Lube-Tech
PUBLISHED BY LUBE: THE EUROPEAN LUBRICANTS INDUSTRY MAGAZINE
No.159 page 1

Breaking the cycle of white etching cracks: How copper-based additives solve one of industry's most puzzling bearing failures

***Rafe Britton**, Consultant, Lubrication Expert, **Sergei Mamykin**, Scientific Advisor-NEOL Copper Technologies, and **Marc Ingram**, Engineer at Ingram Tribology Ltd*

A persistent problem in power and motion

Despite decades of research and steady improvements in bearing design, lubricant formulation, and contamination control, White Etch Cracks (WECs) continue to undermine the expected service life of rolling element bearings. In wind turbine gearboxes, in particular, these subsurface cracks are now recognised as one of the leading causes of unexpected bearing damage. Studies have shown that up to half of bearing failures can be traced back to lubrication-related issues, and yet even machines that are properly lubricated, carefully aligned, and maintained to OEM specifications still suffer from WEC-related failures.

These failures are particularly frustrating because they do not follow the typical progression of surface-initiated damage modes like abrasive wear, adhesive wear, or classical rolling contact fatigue. Instead, they originate deep below the surface, where stress concentrations and microstructural changes lead to the formation of cracks that only later manifest as surface spalling or flaking. Under metallurgical analysis, these cracks are surrounded by White Etch Areas (WEAs)—regions of transformed steel that appear white under etching due to their altered composition and grain structure. When these cracks propagate to the surface, they result in White Structure Flaking (WSF), leading to material loss and eventual bearing failure.

The consequences of WEC failures are far-reaching. In wind energy, they result in extended downtime, costly crane mobilisations, and lost electricity generation. In transportation, they raise safety and reliability risks. In all sectors, they contribute to maintenance unpredictability and increased life cycle costs.

What makes WECs even more challenging is the lack of consensus around their root cause. Once considered rare anomalies, they are now recognised as a recurring and systemic problem across multiple industries and bearing types. Two major schools of thought have dominated the conversation. The first attributes WECs to purely mechanical factors such as high contact stress, sliding, vibration, and material fatigue. In this view, WECs are seen as a subsurface

Lube-Tech
PUBLISHED BY LUBE: THE EUROPEAN LUBRICANTS INDUSTRY MAGAZINE

variant of classical fatigue failure, possibly initiated at material inclusions or microstructural inhomogeneities.

The second school of thought focuses on hydrogen involvement, proposing that hydrogen ingress—either from moisture, lubricant decomposition, or electrical discharges—weakens the steel from within. This theory includes concepts like hydrogen embrittlement and hydrogen-enhanced local plasticity, both of which help explain how WECs can form even under seemingly benign conditions. Stray currents, tribochemical reactions, and elevated temperatures all contribute to an environment where hydrogen can accumulate in critical areas of the steel.

Both perspectives provide valuable insights, yet neither has produced a consistent, practical method of preventing WECs. This has led researchers to propose more integrated hypotheses—ones that consider mechanical, electrical, and chemical stressors as interconnected drivers of failure. Until such models are validated and turned into actionable engineering solutions, WECs will remain one of the most pressing reliability challenges in tribological design and industrial lubrication.

Revisiting an overlooked theory

The mystery of white etching cracks may not be entirely modern. In fact, part of the answer may lie in research that was largely overlooked in the West but foundational in Soviet tribology. In the 1960s, Professor Dmitry N. Garkunov—a leading figure in Soviet-era tribology—proposed two radical ideas that challenged the prevailing assumptions of wear science: the phenomenon of hydrogen wear and the counterintuitive concept of the wearlessness effect.

Garkunov's work was based on the insight that not all wear was mechanical. He and his followers argued that under certain frictional conditions, electrochemical processes could become dominant. When steel components rub together under pressure and temperature—especially at micro-asperity contacts—chemical reactions occur not only within the lubricant but also at the steel surface itself. These reactions, Garkunov believed, are not merely side effects; they are active contributors to material degradation.

