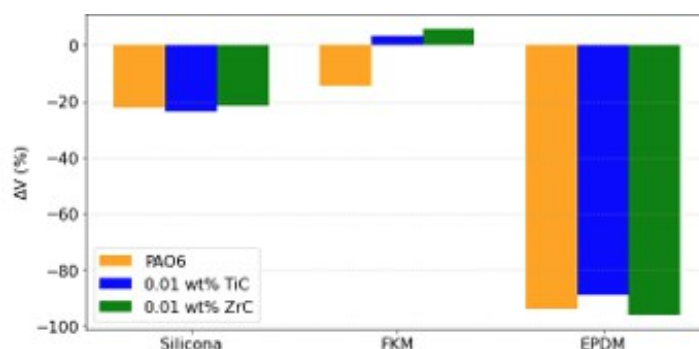


Fig. 1: Volume variation.

Furthermore, mechanical property retention varied significantly. While most fluid-elastomer combinations showed a decrease in tensile strength, the nanofluid containing 0.01 wt% ZrC NPs exhibited the best performance. Elastomers exhibited a marginal decline in the tensile strength of silicone (-3%) and, notably, a slight and enormous increase in the tensile strength of FKM (+6%) and EPDM rubber (+78%), respectively, compared to the unaged material (Fig. 2). These results suggest a high degree of compatibility between the ZrC nanolubricant and FKM seals.

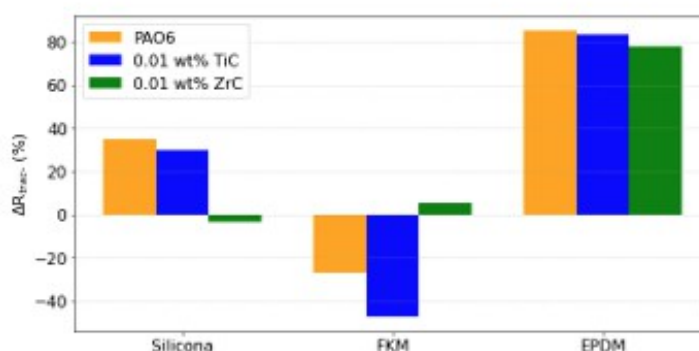


Fig. 2: Tensile strength variation.

In conclusion, regarding compatibility, the nanofluid formulated with 0.01 wt% ZrC NPs presents a promising alternative as an ETF, demonstrating superior compatibility with critical FKM and silicone polymeric seals compared to the PAO6 base oil. The addition of 0.01 wt% ZrC does not negatively impact the chemical compatibility of the base oil and, in some cases, appears to stabilize the mechanical response of the elastomers under thermal stress.

4. Acknowledgements

This research is supported by MCIN/AEI/10.13039/501100011033 through the PID2020-112846RB-C22 project and by Xunta de Galicia (ED431C 2024/06). Dr. M.J.G.G. also acknowledges the support of the Ramón y Cajal grant (reference RYC2023-044120-I), funded by the State Plan for Scientific, Technical and Innovation Research and by the European Social Fund Plus (FSE+).

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Hybrid Ionic Liquid-Polyoxometalate/Ionic Liquid additives for low viscosity EV fluids

