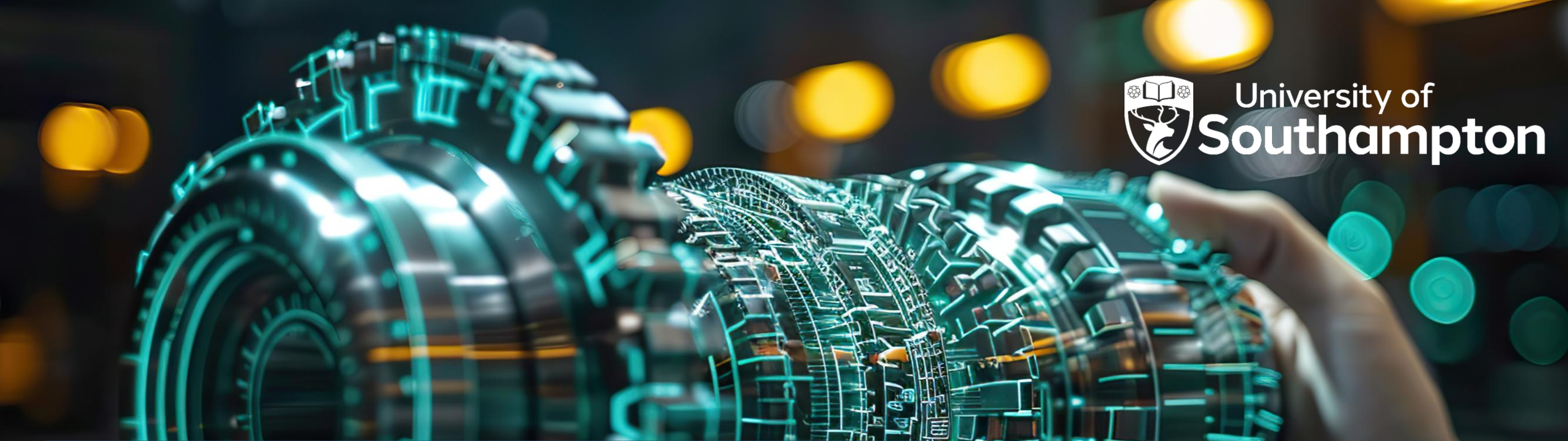

Tribology for Net Zero: a materials and surface engineering perspective

Professor Robert JK Wood, FREng
Professor of Surface Engineering and Tribology
National Centre for Advanced Tribology at Southampton (nCATS) is an EPSRC funded centre
Mechanical Engineering Department
University of Southampton

Talk content

- How tribology, materials and surface engineering are essential to hitting the net zero targets for 2035 & 2050
- Areas that tribology can directly impact and the role of materials
- Green Tribology : 12 principles
- Case studies: small steps
    - Materials for water lubricated bearings
    - Digital tribology, interface imaging and sensing. show elements of the possible AI driven condition monitoring of wear sensors/condition monitoring,
    - Wind turbines materials and materials to protect the leading edge of wind turbine blades.
- Conclusions

What is Tribology?

The word Tribology was derived in 1966 from the Greek word for rubbing - ‘*Tribos*’

Tribology is the science of lubrication, friction and wear.

1.5% GDP wasted in UK industry from poor lubrication, friction and wear management, [1]

[1] H. P. Jost. “Lubrication, Education and Research – A report on the Present Position and Industry’s Needs”. Her Majesty’s Stationery Office (1966), London

Ancient Tribology

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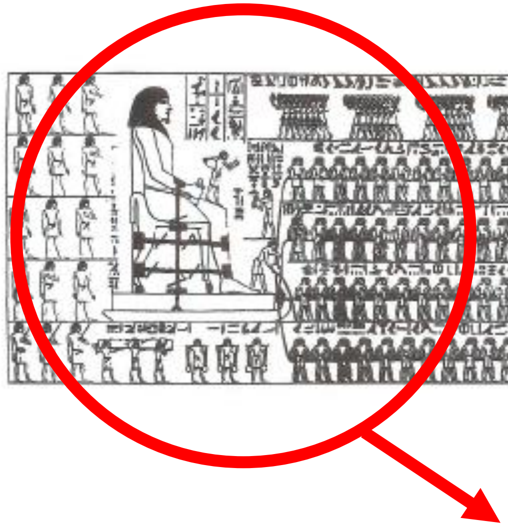
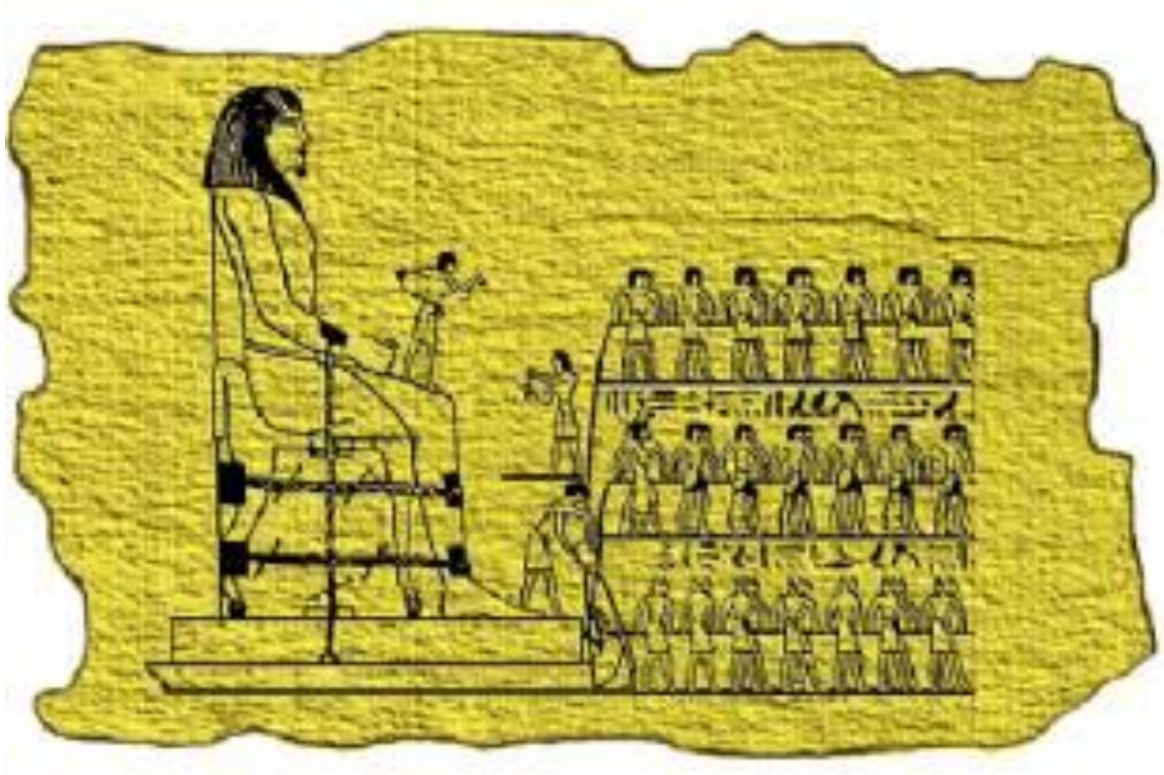
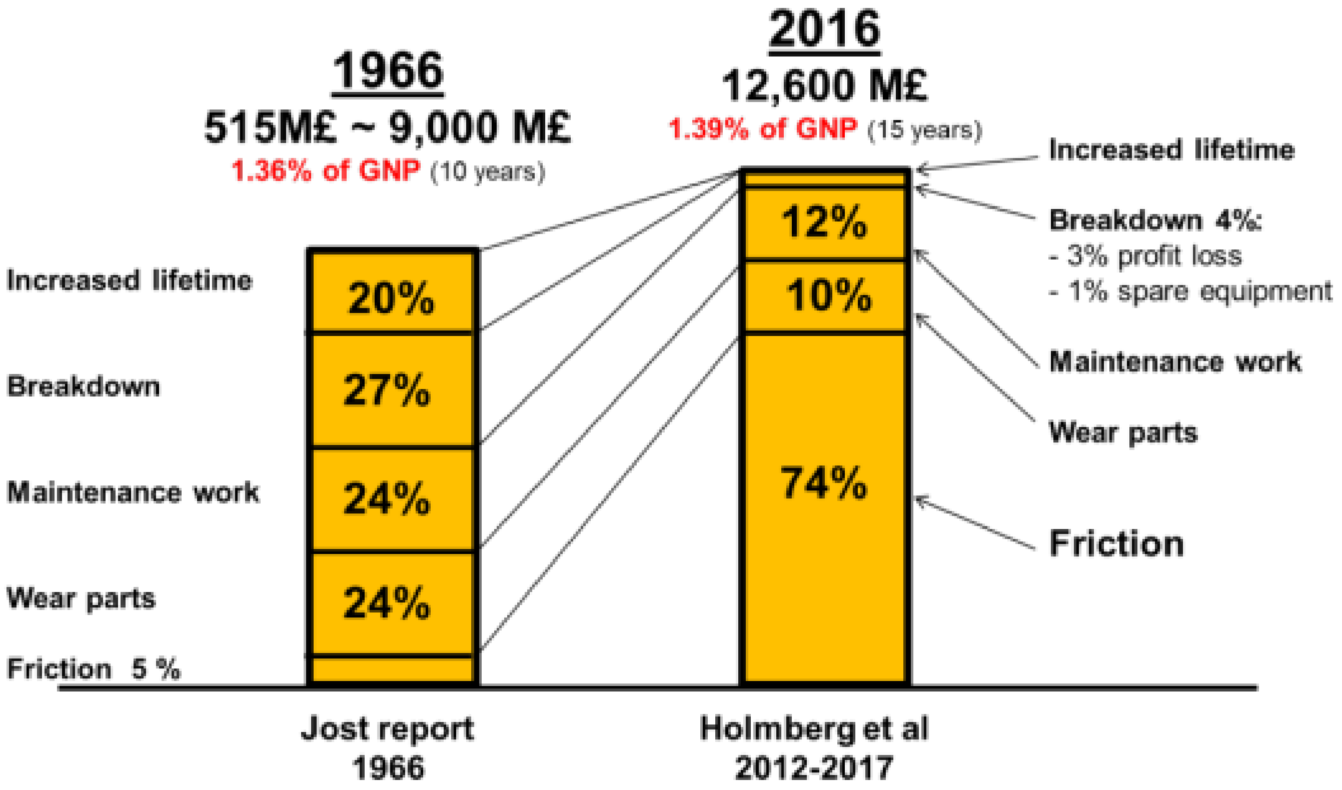


Transporting an **Egyptian colossus**-from the tomb of **Tehuti-Hetep**, EL-Bersheh **(c.1880 B.C).** First recorded tribologist in action lubricating the runners.



Erdemir slides



Around 23% of the world's energy is used simply to compensate for friction and wear at great financial cost, together with significant amounts of CO2 emissions.

Figure 4. Potential savings in UK 1966 and 2016 by implementing new tribology in machines and equipment, 515 million UK pounds converts to 9,000 million UK pounds of 2017 value (Holmberg & Erdemir 2017).

Holmberg, K., Erdemir, A. Influence of tribology on global energy consumption, costs and emissions. Friction **5**, *263–284 (2017). https://doi.org/10.1007/s40544-017-0183-5*

background

Energy transition has become a global and crucial challenge in the 21st century. With the aim of achieving carbon neutrality in 2050, we must reduce our dependence on fossil fuels and implement more environmentally friendly energy sources.

Tribology, **plays a fundamental role in this aim** and in reducing fuel consumption and CO2 emissions

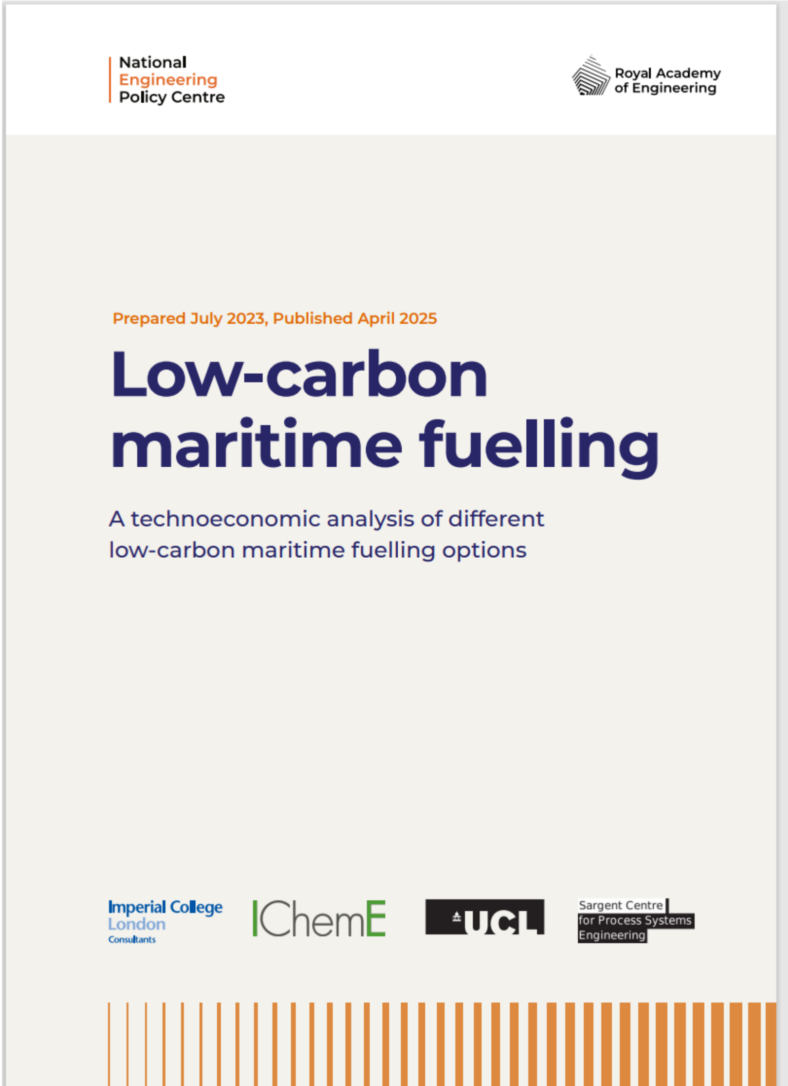
Despite the **evident relationship between friction and energy loss**, little attention has been paid to the effects of friction and wear on energy use and inherent environmental problems.

According to Holmberg, around **200,000 million litres of fuel** are consumed annually just to overcome vehicle friction.

This **friction can be significantly reduced with new tribological solutions** based not only on surface treatments, but also on innovative lubricants and even new machinery designed to maximize the efficiency of a given movement chain..

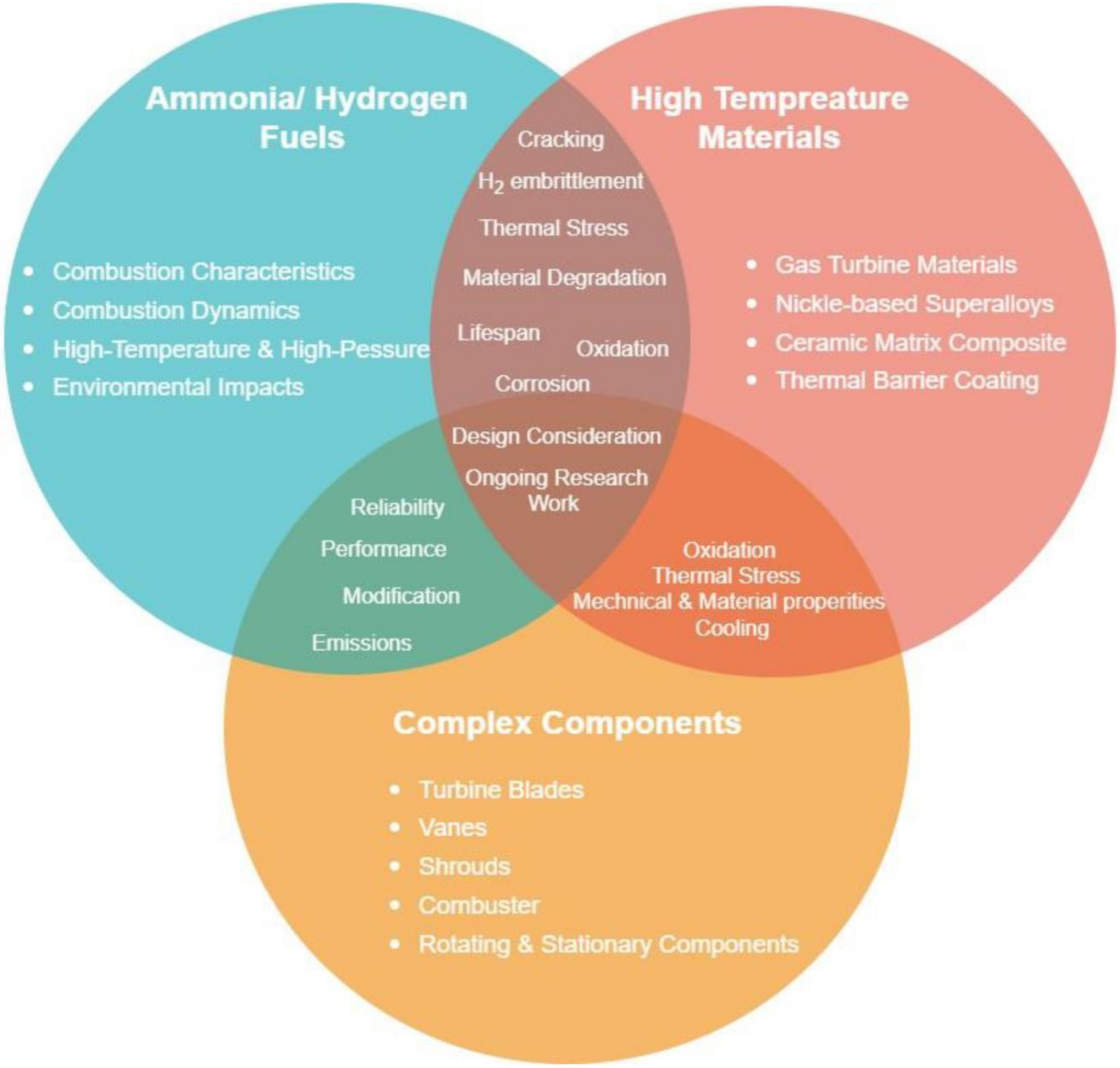
Tribology and Surface Engineering need to pivot to address new challenges

University of Southampton



The report compares four alternative, low-carbon fuel sources that could power UK shipping and maritime transport. The fuels considered are **hydrogen, ammonia, methanol and synthetic hydrocarbons**, which the industry views as the most likely and practical decarbonisation options

outlines what scientific and technological challenges need to be answered and over what timescales to reach net zero carbon emissions in the UK by 2050



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Some challenges

Challenges of handling hydrogen

University of Southampton

The adsorption of hydrogen and dissociated atoms on metal surfaces can cause the formation of metal hydrides that cause damage and compromise the tribological behaviour

Hydrogen permeation in rubber and polymer seals is another problem that leads to their failure, putting the entire system at risk.