The first major contribution of Garkunov's school of science, the concept of hydrogen wear, describes how hydrogen atoms are generated in the friction zone and then absorbed into the steel. These hydrogen atoms originate from the breakdown of hydrocarbon lubricants, water contaminants, or other polar species in the presence of high surface energy. At elevated flash temperatures—often well above 1000°C at the microscopic contact points—iron can undergo polymorphic transitions that release electrons. These delocalised electrons contribute to the dissociation of molecules in the lubricant or adsorbed water, releasing hydrogen ions (H^+).

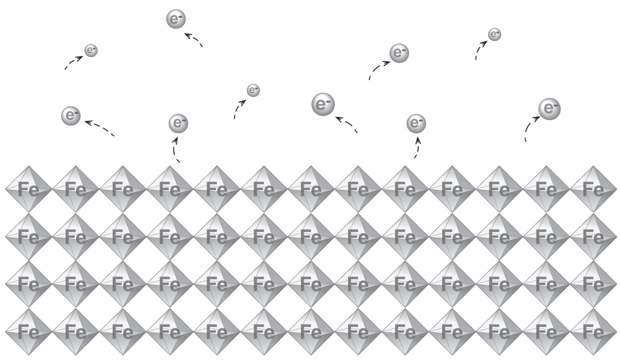

Figure 1: *Electrons' release during polymorphic transition of iron*

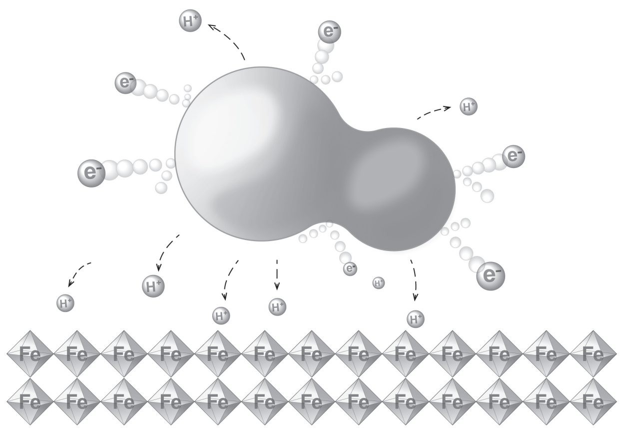

Figure 2: *H+ released from lubricant and water molecules*

Lube-Tech
PUBLISHED BY LUBE: THE EUROPEAN LUBRICANTS INDUSTRY MAGAZINE
No.159 page 3

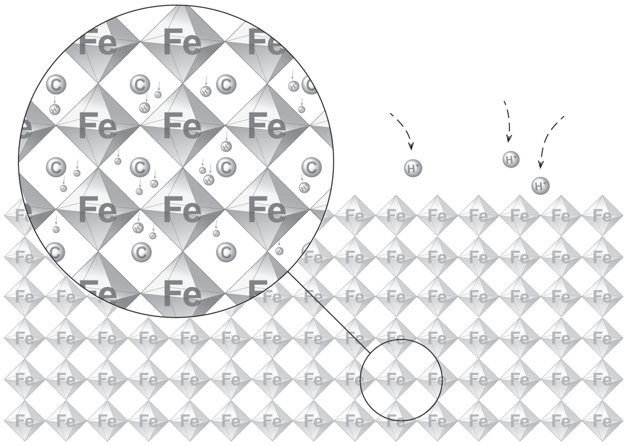

Figure 3: *Released hydrogen penetrates steal*

Under load and, critically, under the influence of stray electrical currents (which are common in electrically driven machines), these hydrogen ions are driven into the steel. Once inside, the hydrogen ions pair with electrons to form atomic hydrogen (H), a form that is small enough to infiltrate grain boundaries, dislocations, and other microstructural weaknesses.

The presence of atomic hydrogen is especially dangerous in high-carbon steels, such as those used in rolling element bearings; it can react with free or loosely bound carbon to form methane gas (CH_4). Because methane molecules are much larger and more volatile than atomic hydrogen, they exert pressure within the steel's microstructure. This leads to localised stress intensification and, eventually, the propagation of cracks. These cracks initiate from below the surface, following grain boundaries or stress paths, and they eventually manifest as White Etching Cracks. The surrounding material, depleted of carbon and subjected to plastic deformation, transforms into the nanocrystalline, decarburised phase that we identify as a White Etching Area (WEA).