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Abstract

In this work, the effect on the tribological properties of three nanomaterials, $[N_{1,1,1,12}]_3[PW_{12}O_{40}]$, $[C_{12}MIM]_3[PW_{12}O_{40}]$ and $[C_{12}Py]_3[PW_{12}O_{40}]$, as additives for a low viscosity polyalphaolefin, PAO6 is presented. Friction tests were performed using an Anton Paar MCR 302 rheometer equipped with a T-PTD-200 tribological module. The best tribological results were obtained for PAO6 + 0.1 wt% $[N_{1,1,1,12}]_3[PW_{12}O_{40}]$. Subsequently, the ionic liquid $[P_{6,6,6,14}][DEHP]$ was selected to explore the synergies with $[N_{1,1,1,12}]_3[PW_{12}O_{40}]$. PAO6 + 0.1 wt% $[N_{1,1,1,12}]_3[PW_{12}O_{40}]$ + 1 wt% $[P_{6,6,6,14}][DEHP]$ improves the antiwear capacity of PAO6 around 87 % in wear track transversal area. Wear was characterized using a Sensofar S-neox non-contact 3D profiler and SEM-EDX. The addition of 0.1 wt% $[N_{1,1,1,12}]_3[PW_{12}O_{40}]$ and/or 1 wt% $[P_{6,6,6,14}][DEHP]$ do not barely change the density and viscosity of PAO6, whereas the electrical conductivity increases up to 70 times.

1. Introduction

Achieving an optimal balance between reducing carbon dioxide emissions and addressing the growing global demand for energy is one of the main challenges facing the global economy today [1]. In this context, electric vehicles (EVs) are a popular alternative for reducing the high emissions of vehicles powered by internal combustion engines. Many automobile manufacturers have adopted the integrated drive unit configuration for EVs. In this approach, the transmission fluid is used to cool the motor and electronic components, as well as lubricate gears and bearings. For this reason, low viscosity is one of the requirements of these fluids. However, low-viscosity lubricants lead to increased wear due to thinner lubricant films [2].

This study introduces the use of polyoxometalates (POMs), a novel additive in this research area. POMs are anionic metal oxide nanoclusters, with tunable size and defined composition and structure. POMs are accompanied by cations that can be carefully selected to provide specific properties to the resulting salt [3]. In this work, the phosphotungstate anion, $[PW_{12}O_{40}]^{3-}$, was selected together with the cations $[N_{1,1,1,12}]^+$, $[C_{12}MIM]^+$ and $[C_{12}Py]^+$. Thus, the nanomaterials tested were $[N_{1,1,1,12}]_3[PW_{12}O_{40}]$, $[C_{12}MIM]_3[PW_{12}O_{40}]$ and $[C_{12}Py]_3[PW_{12}O_{40}]$. On the other hand, ionic liquids are recognized as effective dispersants of nanoadditives in base fluids. The ionic liquid $[P_{6,6,6,14}][DEHP]$ was selected to explore the synergies with $[N_{1,1,1,12}]_3[PW_{12}O_{40}]$.

2. Materials

Repsol granted the PAO6 sample. In a previous study, the compounds $[N_{1,1,1,12}]_3[PW_{12}O_{40}]$, $[C_{12}MIM]_3[PW_{12}O_{40}]$ and $[C_{12}Py]_3[PW_{12}O_{40}]$ were synthesized and thoroughly characterized [4]. Iolitec provided the ionic liquid with a purity higher than 98%.

3. Experimental Techniques

Friction tests were carried out with a MCR 302 Anton Paar rheometer equipped with a tribological cell PTD200 at 120 °C, 20 N and 0.1 m/s [5]. A 3D profilometer was used to evaluate wear in terms of width, depth, and cross-sectional area. The worn track was characterized by SEM-EDX and Raman Microscopy. Viscosity and density at atmospheric pressure were measured with a SVM 3000 Stabinger viscometer. Finally, two Emcee 1153 digital conductivity meters were used to experimental determine electrical conductivities.

3. Results and conclusions

Based on previous analysis, 0.1 wt% of each nanomaterial was selected as additive of PAO6. The best tribological behaviour was obtained with $[N_{1,1,1,12}]_3[PW_{12}O_{40}]$. The addition of this nanomaterial (0.1 wt%) and 1 wt% of $[P_{6,6,6,14}][DEHP]$ led to reductions that were twice as large in wear and friction coefficients.