Interactions between lubricated machine parts and hydrogen also causes additional challenges in terms of condition monitoring, not only in terms of the parameters to be evaluated, but also their reference values and what this tells us regarding the condition of the lubricant and of the equipment.

Is Tribology Approaching Its Golden Age? Grand Challenges in Engineering Education and Tribological Research

University of Southampton

The author further argues that one of the key problems confronting tribology and its future grand challenges is solving the problem of the “third body”. Surfaces have essentially different properties compared with the bulk of materials, and tribological loading massively changes the properties of surface layers. The interface properties of tribological contacts may be influenced by the composition of the atmosphere, humidity, presence of lubricants, adsorbed layers, and wear debris. The intermediate space of and around the interface essentially determines the tribological properties and is called “third body” (Godet, 1990). To exaggerate somewhat, understanding friction means understanding the third body. The influence of the third body in a broad sense has been demonstrated on all scales. Thus, one of the great discoveries of nanotribology was structural superlubricity (COF below 0.01)) in the contact of well-prepared atomically smooth surfaces (Dienwiebel et al., 2004).

Popov VL (2018) Is Tribology Approaching Its Golden Age? Grand Challenges in Engineering Education and Tribological Research. *Front. Mech. Eng*. 4:16. doi: 10.3389/fmech.2018.00016

University of Southampton

HENRY ROYCE INSTITUTE

ROYCE

MATERIAL FUTURES

Unlocking UK economic growth through materials innovation

NATIONAL MATERIALS INNOVATION STRATEGY

THE OPPORTUNITIES

Materials innovation is fundamental to creating impactful solutions for:

Energy solutions
Rising to the net zero challenge

Future healthcare
Delivering beyond biocompatibility for active medical solutions

Structural innovations
Strengthening our infrastructure, built environment and transport systems

Advanced surface technologies
Enhancing product functionality, performance and lifetime

Next-generation electronics, telecommunications and sensors
Driving the future of high-performance connectivity and computing

Consumer products, packaging and specialist polymers
Paving the way for a greener tomorrow

ENHANCING PRODUCT FUNCTIONALITY, PERFORMANCE AND LIFETIME

ADVANCED SURFACE TECHNOLOGIES

Surface engineering and the application of coatings improves the performance, functionality and durability of materials. These products are better able to withstan[d] mechanical wear and corrosion or degradation due to environmental factors, including thermal, chemical and radiation conditions.

Surface engineering treatments range from simple paints t[o] complex metallic depositions, ion implantation and diffusio[n] processes. They play a key role in sectors with high econom[ic] potential, including energy, health and construction.

They often determine the lifetime of a product and can be applied to rejuvenate a structure. They can also add functionality such as reducing, or im[proving] ... conductivity or fricti[on]

Opportunities in this theme

1. Materials and modelling for surface engineering and tribology

Surface degradation through corrosion and mechanical wear commonly causes failure in material systems across industrial sectors. Surface engineering treatments of manufactured products can increase their in-use life and reduce their lifetime cost and energy losses due to friction. Improving our understanding of material surface degradation and tribology by applying large data learning methods and high throughput testing will contribute to a step change in new, environmentally friendly and enhanced surface designs and coatings.

Surface degradation through corrosion and mechanical wear commonly causes failure in material systems across industrial sectors. **Surface engineering treatments of manufactured products can increase their in-use life** and **reduce their lifetime cost and energy losses due to friction**. Improving our understanding of material surface degradation and tribology by applying **large data learning methods and high throughput testing** will contribute to a step change in new, environmentally friendly and enhanced surface designs and coatings.

Green tribology 2008-onwards

(i) Minimization of heat and energy dissipation.

(ii) Minimization of wear is the second most important task of tribology that has relevance to green tribology.

(iii) **Reduction or complete elimination of lubrication and self-lubrication**.

(iv) **Natural lubrication** (e.g. vegetable-oil-based) should be used in cases when possible, since it is usually environmentally friendly.

(v) Biodegradable lubrication should also be used to avoid environmental contamination.

(vi) Sustainable chemistry and green engineering principles should be used for the manufacturing of new components

(vii) **Biomimetic** approaches should be used whenever possible.

(viii) **Surface texturing** should be applied to control surface properties.

(ix) **Environmental implications of coatings** and other methods of surface modification (texturing, depositions, etc.) should be investigated

(x) Design for degradation of surfaces, coatings and tribological components.

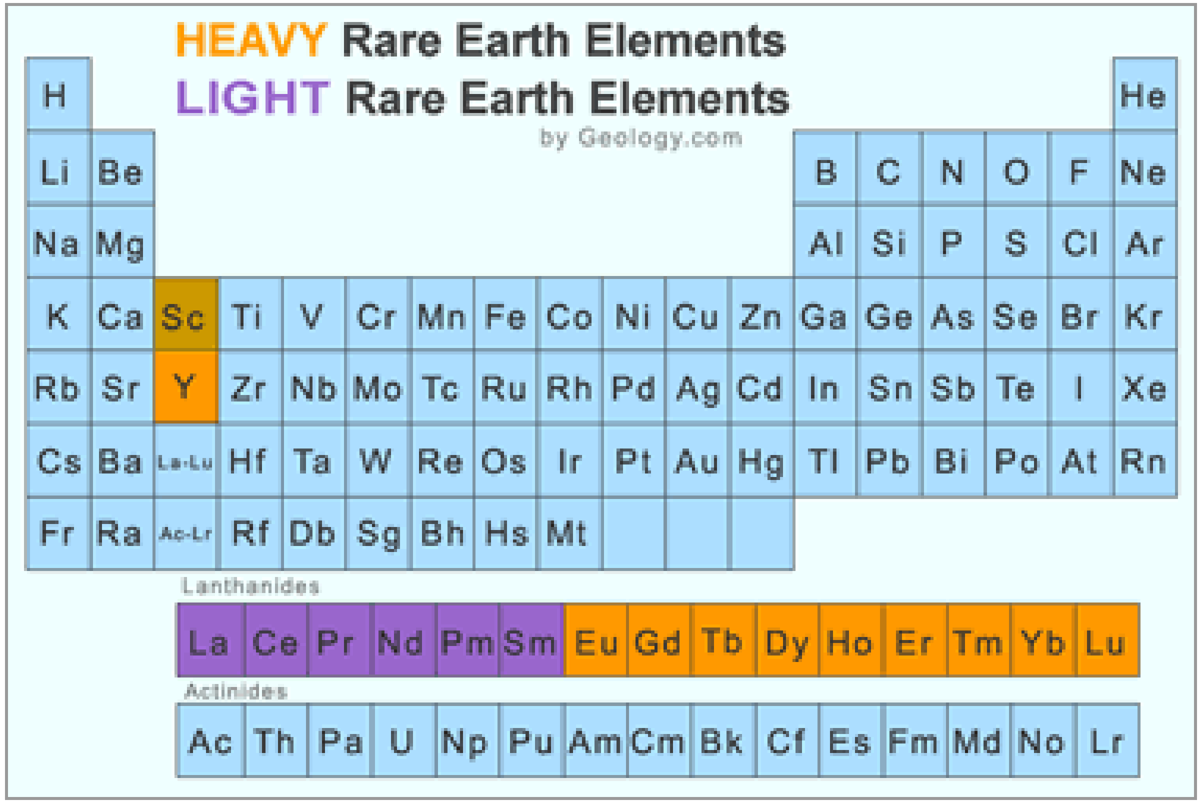
(xi) **Real-time monitoring**, analysis and control of tribological systems during their operation should be implemented

(xii) **Sustainable energy applications** should become the priority of the tribological design

Nosonovsky, M.; Bhushan, B. Green tribology: Principles, research areas and challenges. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* **2010**, *368*, 4677–4694.

Sustainability

University of Southampton



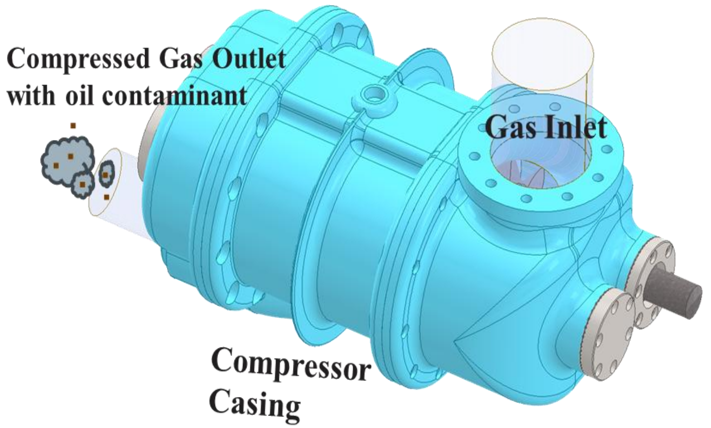
Effect of rare earth elements on tribological behaviour of magnesium alloys

wear rate of Mg–5%Sn–2%Mm alloy is less than that of Mg–5%Sn alloy Mm (Mischmetal - 55% cerium, 25% lanthanum, and 15~18% neodymium, with traces of other rare earth metals totaling 95% lanthanides, plus 5% iron

Investigation of rare earth particulate on tribological and mechanical properties of Al-6061 alloy composites for aerospace application

The results of wear tests showed an improvement of wear rate around 87.28% when compared to Al-6061 alloy with the addition of 2.5 wt% of CeO_2.

Introduction and Need for Research



Traditional Compressors

Oil Lubricated Bearings

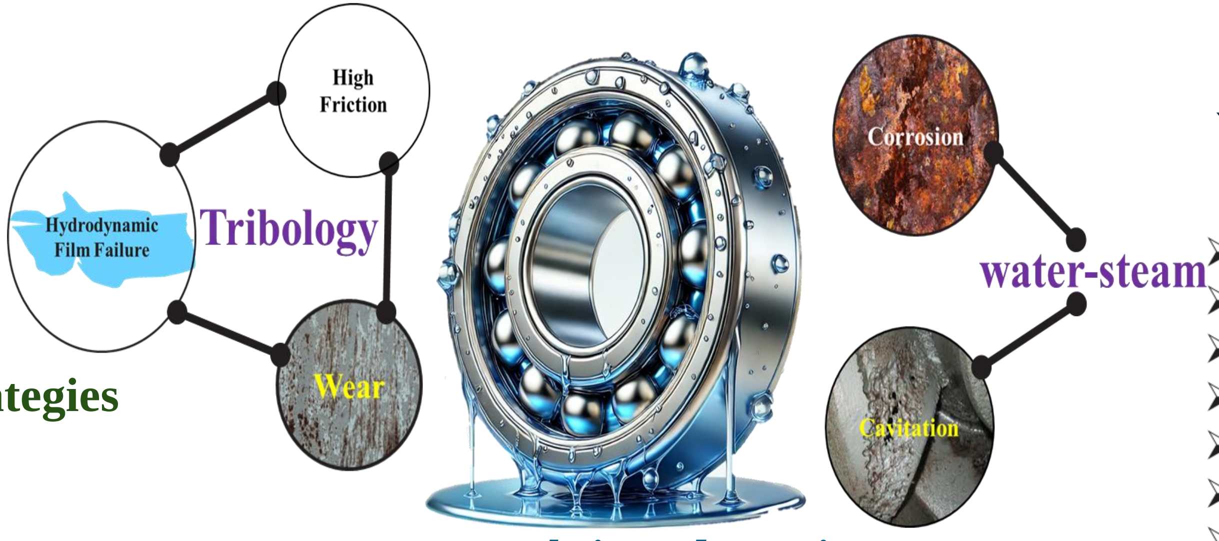
- Need for frequent maintenance
- Oil degradation, Contamination
- Susceptible to Temperature
- Fire Hazard Potential
- Poor Biodegradability
- High *Environment hazard
- Carbon footprint
- Impure compressed air with oil contaminants

Transition To water Lubrication

- Reduced Maintenance Needs
- Better Temperature Tolerance
- No Fire Hazard
- Excellent Biodegradability
- Minimal Environmental Hazard
- Low Carbon Footprint
- Clean, Oil-Free Compressed Air

Solution?

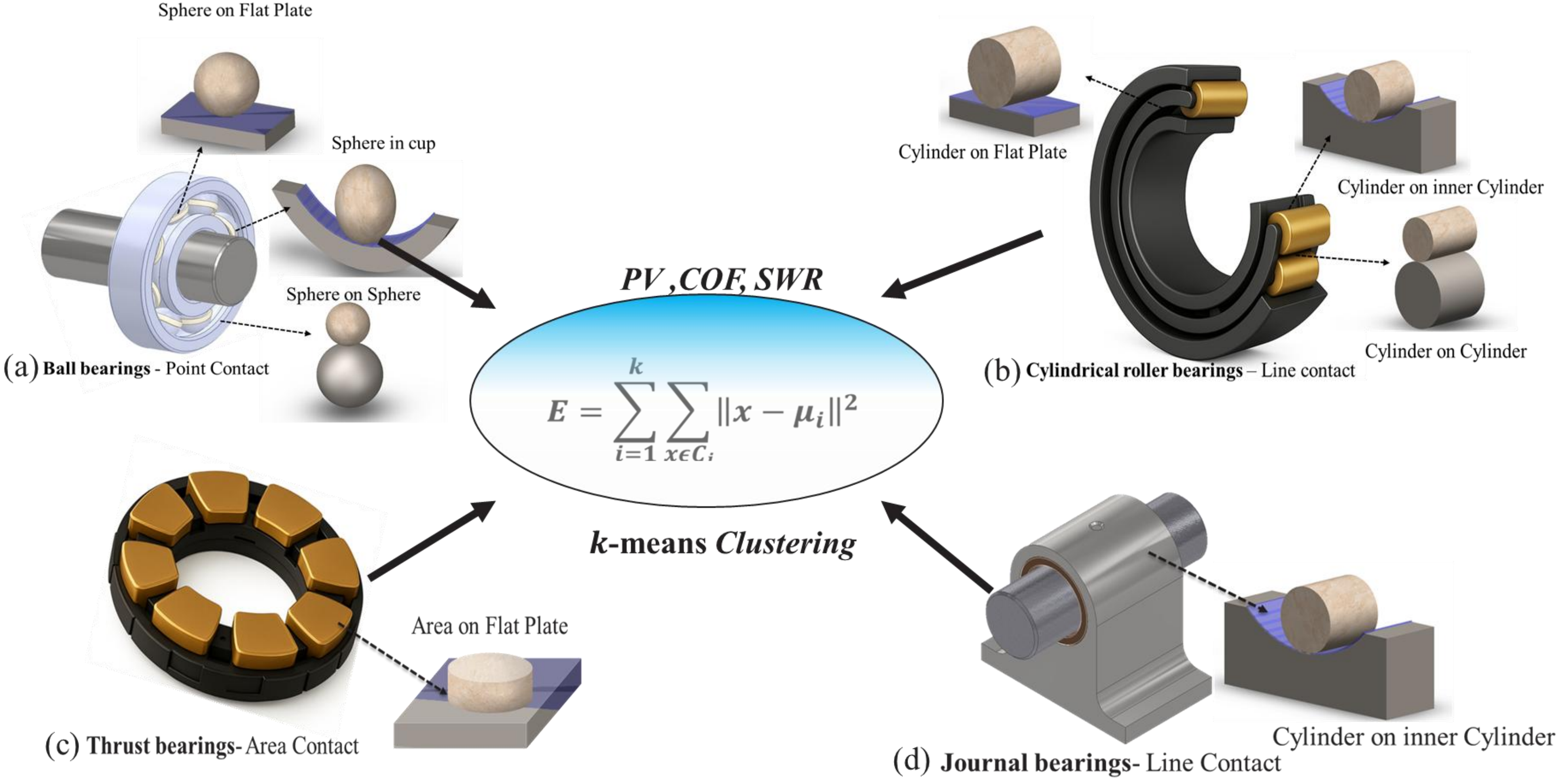
Surface Engineering Strategies



Water Lubricated Bearings

Methodology to identify Suitable surface Engineering solutions

157 literature-based experimental data points used with new data from **TE77 tribometer tests at nCATS**. PV values, calculated using **Hertzian contact models** for various **bearing geometries,** are grouped using ***K*-means clustering**. Contact condition worst case scenario when water film collapses