Garkunov didn't stop there. His second idea was the "wearlessness effect". Under certain friction conditions—particularly where sliding occurs between dissimilar metals or when specific ionically active elements are present—a protective metallic film can spontaneously form on the contact surface. This film has low shear strength, resists oxidation, and does not accumulate dislocations.

$$H^+ + e^- \longrightarrow 1/2\,H_2$$

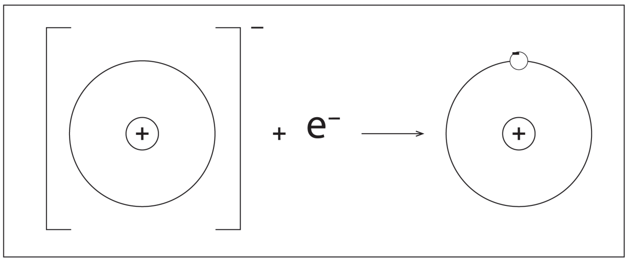

Figure 4: *Hydrogen transforms into atomic state*

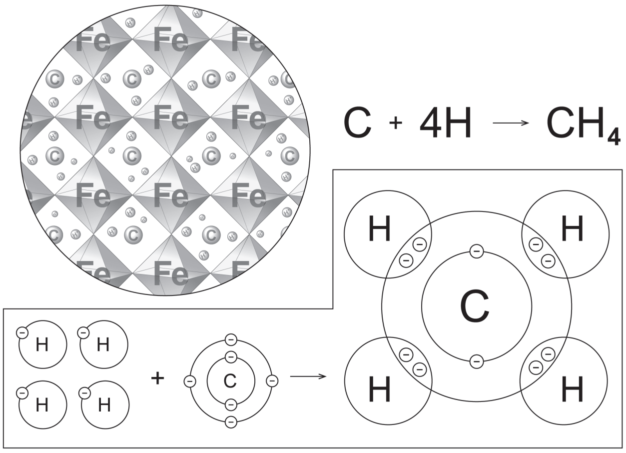

Figure 5: *Hydrogen binds with carbon and forms large methane molecules*

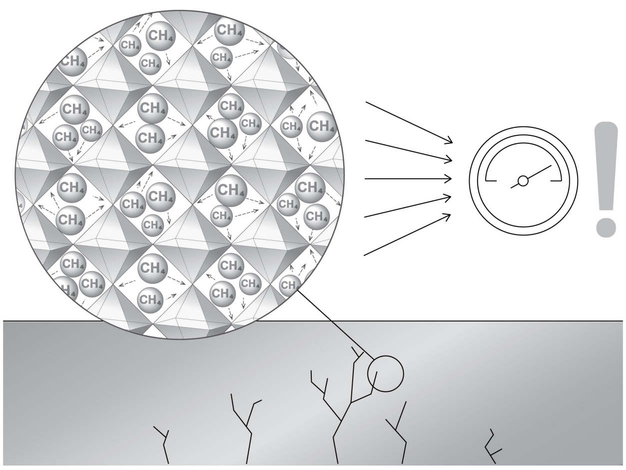

Figure 6: *Localised stress intensification and propagation of cracks*

Crucially, Garkunov and his followers believed that both hydrogen wear and wearlessness could occur under the same operating conditions—but with very different outcomes depending on the materials and chemistry involved. If the surface lacks a protective tribofilm, hydrogen wear dominates. But if the right conditions are created—such as the presence of certain metal ions, like copper—a self-sustaining film can develop that blocks hydrogen ingress and suppresses wear almost entirely.

Viewed through this lens, the typical contributors to WEC formation—mechanical stress, electrical discharge, and tribochemical degradation—are not separate root causes. Rather, they are interconnected symptoms of a deeper process driven by the electrochemical behaviour of hydrogen in the friction zone. The contact zone becomes a kind of micro-reactor, where mechanical energy, electric current, and tribochemistry combine to drive destructive or protective outcomes depending on the chemistry at play.