Acknowledgements

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Assessment of electric-field-induced lubricant film activation in electrorheological biolubricants by optical interferometry

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Abstract

This study investigates the activation of lubricant films in electrorheological (ER) biolubricants under an applied electric field. ER biolubricants based on castor oil and Cloisite 15A nanoclay were analyzed using a colorimetric interferometry on a modified PCS EHD 1 tribometer–interferometer. Results show a rapid increase in film thickness upon electric activation, followed by stabilization. Film enhancement was more pronounced at low entrainment speeds, where dielectrophoretic forces dominate hydrodynamic ones. These findings demonstrate the feasibility of electrically controlled lubrication, contributing to sustainable and adaptive tribotronic systems.

1. Introduction

The growing demand for sustainable and high-performance lubrication has driven the development of smart tribological systems capable of active control [1]. In this context, electrorheological (ER) fluids have emerged as a promising solution due to their ability to reversibly modify their rheological properties under an electric field. This capability opens new possibilities within tribotronics for real-time adaptation of lubrication conditions [2].

Previous advances identified two main mechanisms governing friction behaviour under external electric field: the electroviscous effect, involving changes in viscosity and shear modulus under an electric field, and the electrodeposition of polarized nanoparticles onto charged surfaces [3, 4]. Both mechanisms may affect lubricant film thickness in elastohydrodynamic contacts. However, the lubricant film formation under electric stimulation remains insufficiently understood, particularly for sustainable biolubricants.

This work introduces an innovative experimental approach based on a colorimetric interferometry on a modified PCS EHD 1 tribometer–interferometer, enabling in situ measurement of film thickness in electrified contacts.

2. Materials and Methods

A model ER biolubricant consisting of 6 wt.% Cloisite 15A nanoclay (supplied by Southern Clay Products, USA), dispersed in castor oil (from Guinama, Spain), was used. The dispersion was prepared through mechanical stirring followed by ultrasonic homogenization using an UP400St device (Hielscher, Germany). A total energy input of 0.23 Wh per gram (0.83 kJ/g) in the ultrasonication step was used to ensure a stable and homogeneous dispersion. To prevent thermal degradation, the temperature was maintained below 75 °C by placing the containers in an ice bath throughout the process.

Lubricant film thickness was evaluated using a modified PCS EHD 1 tribometer–interferometer from PCS Instruments (UK). The system was adapted to apply a controlled DC electric field directly within the contact, enabling real-time monitoring of film thickness evolution under the influence of the external electric field. Measurements on a ball-on-disc configuration were conducted at different entrainment speeds under pure rolling conditions.

Film thickness was determined using both Ultra-Thin Film Interferometry (UTFI) and the Spacer Layer Imaging Method (SLIM), with the latter enabling full-field mapping of the contact. A silica spacer layer was preferred to ensure electrical insulation while maintaining measurement accuracy. A dedicated calibration procedure was developed by correlating RGB (Red, Green, Blue) intensity from SLIM interferograms with central film thickness values obtained via UTFI. This approach extended the measurable thickness range up to 800 nm with errors below 3%, allowing accurate and reliable quantification of electrically induced changes in lubricant film thickness.

3. Results and discussion

The results showed that the application of an electric field of 30 V produces a rapid increase in lubricant film thickness within approximately one second after activation (**Fig.1a**). The electrically activated film thickness showed a gradual decrease until a stable steady-state thickness is reached after several tens of seconds, indicating a dynamic response of the lubricant system to electrical stimulation

Film thickness enhancement was more significant at low entrainment speeds. However, the effect diminishes and becomes negligible beyond a threshold speed, suggesting limitations of the activation mechanisms under more dominant hydrodynamic conditions (**Fig.1b**).

Interferometric film maps revealed a uniform thickness distribution across the contact area, indicating either a global modification of the lubricant's rheological properties or a homogeneous nanoparticle deposition process. Overall, these findings confirm the feasibility of dynamically controlling lubricant film thickness through electrical activation, supporting the development of sustainable and adaptive tribotronic lubrication systems.