Steel-steel oil lubricated used as a baseline for comparison with Water Lubricated

Results & Discussion

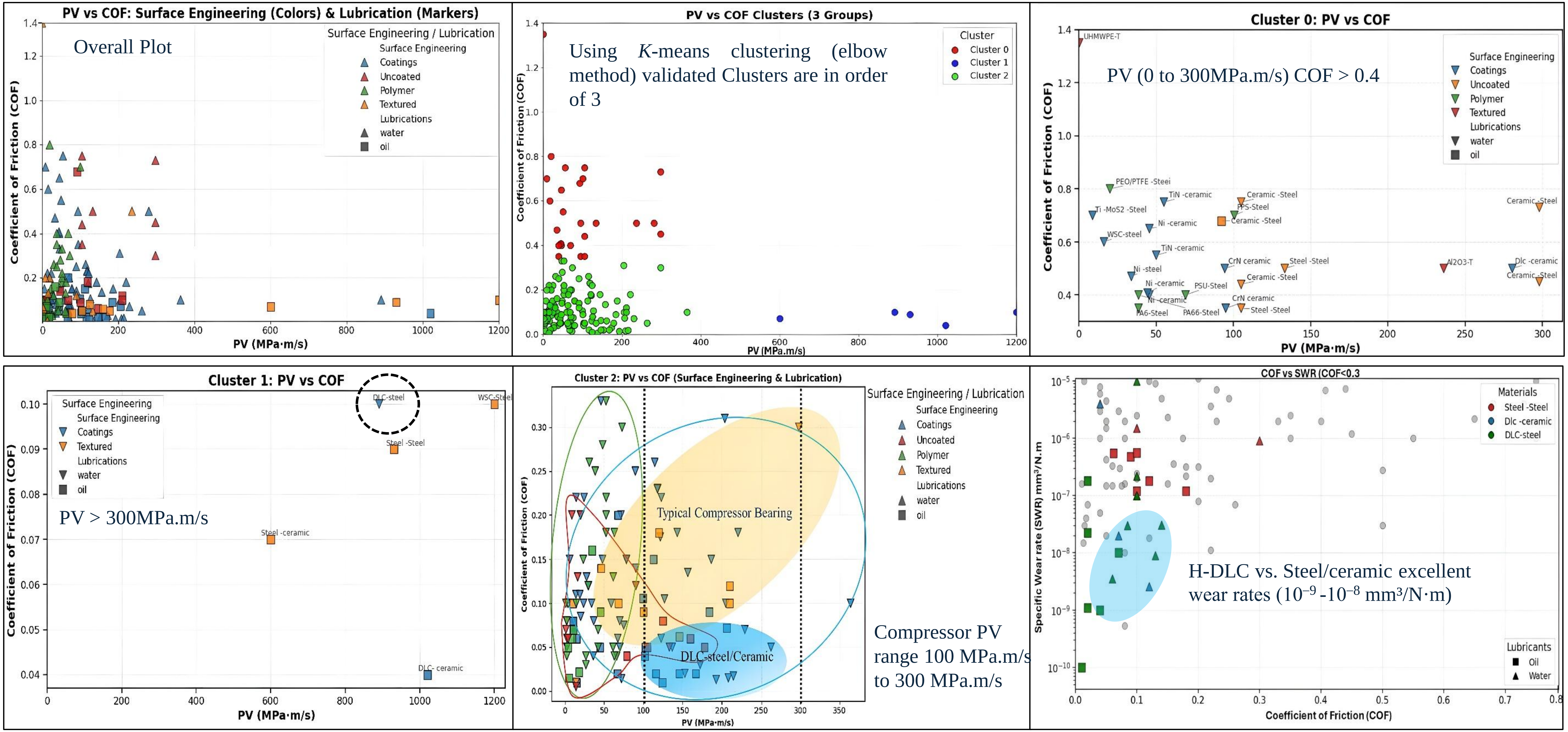
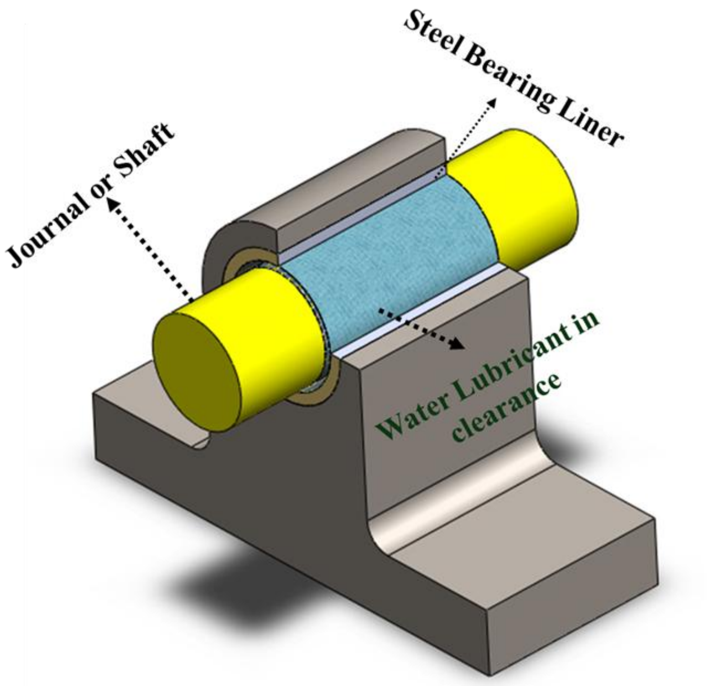


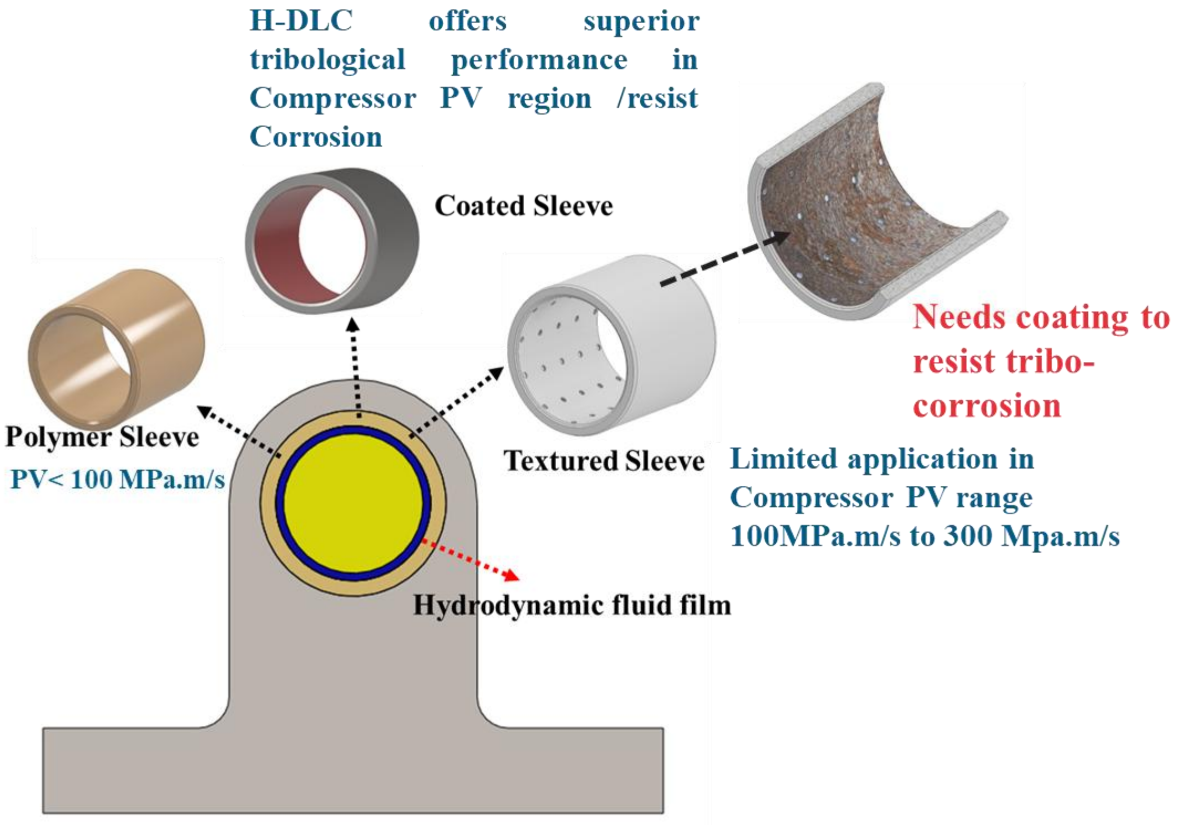
***Figure 2**: Pressure – Velocity (PV), Friction and Wear Rate without and with surface engineering strategies in oil (baseline) and water lubrication tested under different contact and test rigs*

Conclusion

H-DLC coatings, significantly improves performance by reducing COF, wear rates (10^{-8}–10^{-7} $mm^3/N \cdot m$), and corrosion.

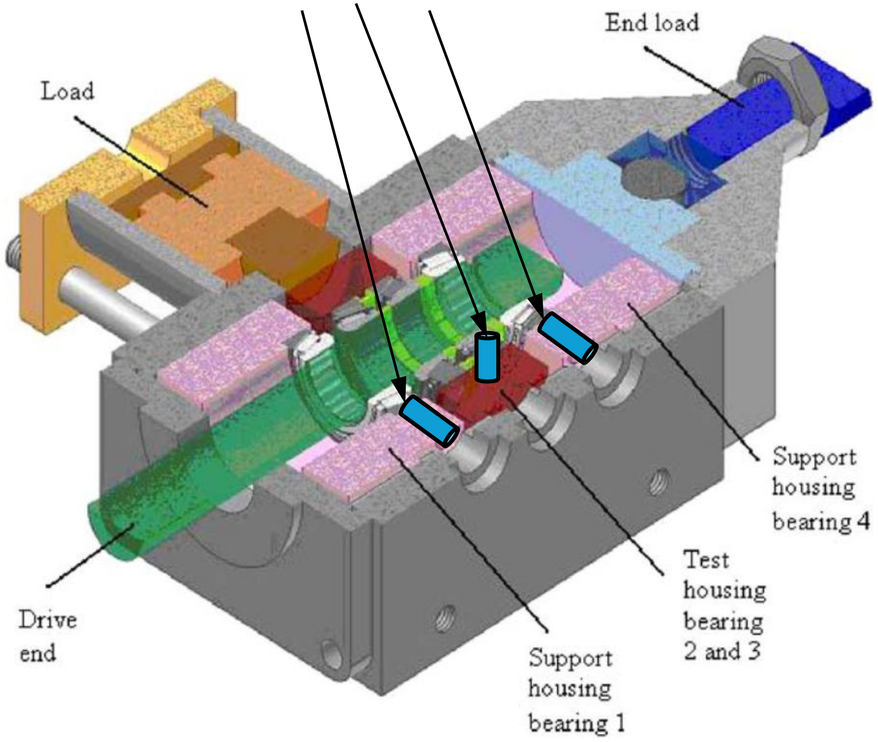
K-means clustering identified three PV-COF-SWR clusters, enabling material and surface design for high-PV applications like screw compressor bearings (100–300 MPa·m/s).





Case studies : going digital : generating data

Tapered roller bearing monitoring



Bearing test rig and sensor positions

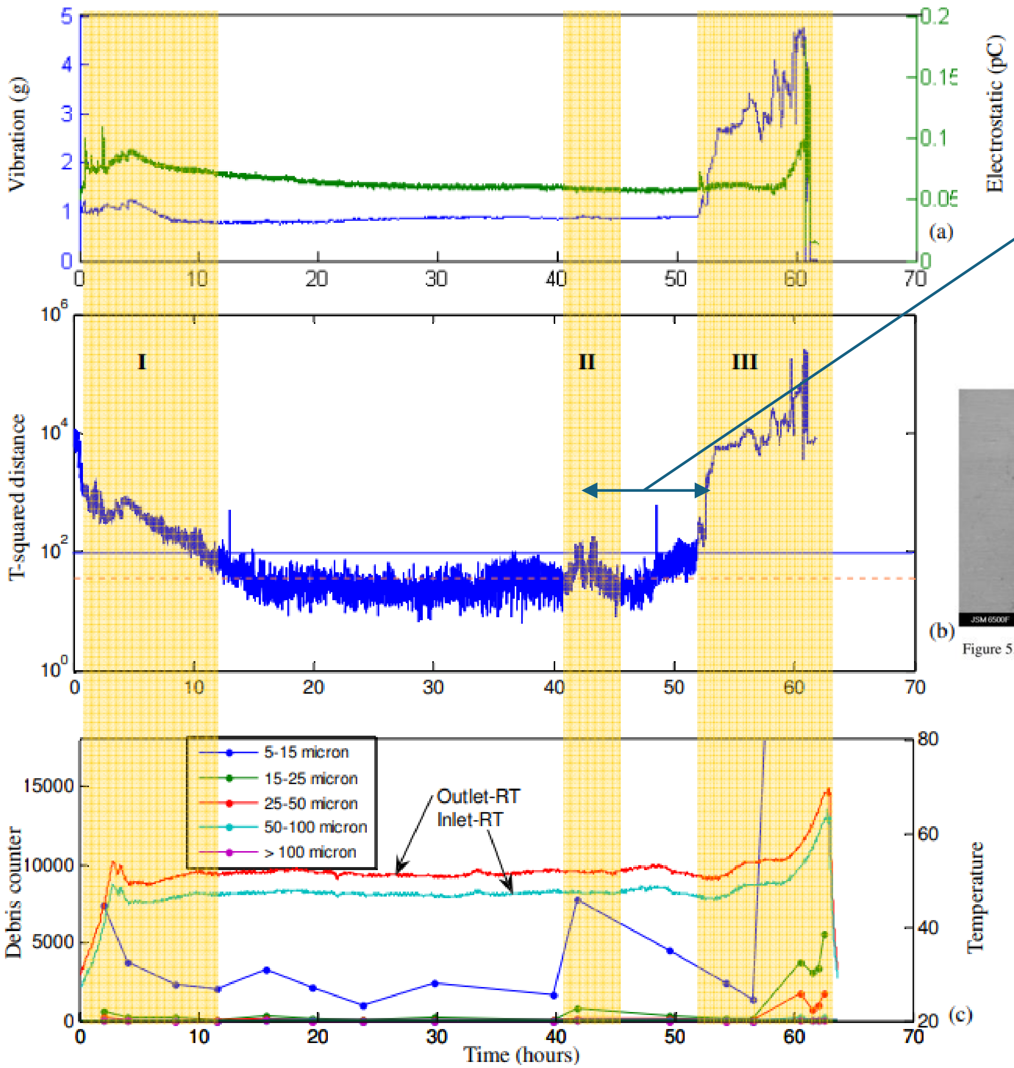


Figure 5.18 (a) vibration and WSS2 RMS traces, (b) anomaly detection results of the test 20 and (c) trends of the debris counter and temperature

12 hours earlier warning than vibration that wear (delamination on outer race and roller spalling) was starting

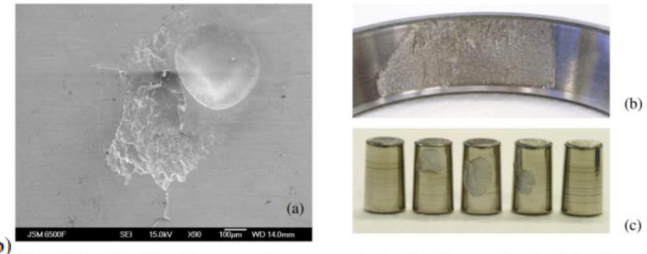


Figure 5.19 (a) Condition of inner race, (b) outer race and (c) rolling elements of bearing 4 after the testing 20[11]

Chen, S.L., 2009. *Development of automated bearing condition monitoring using artificial intelligence techniques* (Doctoral dissertation, University of Southampton).