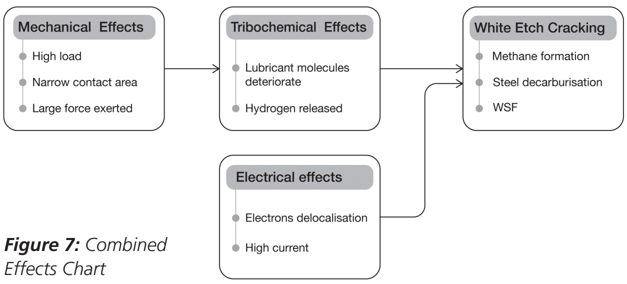

Figure 7: *Combined Effects Chart*

This integrated view helps explain modern reliability issues. In wind turbines, for instance, bearings are exposed to variable loads, transient contact conditions, and stray electrical currents from the generator system. These are precisely the ingredients for hydrogen generation and ingress. Likewise, in rail applications, regenerative braking introduces electrical discharges that pass through axlebox bearings. In both cases, the machinery may appear to be operating within mechanical specifications—but if the lubricant chemistry is not designed to counteract hydrogen wear, subsurface damage may occur.

What makes Garkunov's theory so compelling today is that it bridges the divide between the two dominant hypotheses for WEC formation—mechanical fatigue versus hydrogen embrittlement—and unites them within a single framework. It explains why WECs can occur even when conventional fatigue indicators are absent. And it suggests that by modifying lubricant chemistry—specifically, by promoting protective tribofilm formation and preventing hydrogen diffusion—we may finally have a way to stop WECs at their source.

Putting it to the test: Simulating electrically induced WECs

To validate the hypothesis that copper-based lubricant additives could suppress the formation of White Etching Cracks (WECs), the research team designed a controlled laboratory test capable of closely replicating the tribological, thermal, and electrical conditions under which WECs are known to form in real-world machinery.

At the core of the experiment was a modified three-ring-on-roller tribometer, built around the Micropitting Rig (MPR) developed by PCS Instruments. For this study, the standard rig was significantly upgraded to enable electrically induced WEC testing—a relatively new and complex area of tribological simulation.

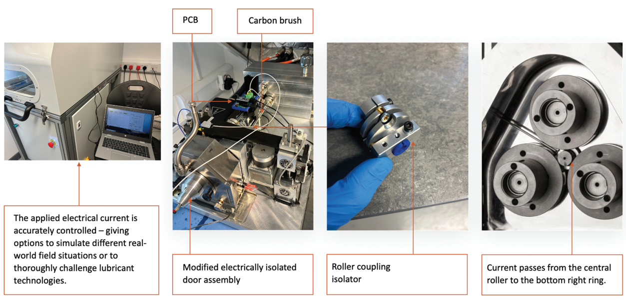

Figure 8: *Modified MTM*

Test configuration: rolling contact under electrical load

The MPR test geometry features a 12 mm diameter roller pressed against three rotating rings with a much larger diameter of 54.15 mm. The roller is chamfered so that only a 1 mm-wide cylindrical track contacts the rings. This creates a focused, repeatable contact path ideal for simulating the highly stressed regions of a bearing raceway. A load of 500 N is applied through the top ring, resulting in a maximum Hertzian contact pressure of 1.9 GPa, representing what's seen in the wind turbine main shaft or intermediate bearings.

Unlike conventional bearing tests that rely on rolling alone, the MPR introduces controlled sliding via independently driven rings and roller shafts. For this experiment, the test used a slide/roll ratio of 0.3, with the roller and rings rotating at linear speeds of 1.495 m/s and 1.105 m/s, respectively. This moderate sliding ratio promotes micro-slip and surface interactions critical to lubricant film breakdown, hydrogen release, and tribofilm formation.

The contact components were made from AISI 52100 bearing steel—a standard choice for bearing applications—with the rings hardened to 750 Hv and the roller slightly softer at 650 Hv. All surfaces were polished to 0.15 μm Ra to ensure consistent boundary and mixed lubrication regimes. Under the test conditions, the estimated elastohydrodynamic (EHD) film thickness was 150 nm, resulting in a Lambda ratio close to 1, meaning the contact was operating in mixed lubrication, where surface asperities interact intermittently, allowing wear mechanisms to manifest.

To replicate thermal conditions in gearbox bearings, the test cell was heated to a bulk temperature of 100 °C, controlled precisely throughout the test duration. This elevated temperature increases lubricant degradation rates and accelerates hydrogen release, making it essential for simulating WEC-prone environments.