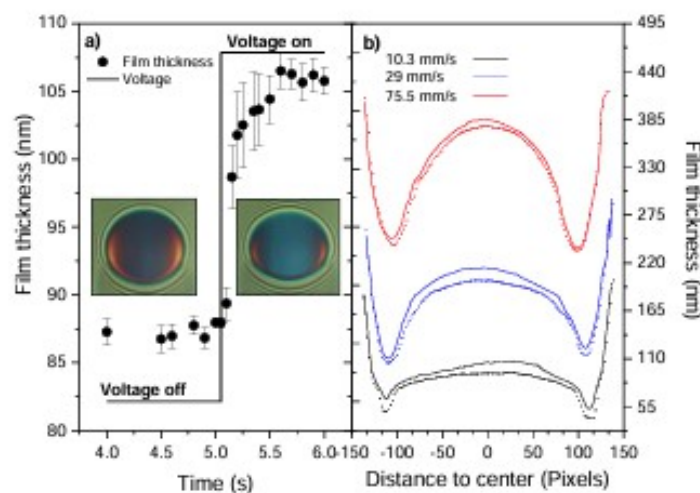


Fig.1 a) Evolution of the central film thickness at 10 mm/s and electric potential of 30 V (interferometric images included) for the nanoclay-based ER biolubricant studied; b) Film thickness profiles in the transversal directions at different entrainment speeds at 0V (dash line) and 30 V (solid line).

4. Conclusions

The modified optical interferometry setup successfully enabled the measurement of lubricant film thickness under an external electric field, confirming active control in nanoclay-based ER biolubricant. The combined UTFI-SLIM calibration ensured accurate measurements up to 800 nm with low error. Application of 30 V increased film thickness and revealed a transient response before reaching steady state. Additional mechanisms beyond the electro-viscous effect, such as particle entrainment within the contact or electro-deposition of particles on the contact surfaces, may also contribute to the overall response. Further studies will be required to clarify their relative influence.

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Electroactive Nanocellulose Biolubricant Under Electric Fields: Squeeze-Flow Evidence of Improved Load Carrying Capacity

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Abstract

The development of environmentally sustainable lubricants capable of actively adapting to changing operating conditions is of increasing interest in tribology. Conventional anti-wear additives and nanoparticle-enhanced lubricants, while effective, rely on passive mechanisms and often raise environmental concerns. Electrorheological (ER) fluids offer a promising alternative by enabling real-time modulation of rheological properties and tribological behaviour through the application of an external electric field. Building on this concept, the present work investigates the squeeze-flow behavior and load-carrying capacity of novel electroactive biolubricants formulated from castor oil and crystalline nanocellulose (CNC), nanoparticle selected for its sustainability, polarizability, and ability to form field-induced structures.

1. Introduction

An early study by Korenaga et al. [1] demonstrated a remarkable fourfold increase in lubricant film thickness when a low molecular weight liquid crystal was used in an electrified tribological contact. This enhancement was attributed to the so-called electro-viscous effect. In contrast, and in alignment with the Sustainable Development Goals (SDGs), we advocate for simple and environmentally friendly lubricant formulations based on nanocrystalline cellulose dispersed in castor oil, which have also demonstrated electrorheological (ER) behavior.

Previous studies demonstrated that these ER biolubricants undergo electro- and shear-induced structuring [2], suggesting that electric fields could be used to dynamically enhance their in-service performance. Here, we examine whether such structuring translates into improved resistance to compression under electrified parallel-plate conditions, a key indicator of load-carrying capacity in tribological contacts.

2. Materials and Methods

Castor oil, supplied by Guinama (Spain), was selected as the base fluid due to its favorable physicochemical properties. At 25 °C, it exhibited a dynamic viscosity of 735 mPa·s. Commercial crystalline nanocellulose (CNC) was obtained from Nanografi Co. Ltd. (Turkey). Produced via sulfuric acid hydrolysis, resulting in the presence of sulfate groups, CNC particles have diameters ranging from 10 to 20 nm, lengths between 0.3 and 0.9 µm, and exhibit 100 % crystallinity as determined by X-ray diffraction (XRD).