Methodology

Steel/steel line contact with real-time electrostatic and friction measurements on TE77

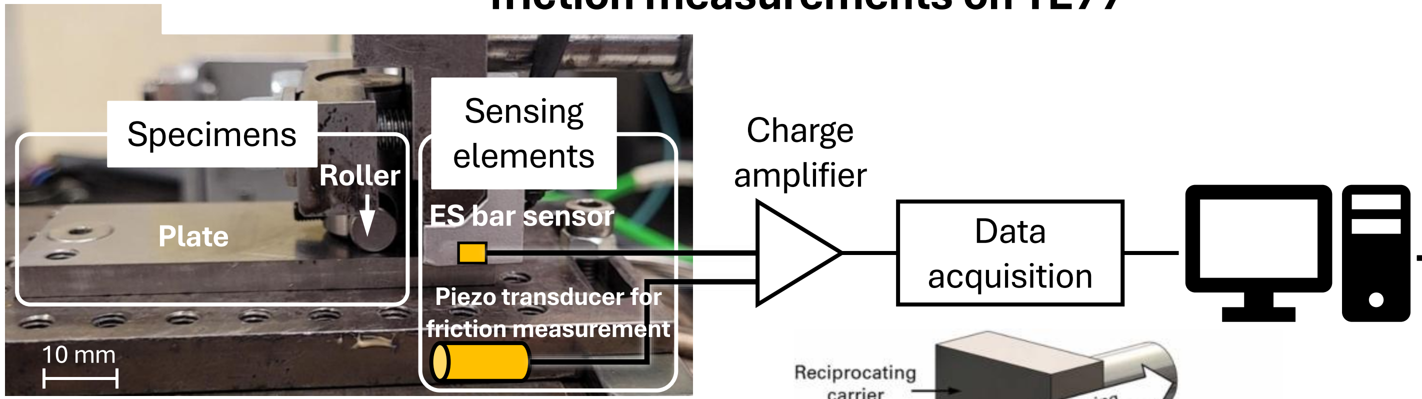
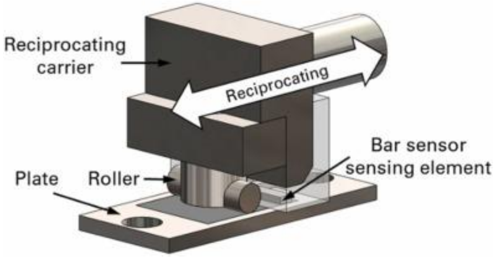
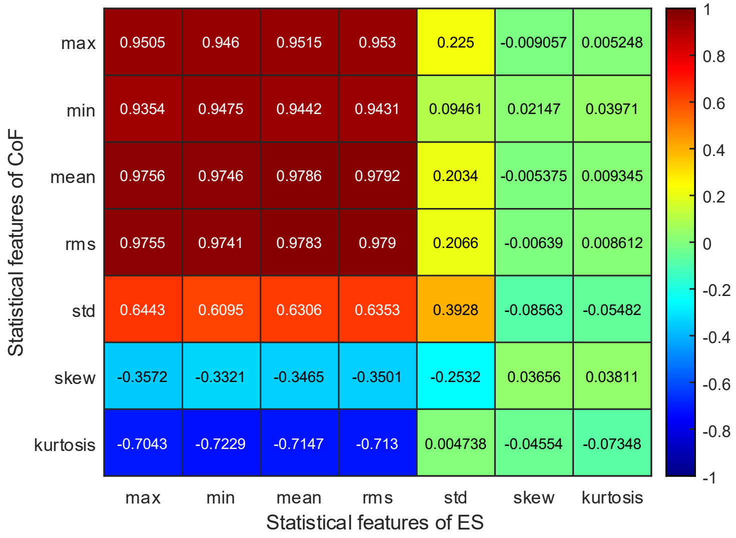


Plate: BO1 BS4659 tool steel
Roughness: Ra 0.052 ± 0.001 μm
Roller: AISI 52100 steel
Roughness: Ra 0.032 ± 0.005 μm
Dry or starved-lubricated (PAO4)

Sampling rate=1 kHz
Amplification=1 V/pC
Hardness: 850 HV roller and 800 HV plate

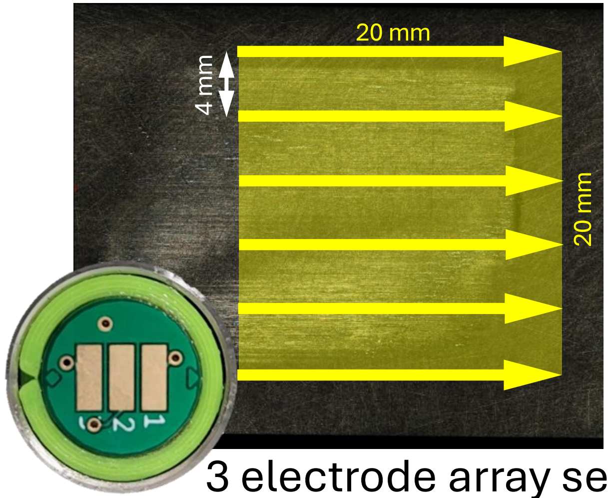


Correlation analysis

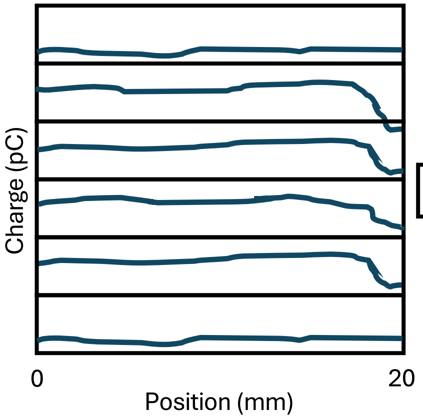


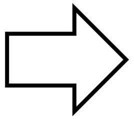
	max	min	mean	rms	std	skew	kurtosis
max	0.9505	0.946	0.9515	0.953	0.225	-0.009057	0.005248
min	0.9354	0.9475	0.9442	0.9431	0.09461	0.02147	0.03971
mean	0.9756	0.9746	0.9786	0.9792	0.2034	-0.005375	0.009345
rms	0.9755	0.9741	0.9783	0.979	0.2066	-0.00639	0.008612
std	0.6443	0.6095	0.6306	0.6353	0.3928	-0.08563	-0.05482
skew	-0.3572	-0.3321	-0.3465	-0.3501	-0.2532	0.03656	0.03811
kurtosis	-0.7043	-0.7229	-0.7147	-0.713	0.004738	-0.04554	-0.07348

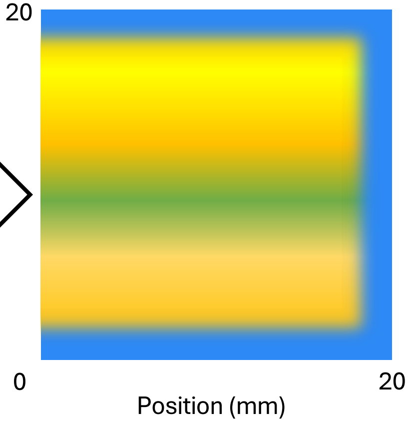
Ex-situ charge map generation using array sensor



3 electrode array sensor







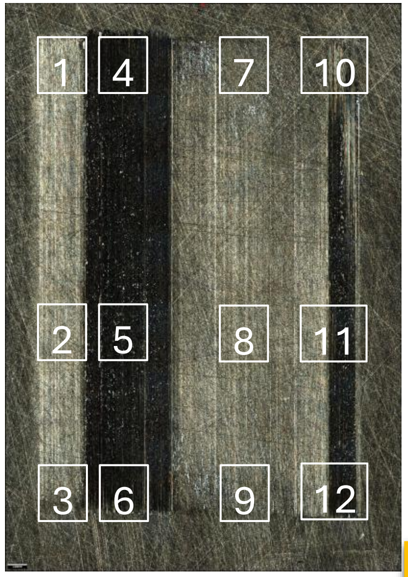
Outlier detection of online friction and ES data using ML algorithms

- Feature regression with L2 penalty
- Isolation forest
- One-class support vector machine
- Long-short term memory
- Autoencoder √

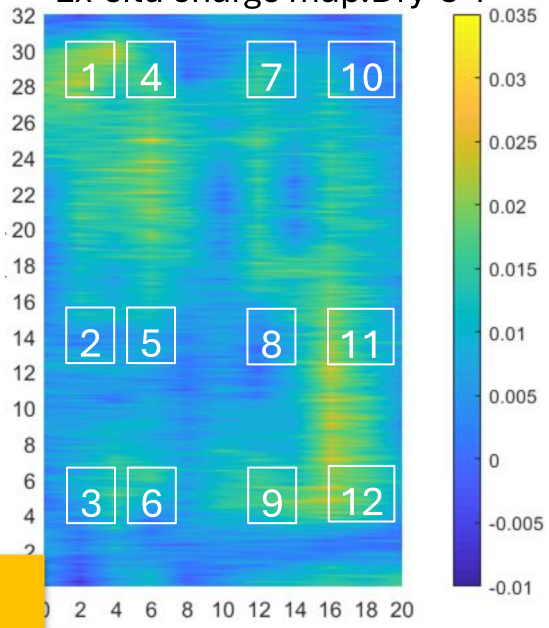
Results and discussion

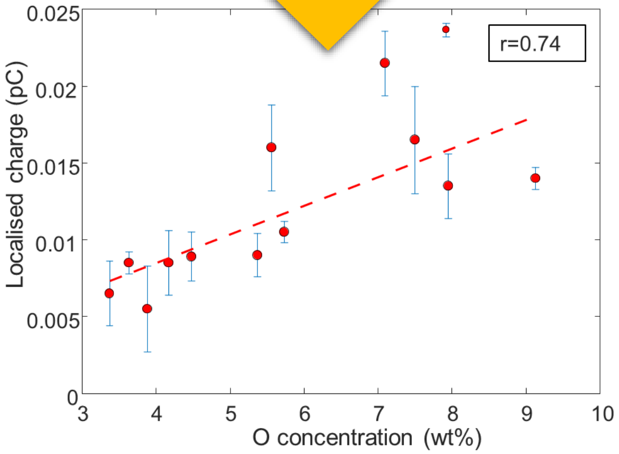
Investigation of charge and wear distribution under dry conditions

Wear scar. Dry-3-1



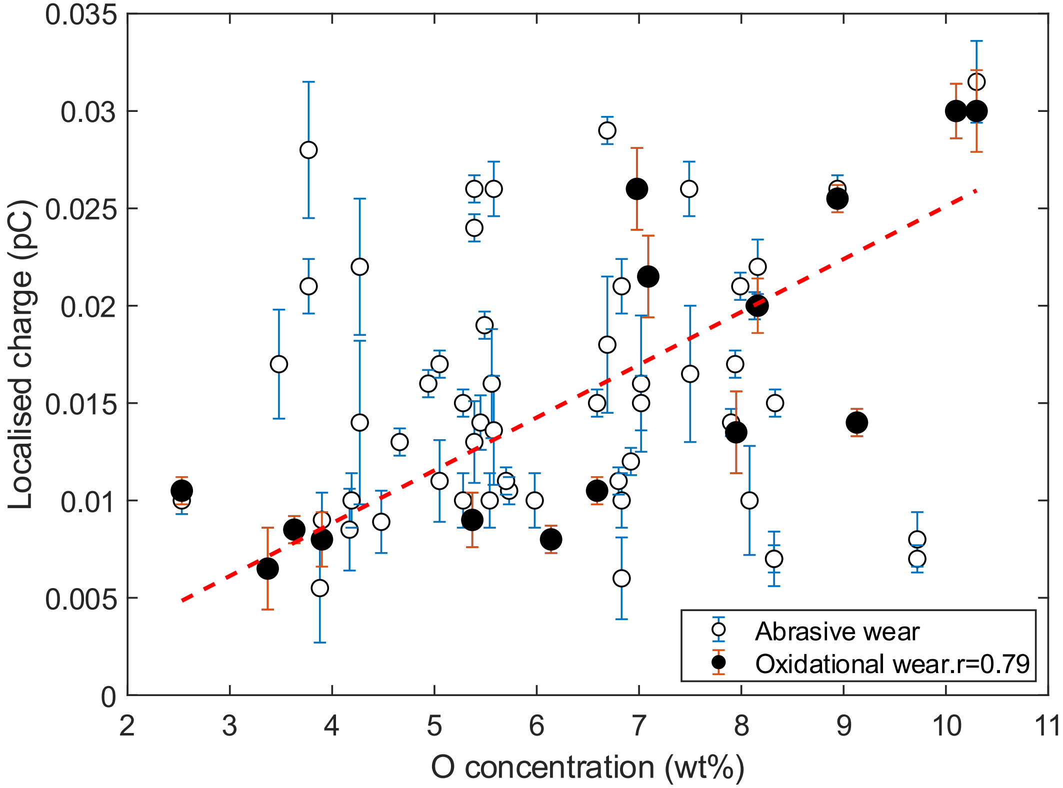
Ex-situ charge map.Dry-3-1





EDS used to quantify oxygen levels on surface

Charge and oxygen concentration data from all the dry sliding tests

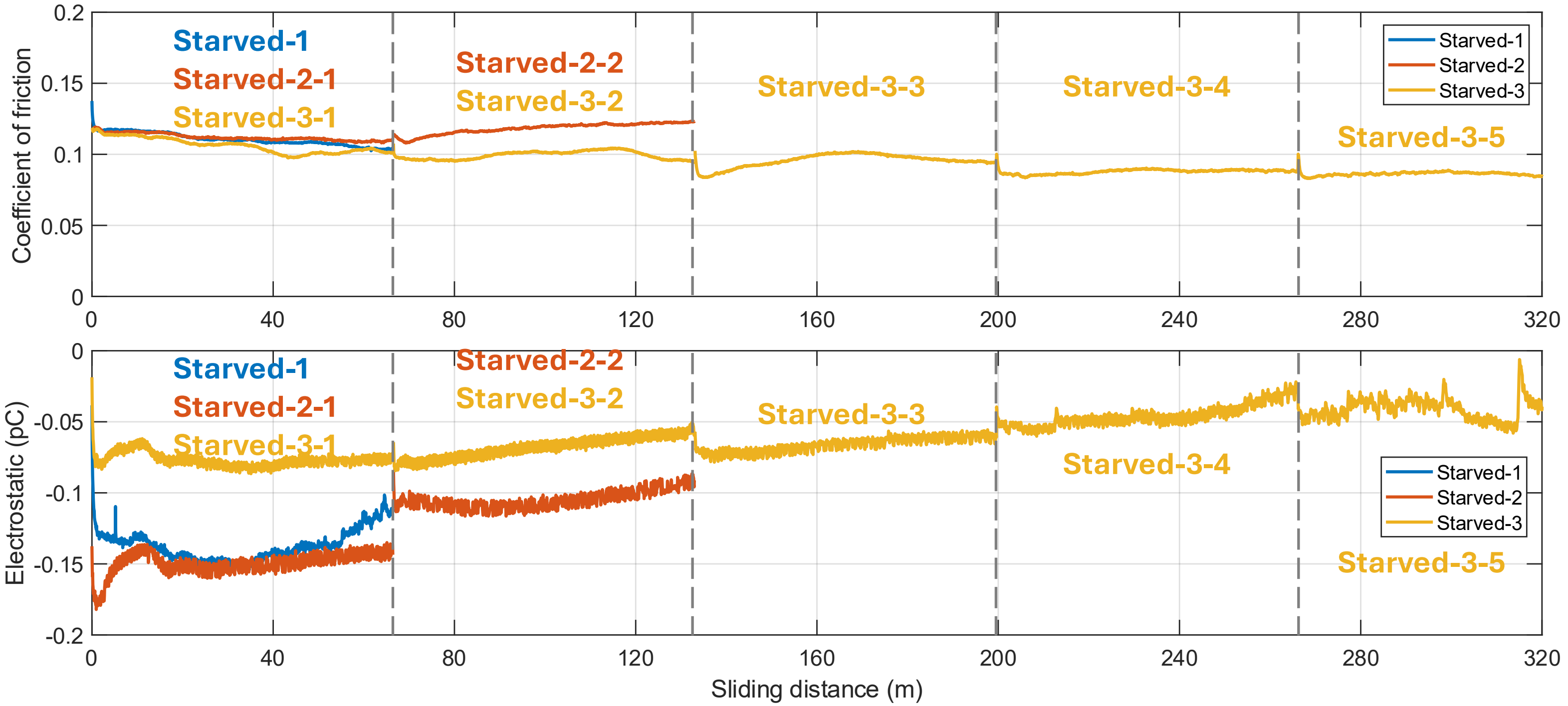


- Charge and oxygen concentration exhibits a nearly linear relationship in the oxidational wear regions
- Less correlation in abrasive wear regions is due to removal of wear debris and formation of oxide with different compositions

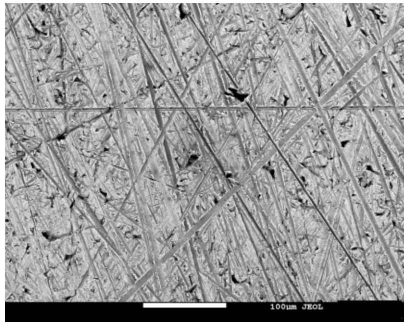
Results and discussion

University of Southampton

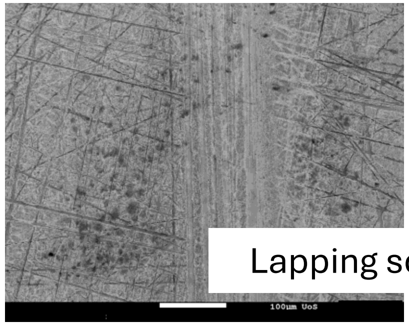
Real-time friction and charge measurements in starved-lubricated conditions



Virgin surface

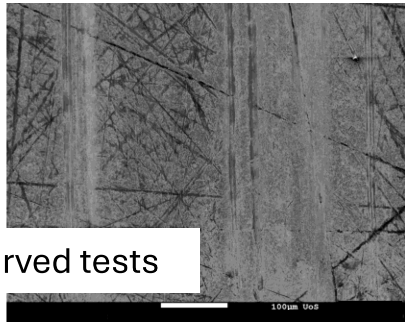


After Starved-1



After Starved-2

After Starved-3



Lapping scar polished off after the starved tests

- Tests started with a lambda ratio of 0.34, at boundary lubrication
- Friction and charge not correlated because they are determined by different mechanisms.

Friction is lower and less noisy than that of dry tests

↑

Lapping scars on virgin surfaces were polished off and no significant damage was observed

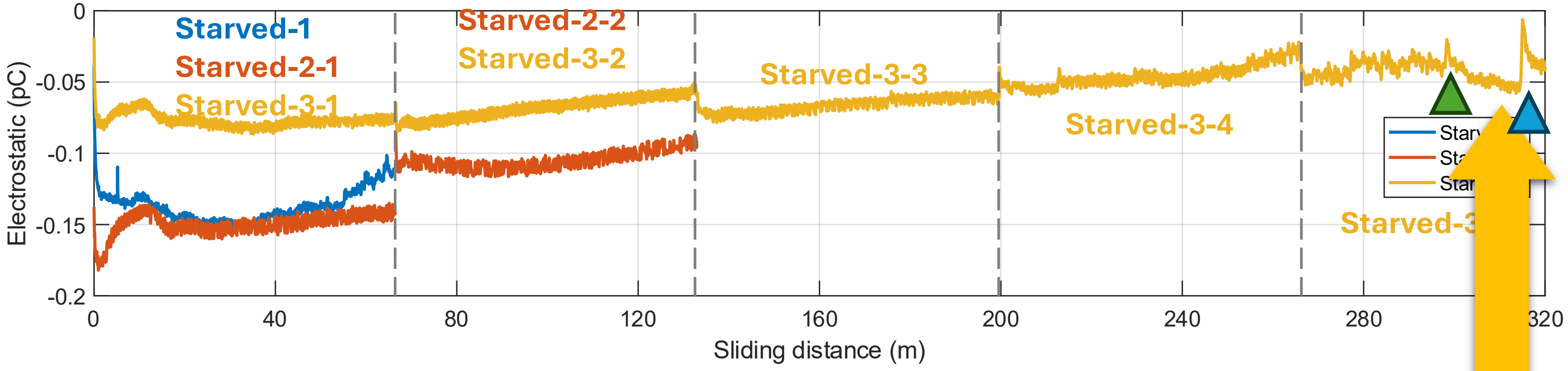
Charge exhibited **negative** in starved-lubricated tests

↑

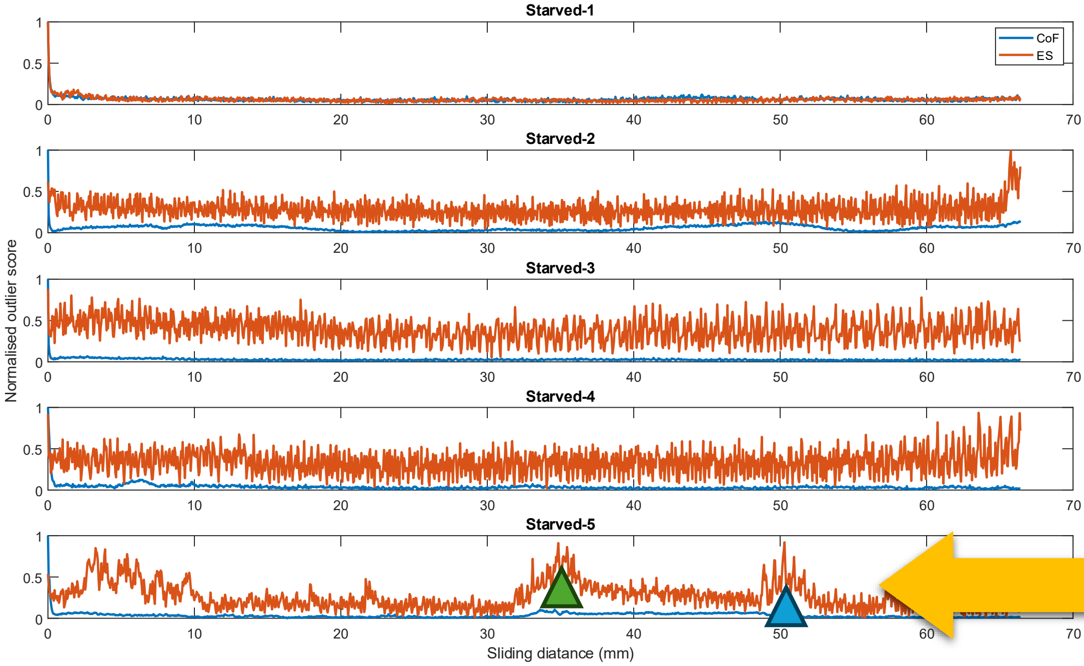
Charge sources: tribocharging and oil degradation

Results and discussion

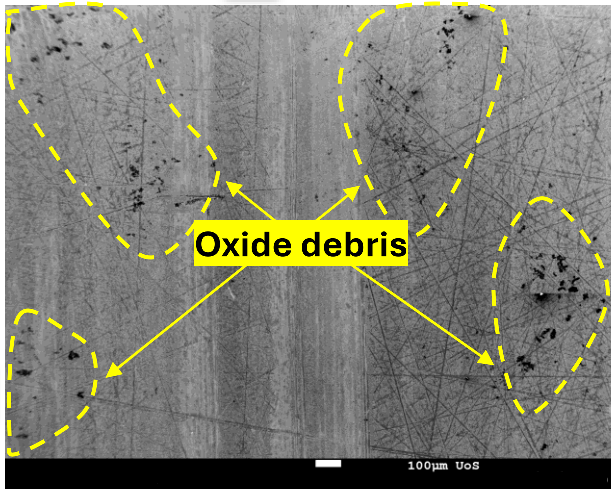
Outlier detection of debris in starved-lubricated conditions



- Charge tended to approach zero due to accumulation of oxide debris
- Charge exhibited earlier signs of oxide debris than friction



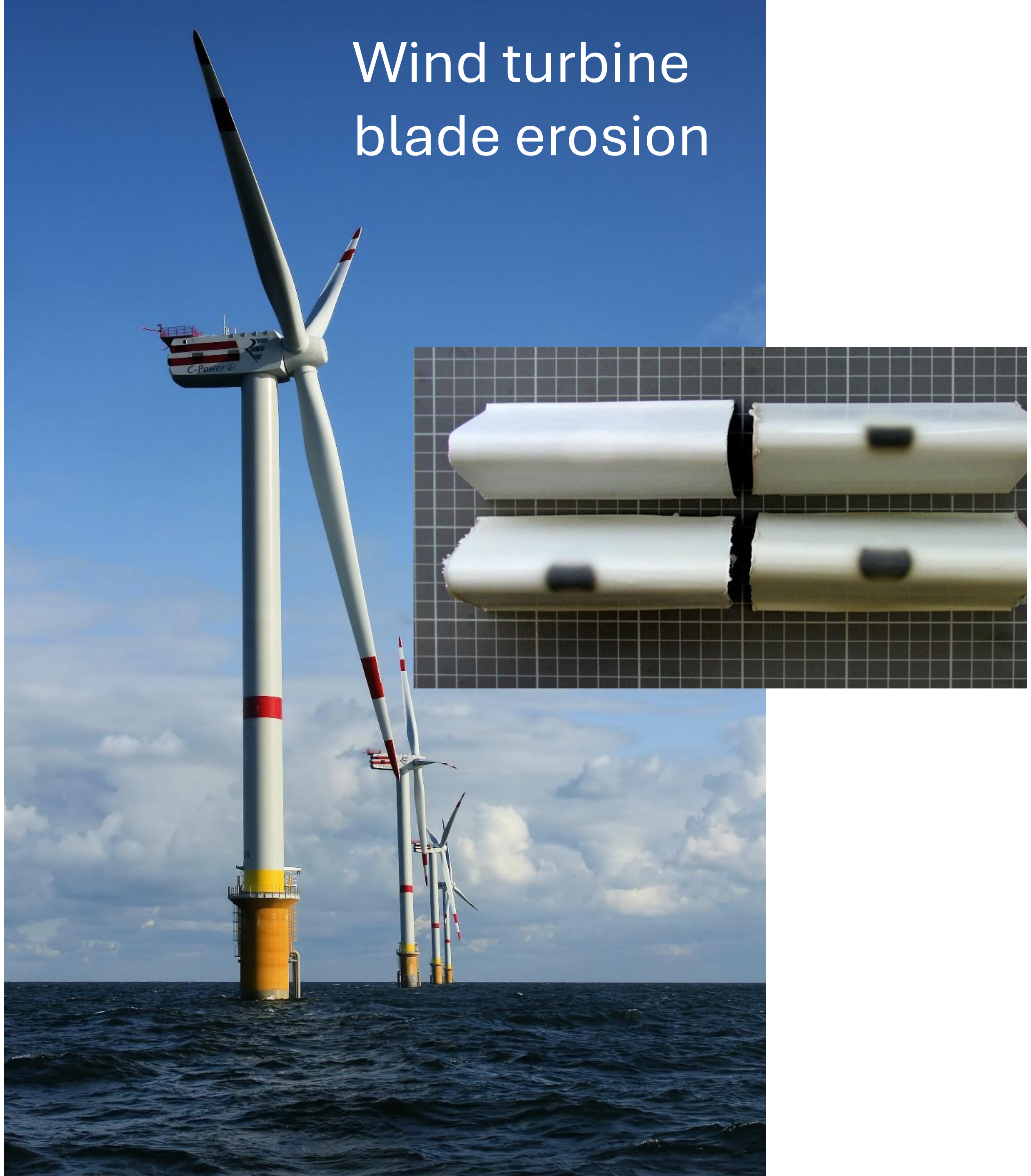
Outlier detection using Autoencoder algorithm

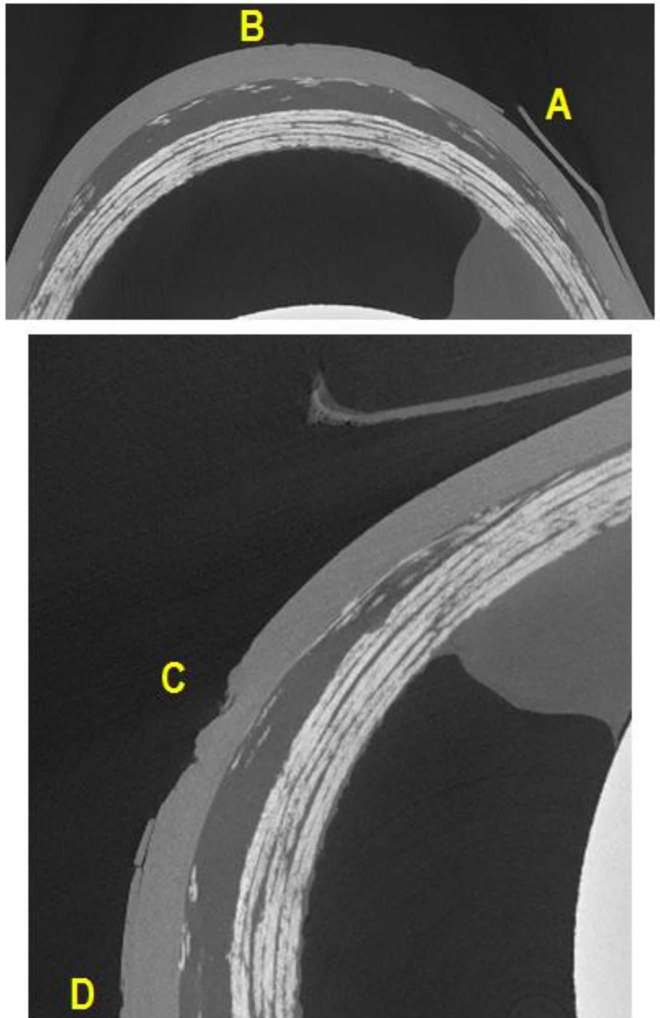


Wear rates of the rollers 10^{-5} mm^3/Nm for dry and 10^{-7} mm^3/Nm for starved