The CNC in castor oil biolubricants were prepared by ultrasonic homogenization using an UP400St device (Hielscher, Germany), with a total energy input of 7 Wh per sample. To prevent thermal degradation, the temperature was maintained below 75 °C by placing the containers in an ice bath throughout the process. Tests were performed across a range of nanoparticle concentrations between 0.5 and 6 wt.%.

Squeeze-flow experiments were conducted using a strain-controlled ARES-G2 rheometer (TA Instruments, USA) equipped with 25 mm smooth parallel plates, with initial gap of 500 µm, applying a constant approach velocity of 0.5 µm/s under a DC voltage of 300 V. The required voltage was delivered using a Keysight 33210A function generator (Agilent, USA) in combination with a Trek 609E-6 high-voltage amplifier (Trek Inc., USA). For the sake of comparison, tests were also conducted in the absence of voltage.

3. Results and discussion

Results reveal that CNC-based biolubricants exhibit compression behaviors markedly different from the Newtonian response predicted by Stefan's equation [3]. Even in the absence of an electric field, CNC

dispersions deviate from the theoretical $N \propto h^{-3}$ scaling, displaying three distinct quasi-linear regions with slopes that evolve systematically with concentration. These deviations may be attributed to particle agglomeration, localized concentration gradients, and the inability of the viscous carrier fluid to uniformly entrain the particulate phase at small gaps.

Under electric activation, all CNC dispersions show a pronounced rightward shift in the force–distance curves, indicating that the maximum measurable load (20 N) is reached at larger compression gaps. This effect intensifies with increasing CNC concentration. The observed behavior does not conform to the Bingham-based squeeze-flow model typically used for ER fluids [3]. This outcome suggests that field-induced particle deposition and formation of compact columnar structures restricted particle mobility and dominated the mechanical response. These mechanisms lead to compression resistances significantly higher than those predicted from shear-derived yield stresses.

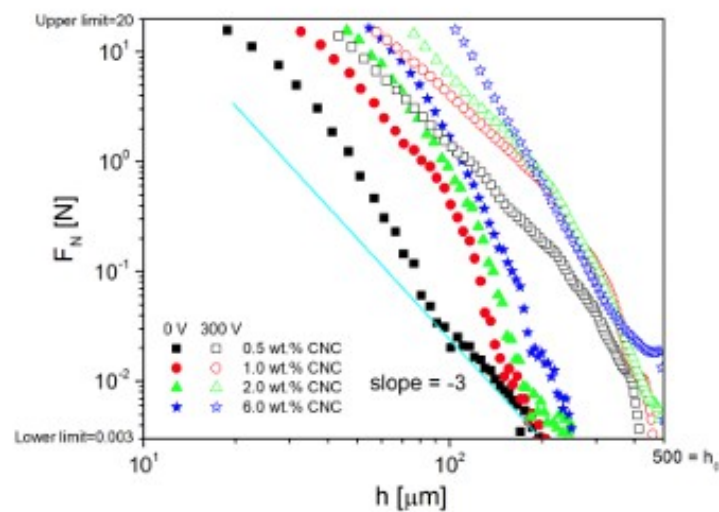


Fig.1 Evolution with time of the normal force exerted by CNC/castor oil dispersions in squeeze flow tests, as a function of concentration (0.5 to 6 wt.%), in the absence and presence of voltage (0 and 300 V).

4. Conclusions

Overall, the results demonstrate that electro-activation substantially enhances the load-carrying capacity of these ER biolubricants, particularly within the 0.5–1 wt.% CNC concentration range where a notable transition in behavior occurs. These findings support the potential of sustainable, electro-responsive lubricants as active components capable of modulating compression resistance and enhancing film thickness under applied electric fields.