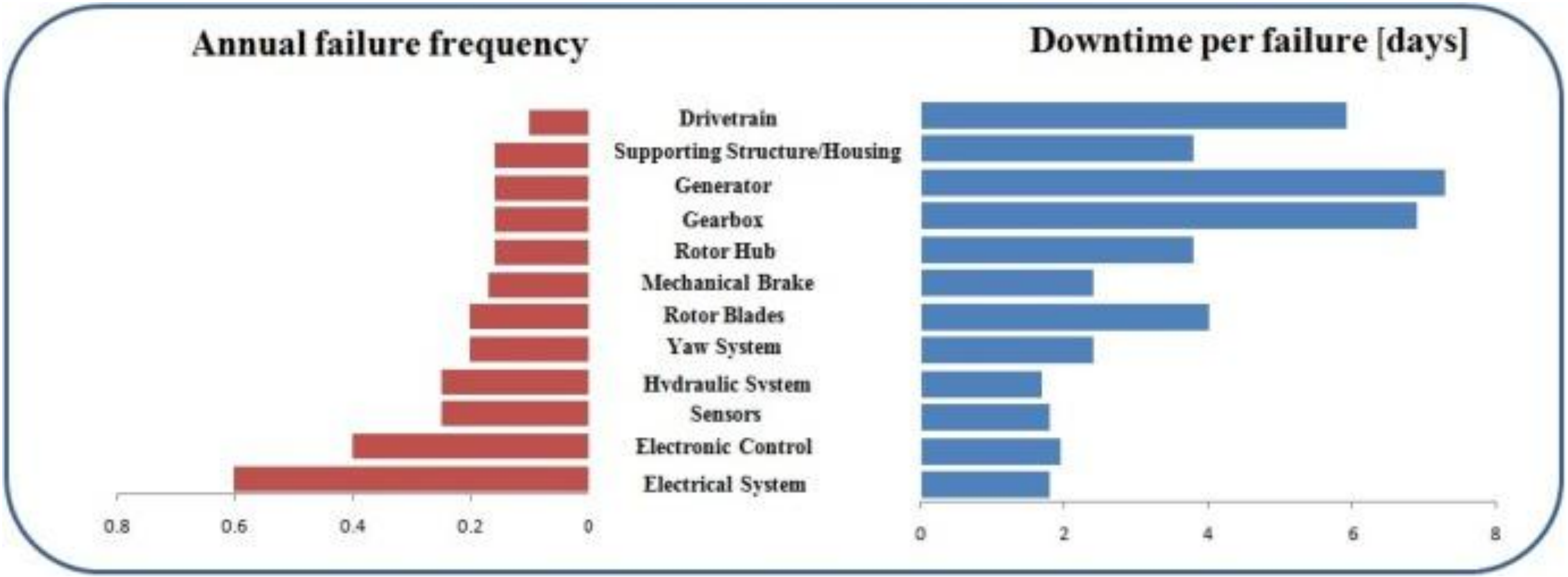
Wind turbine blade erosion

University of Southampton

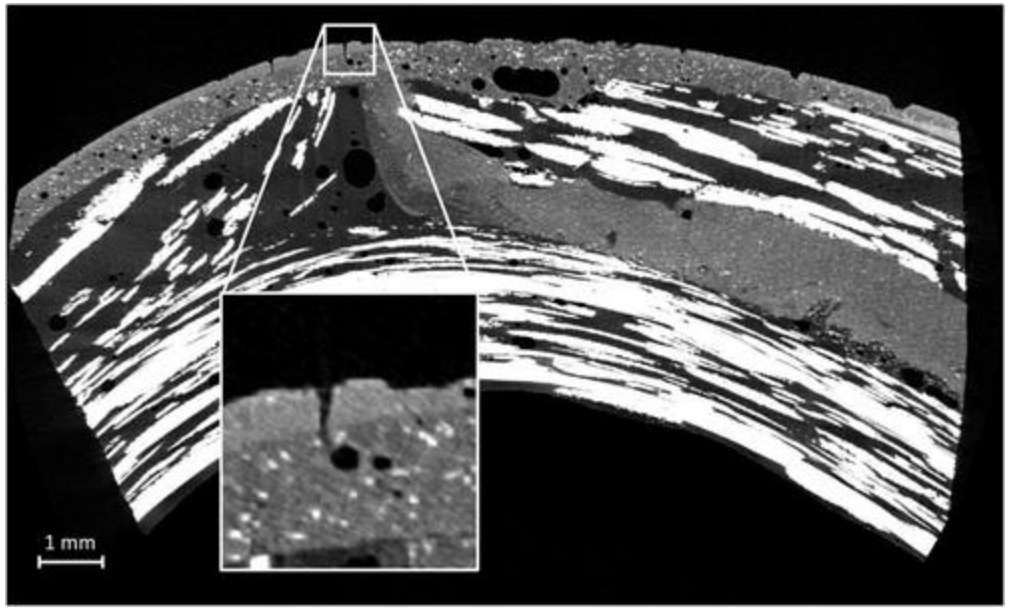


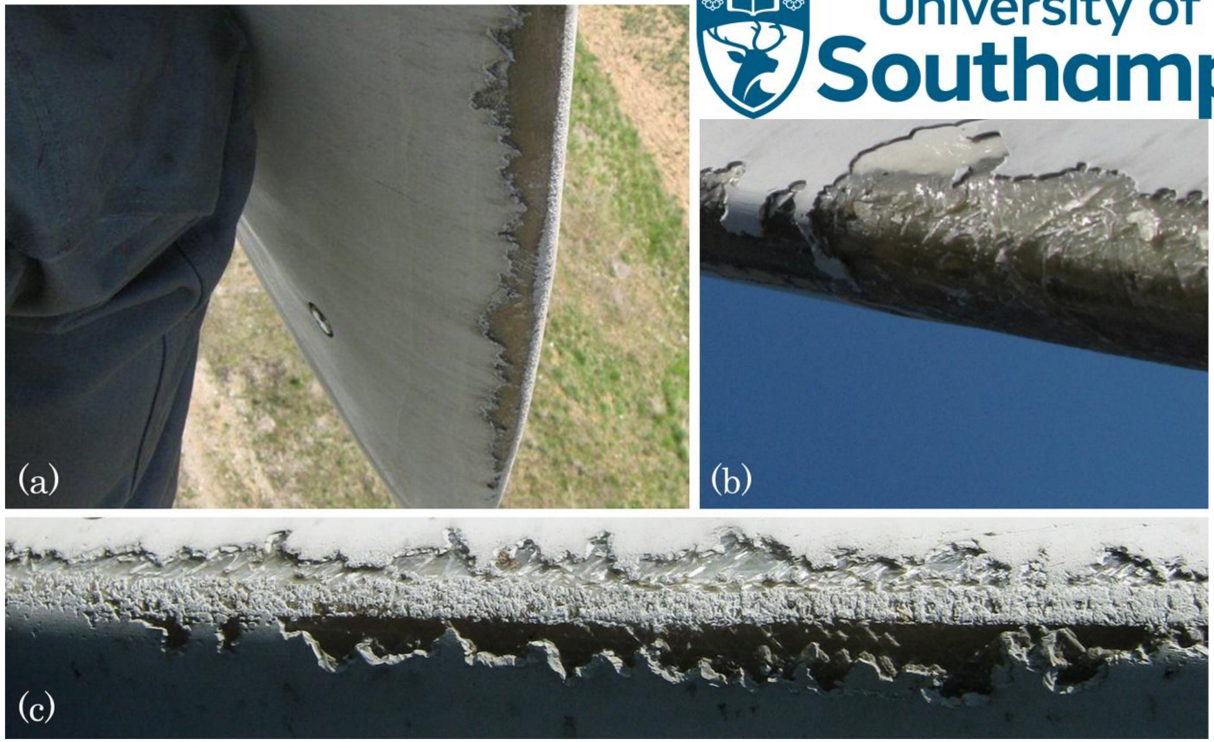


Failure rate and downtimes of Wind Turbine components

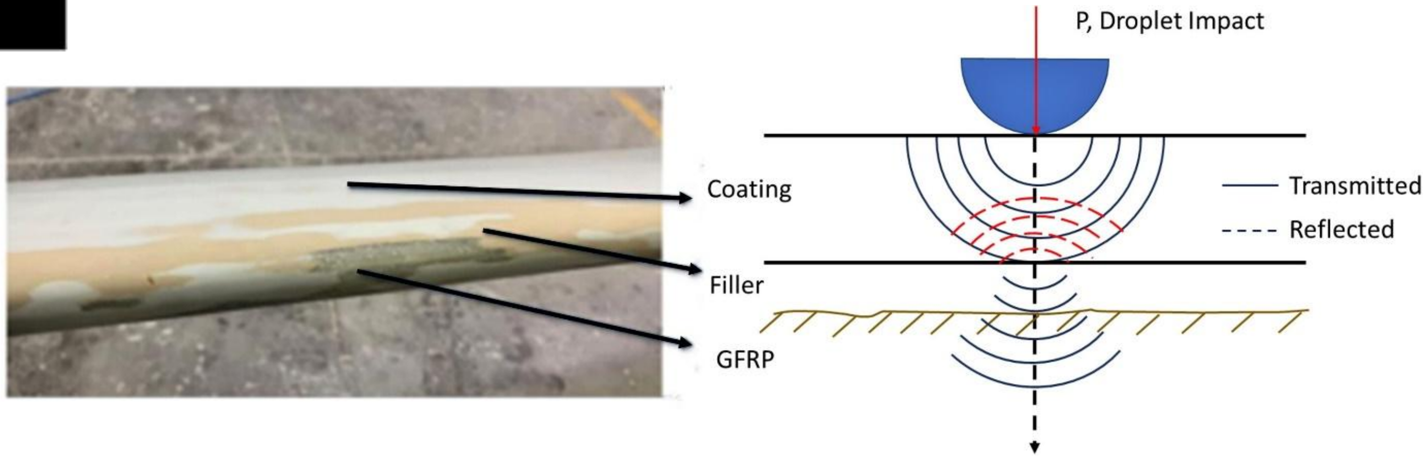


Anil Dhanola, H.C. Garg, Tribological challenges and advancements in wind turbine bearings: A review, Engineering Failure Analysis, Volume 118, 2020, 104885, https://doi.org/10.1016/j.engfailanal.2020.104885.



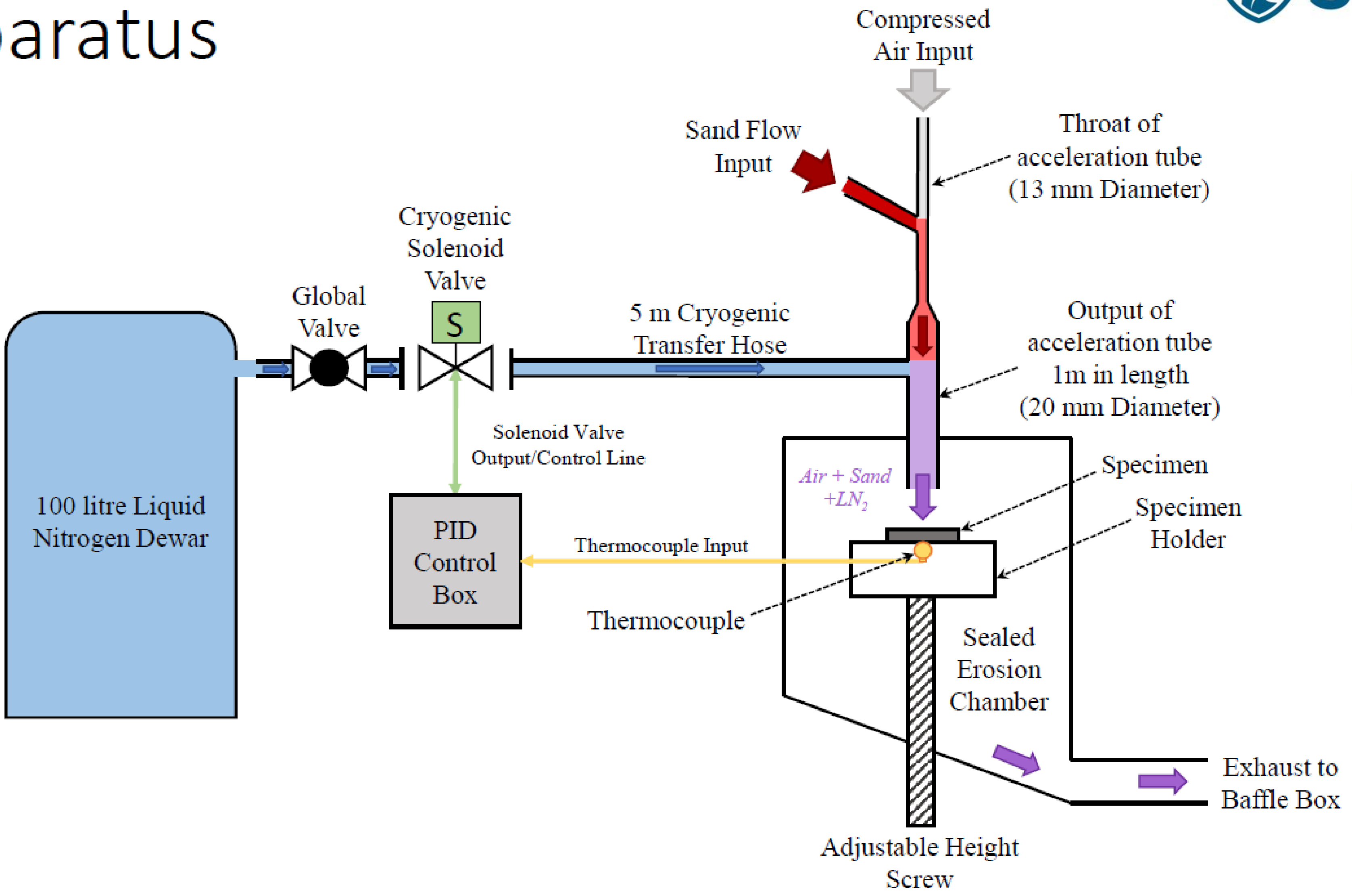


Fæster S, Johansen NF-J, Mishnaevsky L Jr, Kusano Y, Bech JI, Madsen MB. Rain erosion of wind turbine blades and the effect of air bubbles in the coatings. *Wind Energy*. 2021; 24: 1071–1082. https://doi.org/10.1002/we.2617



Domenech, L.; García-Peñas, V.; Šakalytė, A.; Francis, D. P.; Skoglund, E.; Sánchez, F. Top Coating Anti-Erosion Performance Analysis in Wind Turbine Blades Depending on Relative Acoustic Impedance. Part 2: Material Characterization and Rain Erosion Testing Evaluation. *Coatings* 2020, 10, 709. DOI: 10.3390/coatings10080709.

Apparatus



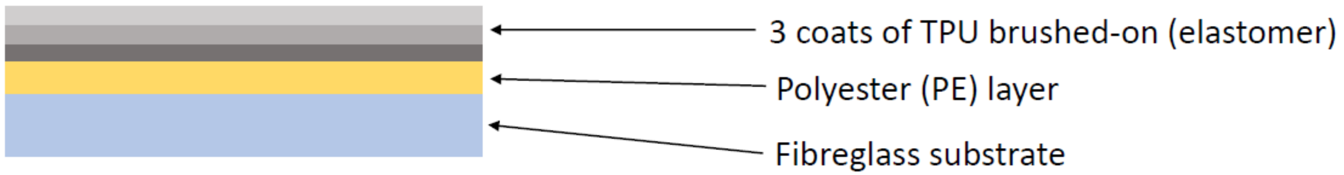
Mike Godfrey et al, The effect of temperature on the erosion of polyurethane coatings for wind turbine leading edge protection, Wear, 476, 2021, 203720, https://doi.org/10.1016/j.wear.2021.203720.

Samples

Both coatings were 0.4 mm thick

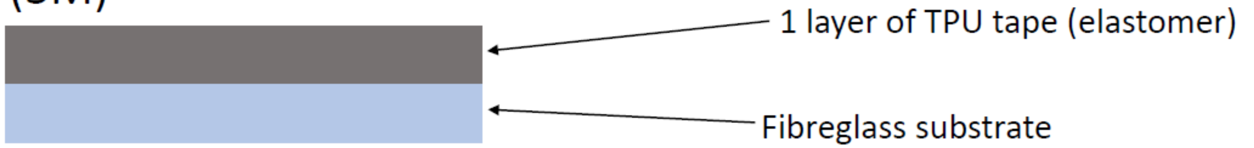
Two coatings were tested.

1) A commercial brush-on TPU coating (PB)



3M (product number W8607)

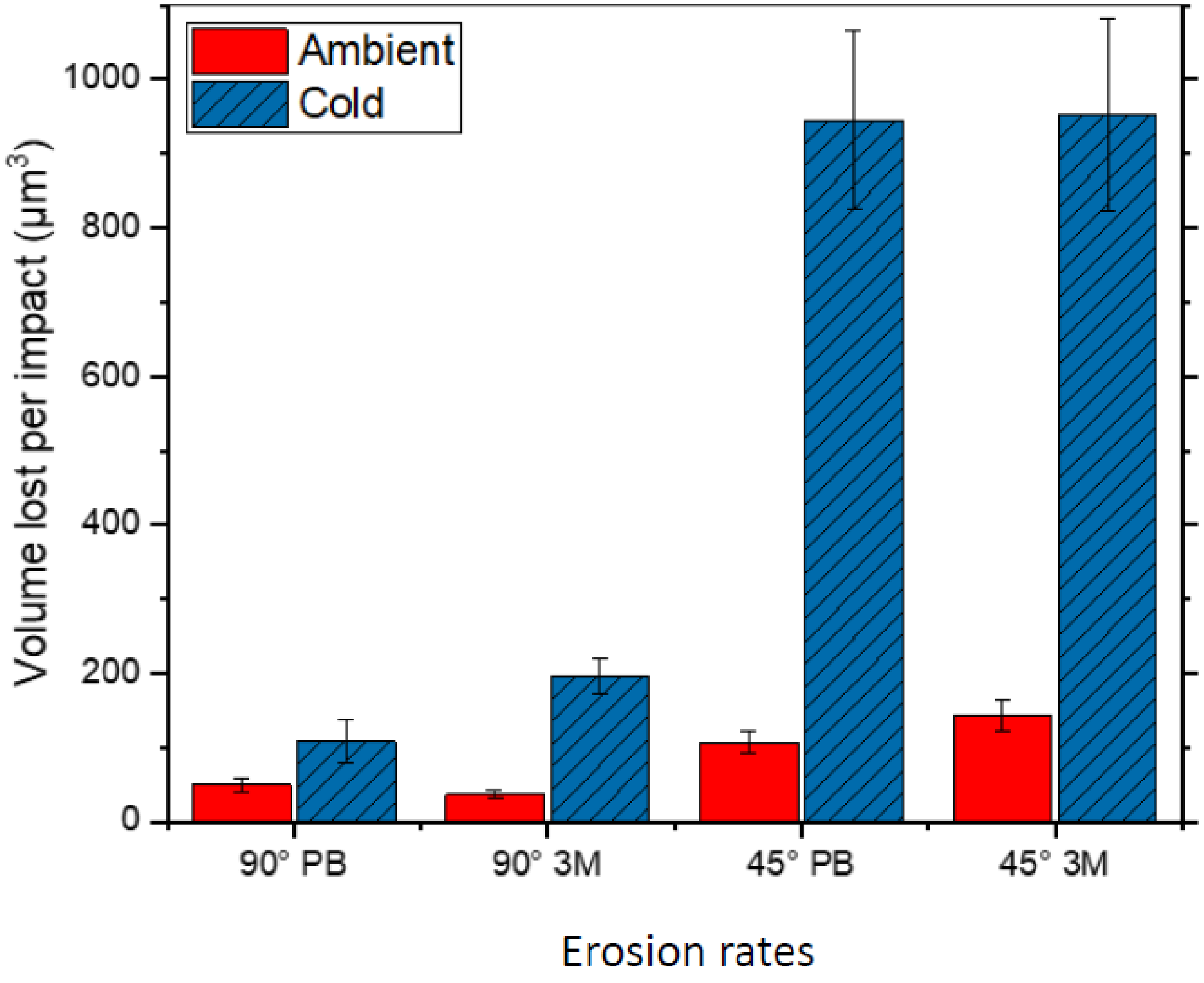
2) 3M tape (3M)



Fiberglass used as substrate for a commercial PU coating.
Polyester layer was used between substrate and PU topcoat and compared to 3M tape applied on the substrate.

Results: erosion rate

The erosion rate at -30°C was much faster than at 25°C.



A **sand concentration** of **1.3×10^{-4} %** was used.

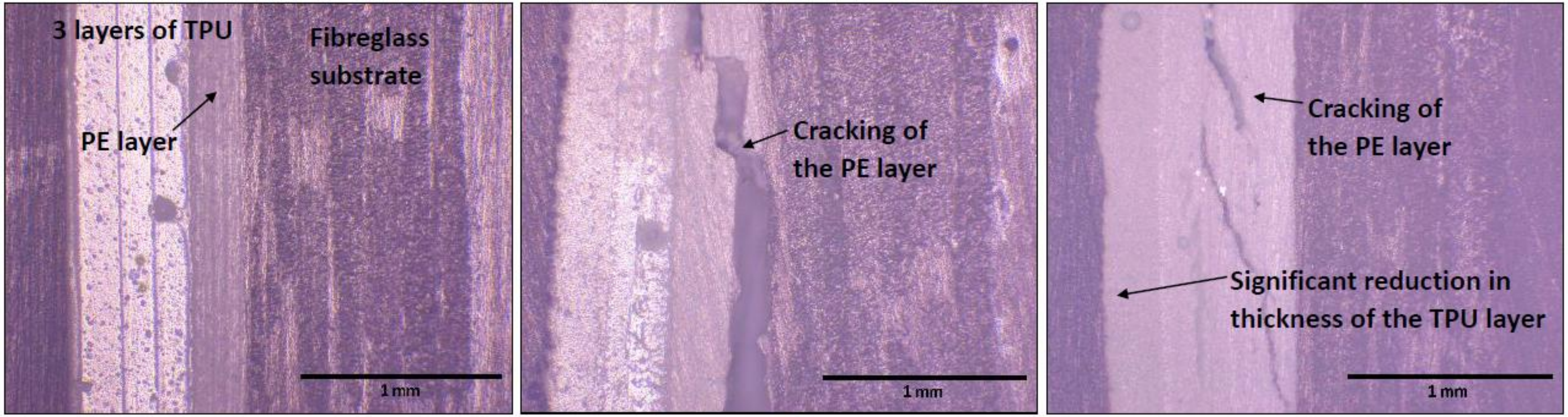
Velocity calibration was performed with a high-speed camera and was **68±8 m/s**.

Testing was conducted at **25°C and -30°C**.

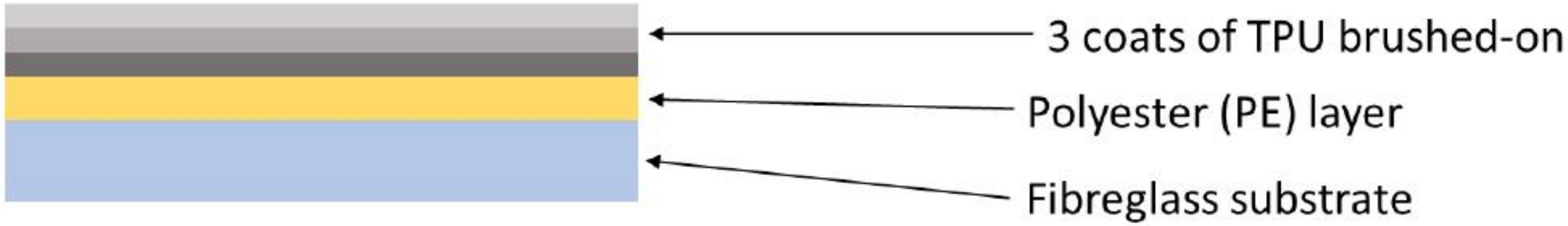
The coatings were tested at **90° and 45°** impingement.

The glass transition temperature for the coatings was between -5 and 5°C

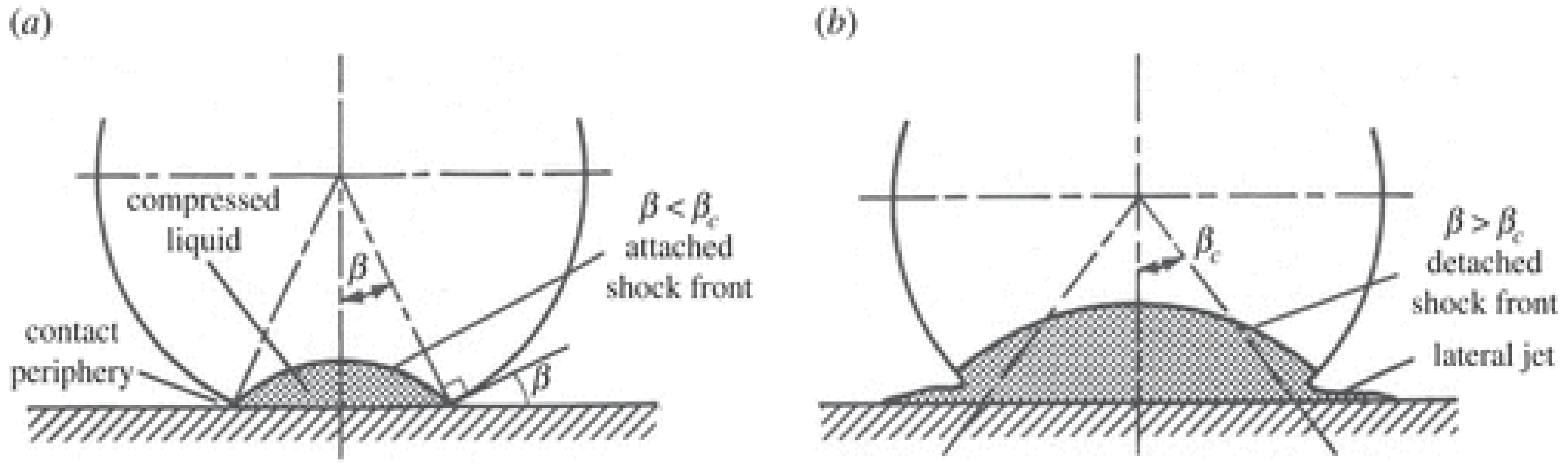
Degradation of PB



Uneroded | Ambient erosion (1 hour) | Cold erosion (15 mins)



Water droplet erosion



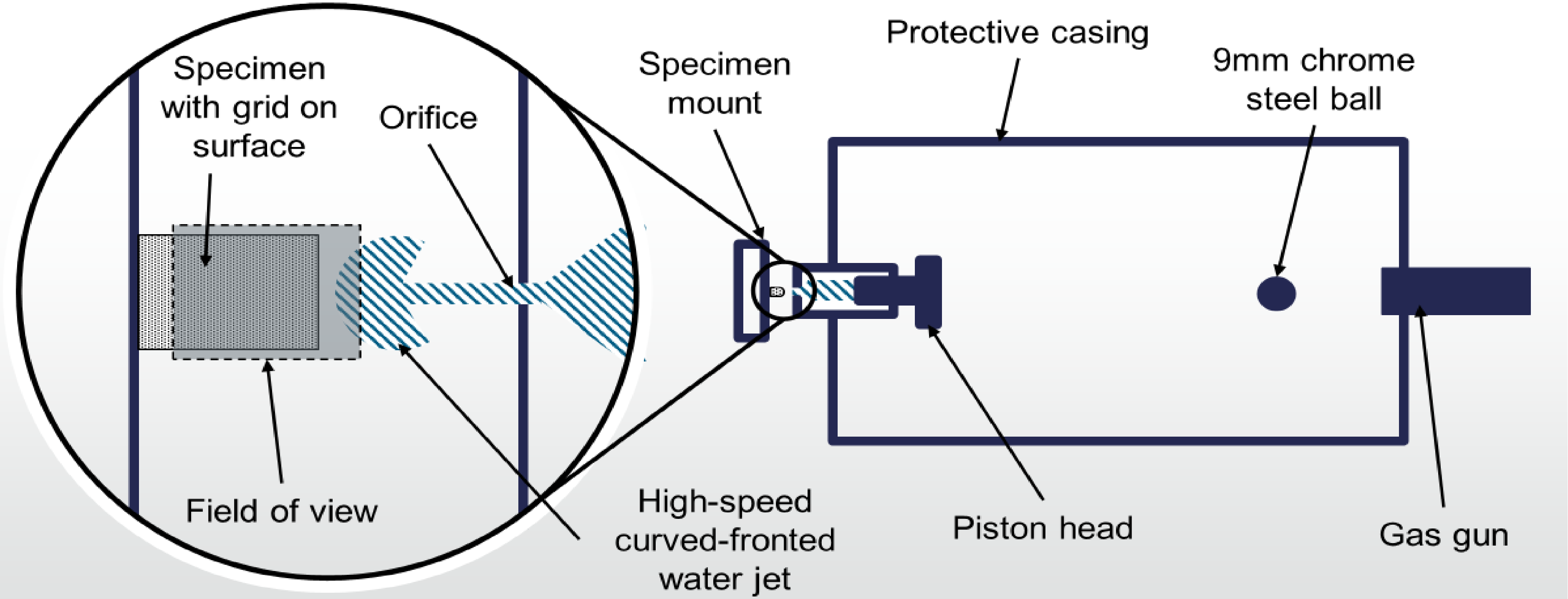
Two main stages of a high-speed droplet impingement: compressible and flow

(a) Initial 'compressible' stage, the compressed liquid generates the high 'water-hammer' pressure on the solid surface.

(b) Secondary 'flow' stage, lateral outflow jetting interacts with discontinuities or pits on surface to contribute to water droplet erosion

Investigating high-speed liquid impingement with full-field measurements, Volume: 479, Issue: 2277, DOI: (10.1098/rspa.2023.0023)

Producing High-Speed Water Jets



Burson-Thomas, Charles B., et al. "Water droplet erosion of aeroengine fan blades: The importance of form." Wear 426 (2019): 507-517.

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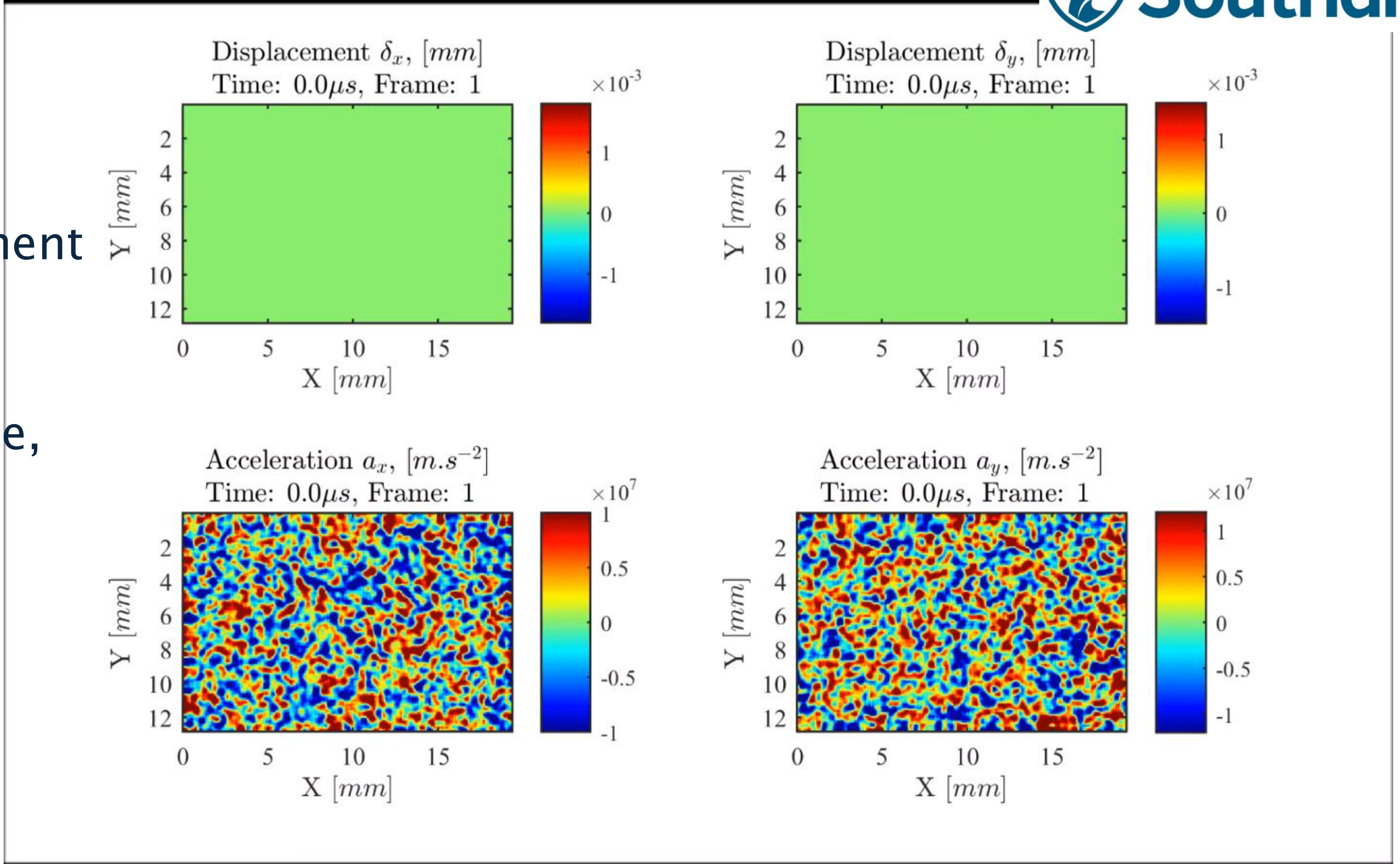
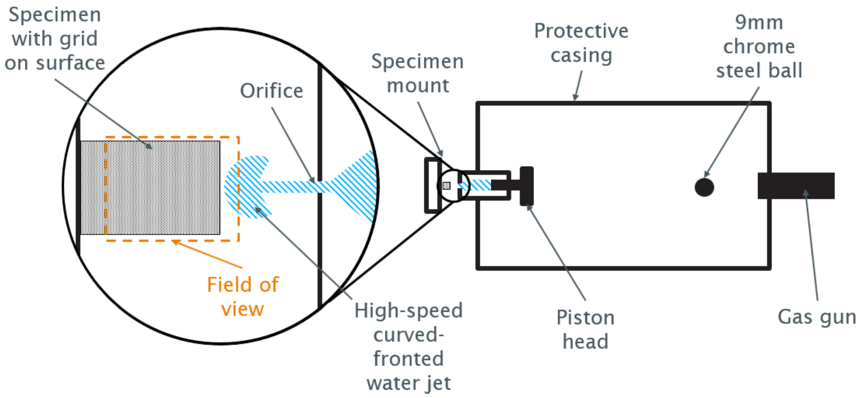
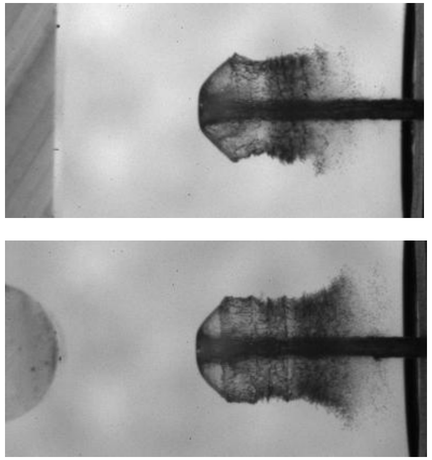
Impingement velocity, $235 ms^{-1}$

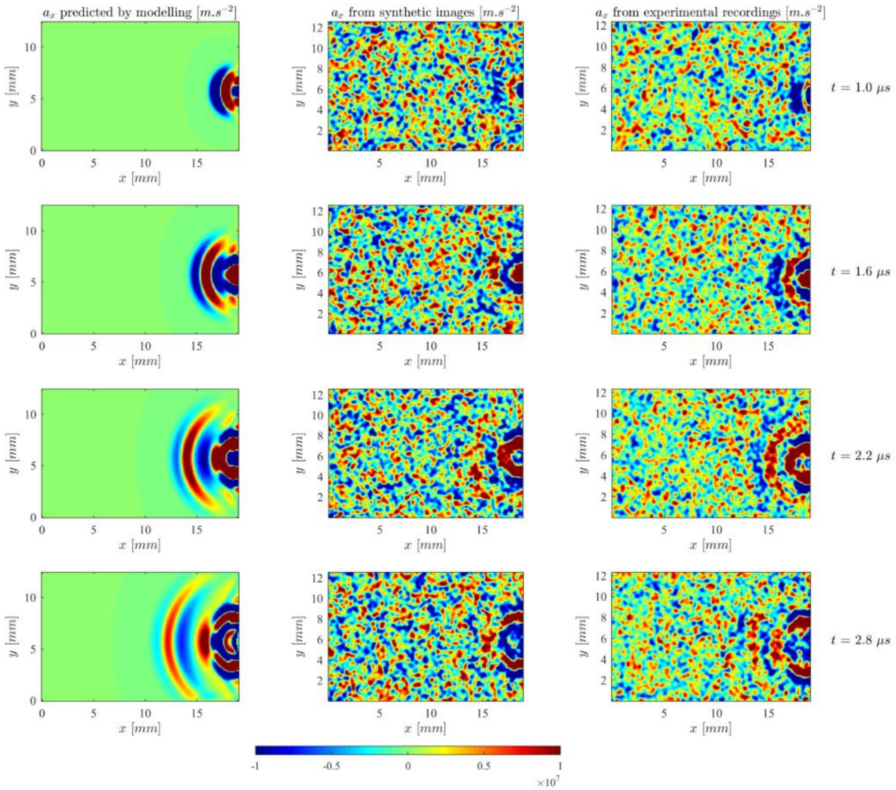
Frame rate, 5MHz



Erosion of blade leading edges; fundamentals



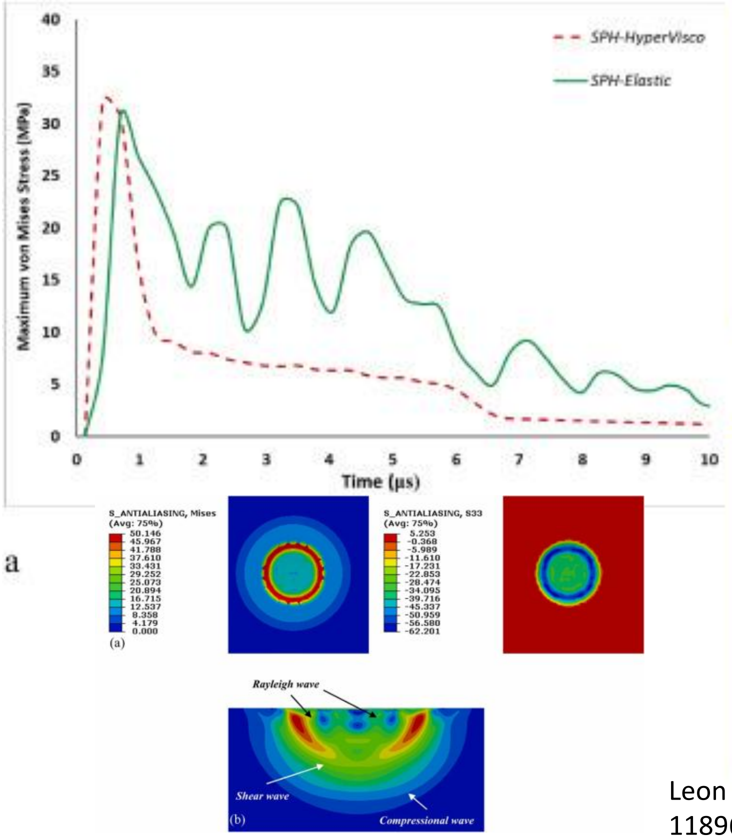


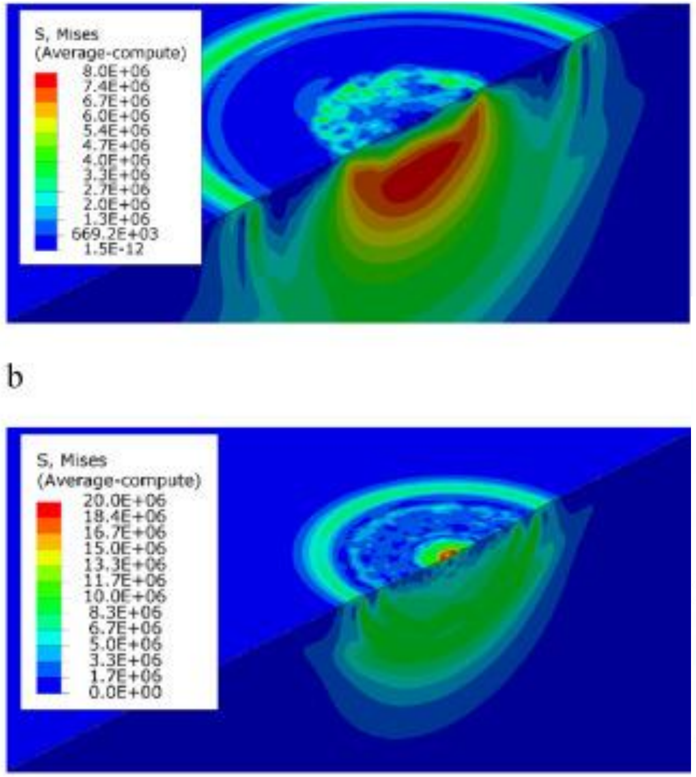


Burson-Thomas C. B., Harvey T. J., Fletcher L., Wellman R., Pierron F. and Wood R. J. K., 2023, Investigating high-speed liquid impingement with full-field measurements, *Proc. R. Soc. A.* **479** 20230023, http://doi.org/10.1098/rspa.2023.0023