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The key role of plastic revalorization in the development of sustainable lubricants bases



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GENERAL OVERVIEW

From 2006 to 2024, the generation of plastic waste in the EU escalated by nearly 34%, reaching 32.7 million tones, yet the recycling rate remained below 30% (Figure 1)¹. This issue underscores the importance of the 2018 European Strategy for Plastics², which drove the upcycling of waste into high-value products, such as lubricants.

THE CHALLENGE & THE SUSTAINABLE ALTERNATIVE

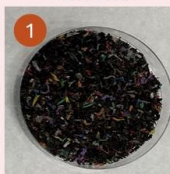
The present study develops an efficient and innovative solution for the valorisation of industrial plastic waste in lubricant applications. With increasing regulations and public awareness, there is a general trend towards using more ecofriendly bases or re-refined base oils. Low MW poly- α -olefins (PAOs) are among the most frequently employed sustainable synthetic base fluids as an alternative to mineral bases. These compounds are frequently produced by catalytic oligomerization of α -olefins.³

Plastics waste management 2024, in the EU27+3



Figure 1. Plastic waste management in 2024, in the EU27+3¹

Plastic waste



Plastic & biomass waste



Figure 2 & 3. Waste used in the thermal pyrolysis process ((1) plastic waste, (2) plastic & biomass waste).

PROJECT OBJECTIVE

The aim of this research is to obtain α -olefins by thermal pyrolysis of plastic waste (Figure 2 & 3), followed by chemical modification via oligomerization, to produce alternatives bases with enhanced properties, potentially replacing conventional mineral oils and contributing to the use of re-refined oils (Figure 4).

METHODOLOGY & CHARACTERIZATION

The project assess physicochemical and tribological properties of lubricating base oils derived from significant quantities of industrial plastic waste, including mainly PE, PP, PUR, PVC (Figure 2 & 3).

PAO PRODUCTION PROCESS



Figure 4. Pao production process ((A) Neoliquid's facilities, (B) liquid fraction obtained from thermal pyrolysis & (C) PAO obtained from the chemical transformation of the liquid fraction).

KEY RESULTS

Results from thermal/oxidation stability, viscosity, and wear tests prove that the novel base lubricants obtained exhibit similar properties compared to commercial oils (petroleum base or synthetic). These findings suggest that industrial plastic could be a feasible alternative feedstock when producing high-performance lubricants, contributing to more sustainable material reuse (Table 1).

OUTSTANDING RESULTS

Table 1. Performance comparison between final products and commercial PAO 6.

	Viscosity	TGA Noack	Brugger Test	OOT
Final product 1	25 cSt	41%	≈ 47 N/mm ²	194 °C
Final product 2	62 cSt	36%	≈ 44 N/mm ²	203 °C
PAO 6 (commercial product)	31 cSt	17%	≈ 29 N/mm ²	211 °C

OXIDATION ONSET TEMPERATURE (OOT) RESULTS

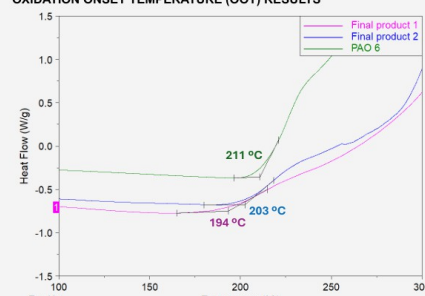


Figure 5. OOT of final product 1 (pink), final product 2 (blue) & commercial PAO 6 (green).

CONCLUSIONS & ENVIRONMENTAL IMPACT

Final base oils exhibit high thermal stability and remarkable anti-wear properties, demonstrating that this circular strategy can deliver a sustainable, high-performance alternative. The approach is expected to reduce landfill plastic waste, mitigate environmental impact, and improve resource efficiency.

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