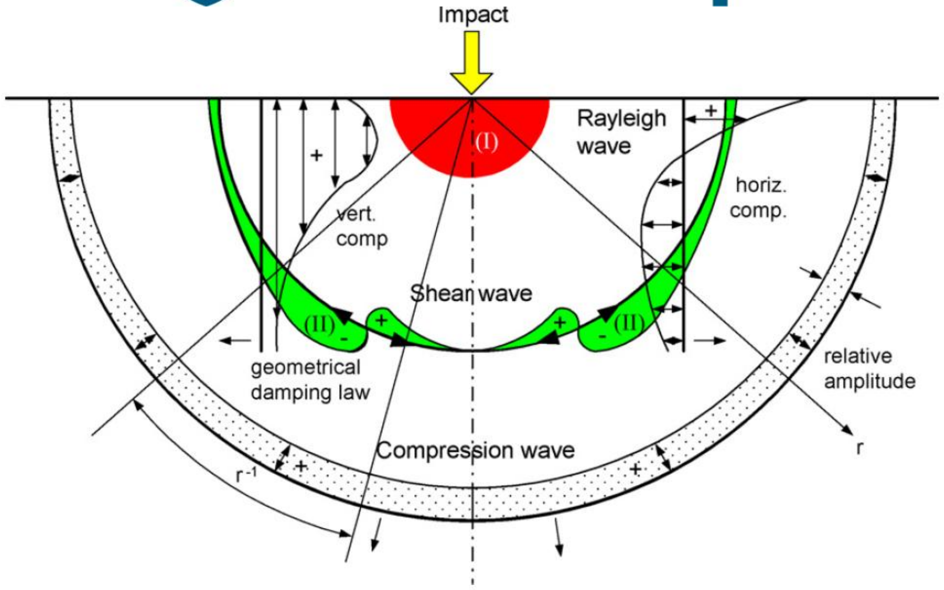
Stress waves produced

When dynamic impact event occurs on surface of elastic, homogeneous, isotropic solid, 3 types of elastic wave will propagate: **Compression, Shear and Rayleigh**

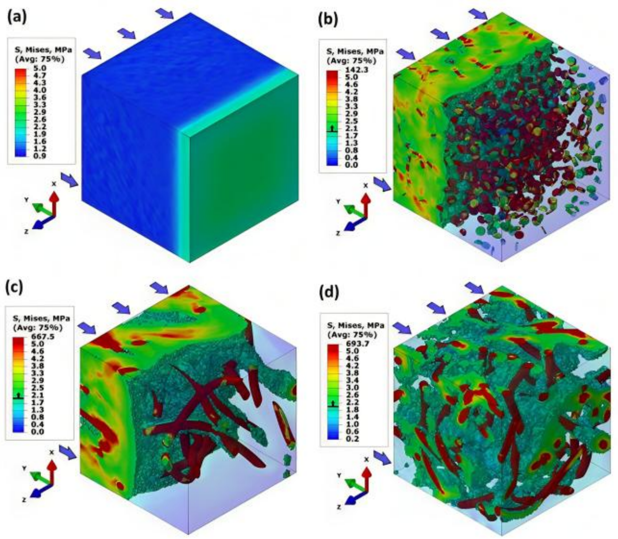


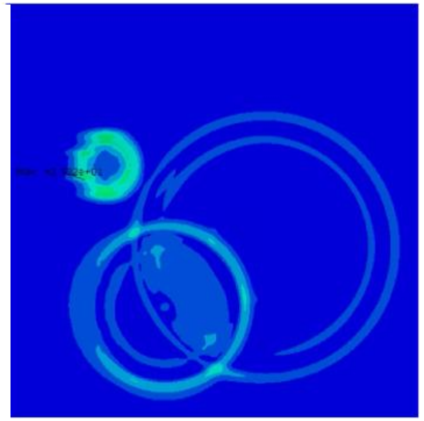


Leon Mishnaevsky, Renewable Energy, Volume 215, 2023, 118966, https://doi.org/10.1016/j.renene.2023.118966.



Haosheng, C. and Shihan, L., 2009. *Wear*, 66, 1-2, 69-

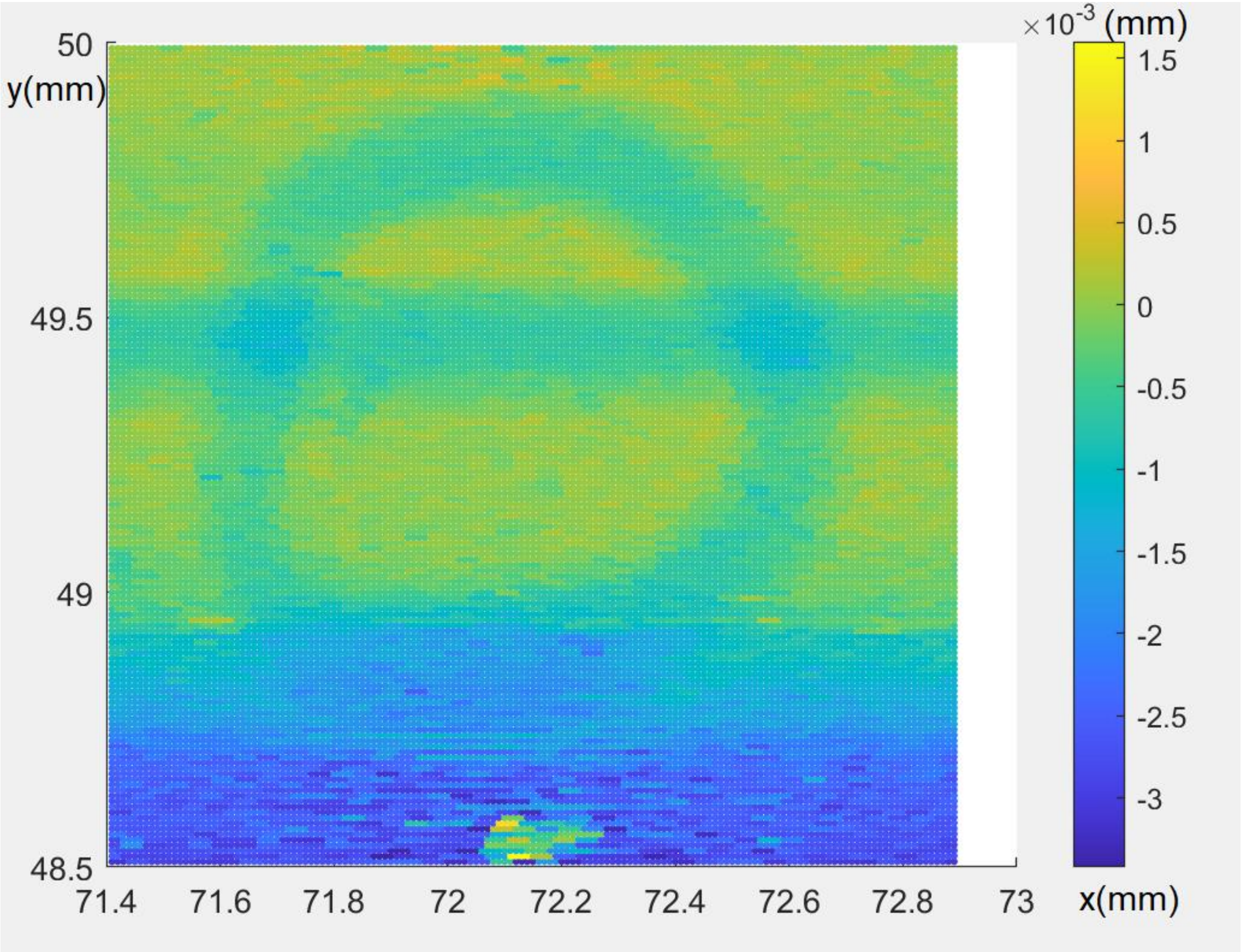




Multiple impact modelling

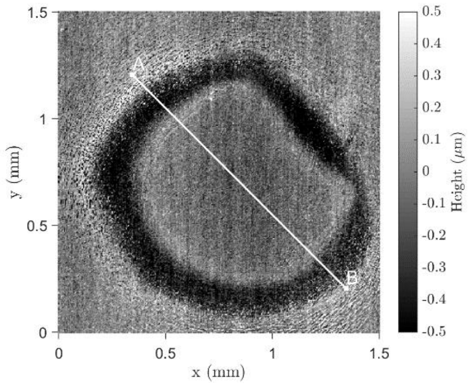
WDE Damage

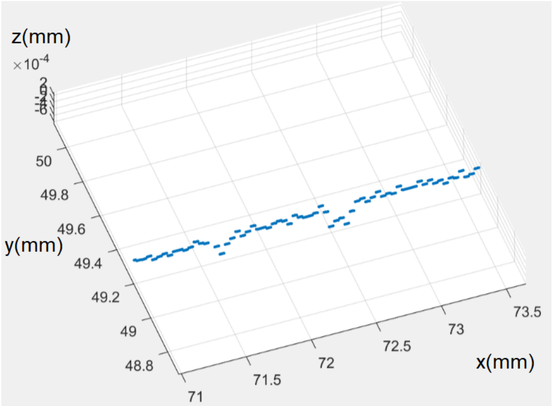
Single curved fronted jet damage on curved PMMA sample (LEE simulation)



damage is deeper for
the y-direction depressions.

A non-linear pressure distribution was predicted by Engel in [9] as the presence of a 'maximum pressure ring' about the central point of impact





Conclusions

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By developing new materials, lubricants, coatings, and surface finishing techniques that reduce friction and wear, both energy efficiency and machine lifetime will improve, which will enable transition to Net Zero. Green tribology coined 2009 and gives framework to produce technology to help hit net zero targets

Some potential areas for R&D:

- Barrier coating for equipment handling hydrogen
- Self lubricating coatings/surfaces for low friction for dry contacts
- Lubricant/new fuel/surface interactions
- Lightweighting for harsh environments and use of polymers
- Surfaces that enhance detection of distress
- Use of modern experimental techniques and ML/AI


QM2 at Southampton docks

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Thank you for listening
and
questions / thoughts are very welcome

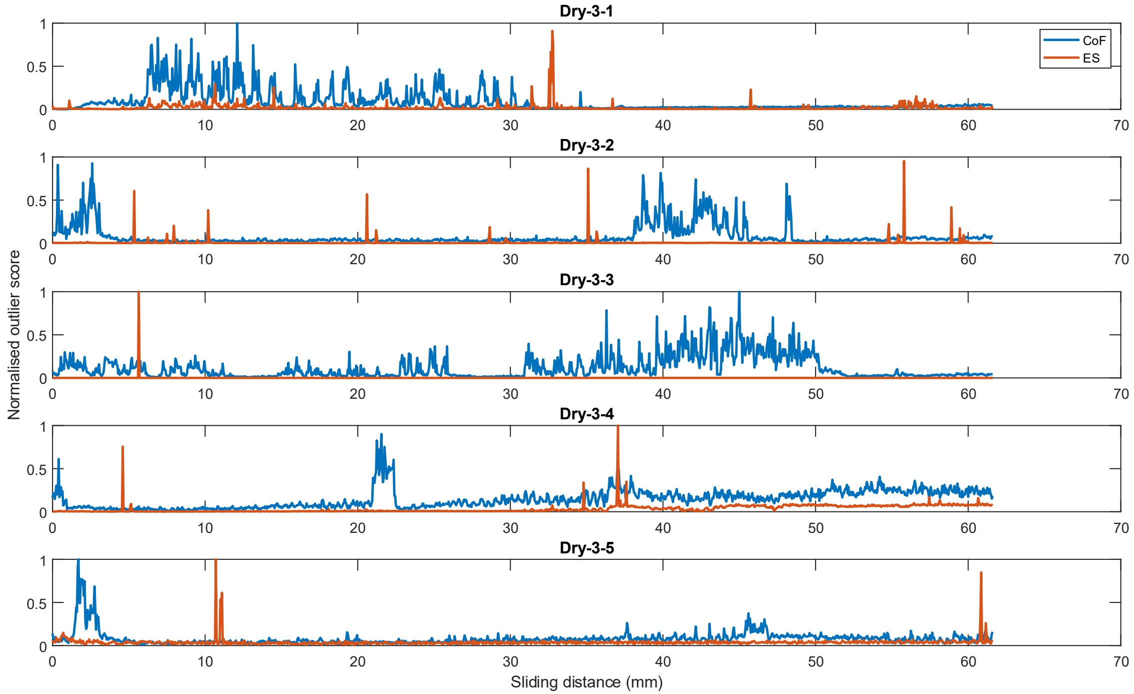
Biomimetics

- Nature-inspired bionic surfaces offer valuable examples of effective texturing strategies, encompassing various geometric and topological approaches tailored to mitigate frictional effects and related functionalities in various scenarios.
- By employing biomimetic surface modifications, for example, roughness tailoring, multifunctionality of the system can be generated to efficiently reduce friction and wear, enhance load-bearing capacity, improve self-adaptiveness in different environments, improve chemical interactions, facilitate biological interactions, etc.
- However, the full potential of bioinspired texturing remains untapped due to the limited mechanistic understanding of functional aspects in tribological/biotribological settings.
- four major wear conditions: sliding, solid-particle erosion, machining or cutting, and impact (energy absorbing). Furthermore, it explores how topographies and their design parameters can provide tailored responses (multifunctionality) under specified tribological conditions.

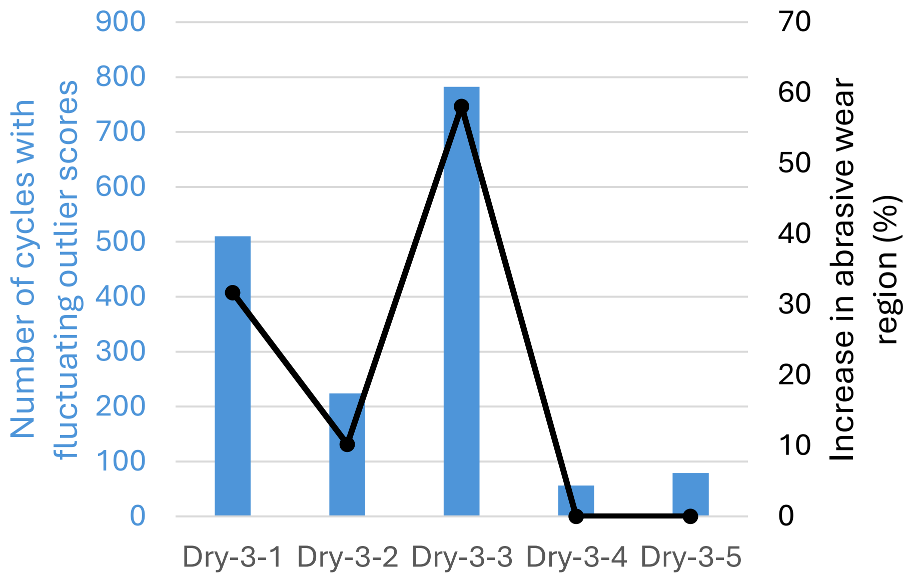
Kumar, R.; Rezapourian, M.; Rahmani, R.; Maurya, H.S.; Kamboj, N.; Hussainova, I. Bioinspired and Multifunctional Tribological Materials for Sliding, Erosive, Machining, and Energy-Absorbing Conditions: A Review. *Biomimetics* **2024**, *9*, 209. https://doi.org/10.3390/biomimetics9040209

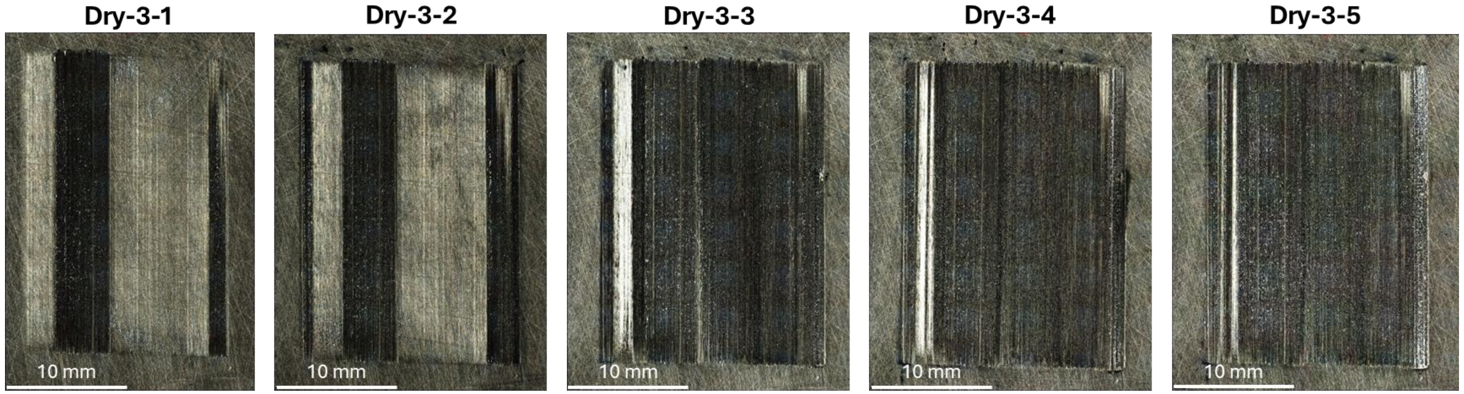
Results and discussion

Correlation between outlier and abrasive wear evolution



Outlier detection using Autoencoder algorithm





- Correlation of the fluctuation on outlier scores with the progression of abrasive wear