Electrical modification: Simulating stray currents

To simulate stray currents seen in wind turbines and e-motor driven machinery, the test introduces a continuous DC electrical current through the tribological contact.

A custom slip ring assembly was integrated into the MPR rig, allowing the team to apply a stable 250 mA DC current directly across the roller and rings during operation. This current level corresponds to a current density of approximately 750 mA/mm^2—a threshold known from previous literature to induce electrically assisted WEC damage reliably.

Maintaining electrical insulation between rotating and stationary components was critical. On the roller side, an inline torque meter was connected through a Mercotac slip ring and ceramic bearing assembly to ensure electrical isolation while allowing current flow through the wear track. On the ringside, a spring-loaded carbon brush applied the current to the shaft, with force finely adjusted via a tension screw to maintain a stable and consistent electrical contact. Voltage and current were monitored continuously throughout the test.

The Lubricants: Formulated for comparison

The test was conducted using two ISO VG 320 lubricants with matched base oil viscosity and application intent—designed for wind turbine gearboxes—but with distinctly different additive chemistries:

- Lubricant A was a commercially available, OEM-approved synthetic gear oil, formulated with conventional ashless antiwear and antioxidant packages. It served as the control, representing current industry-standard oils used in high-reliability applications.
- Lubricant B was a prototype formulation developed for this study, featuring an additive package that included an oil-soluble organic copper salt, along with an antioxidant, a dispersant, and an antifoam

agent. The copper salt was explicitly designed to promote the formation of a protective tribofilm, reduce surface temperature at asperity contacts, and interfere with hydrogen ingress—all according to the hydrogen wear mitigation hypothesis discussed earlier.

Post-test analysis: Surface and subsurface investigation

After completing test run (run off set at 200 million contact cycles), the rollers were sectioned and subjected to detailed post-test analysis using surface microscopy and subsurface serial sectioning—the gold standard for detecting WECs and WEAs.

Surface inspection began with optical microscopy, which identified visible pitting or material disruption. Subsurface evaluation followed a serial grinding and polishing protocol, exposing sequential cross-sections of the roller at 0.1 mm intervals across the wear track. Each slice was etched with Nital and then examined under a metallurgical microscope to reveal any signs of white etching features, crack networks, or changes in microstructure.

This thorough examination allowed the researchers to distinguish between surface-initiated pitting, subsurface cracking, and full-fledged WEC networks. The goal was to detect wear and understand its origin, propagation path, and relationship to the test environment.

What the results revealed

The results from the MPR test were conclusive and striking.

Lubricant A exhibited symptoms consistent with early stage bearing failure as the test progressed. Vibration levels steadily increased—a typical early warning sign of crack formation or pitting initiation within the tribological contact. Eventually, the software automatically halted the test before 75 million contact cycles when the vibration exceeded a set threshold, indicating that damage had progressed beyond a tolerable limit.

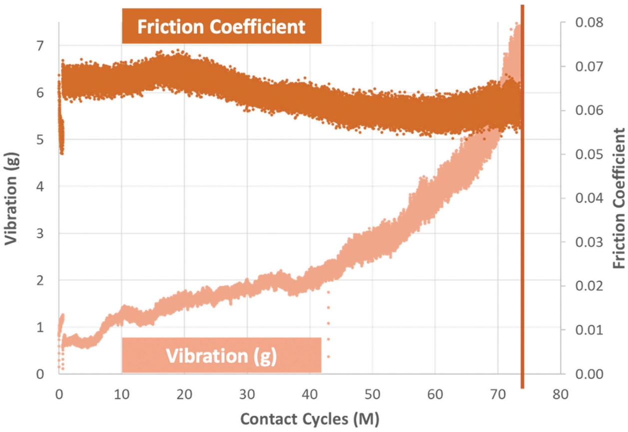

Figure 9: *Lubricant A performance data*

Post-test inspection of the roller revealed visible pitting across the wear track, with multiple isolated pits observed at both low and high magnification. These pits were not shallow surface abrasions but the result of subsurface crack propagation, consistent with WEC-type failures. The morphology of these features differs from micropitting, which tends to be shallow, surface-initiated, and fatigue-driven. These pits had steep walls and irregular floors, suggesting a deeper, more catastrophic failure mechanism.

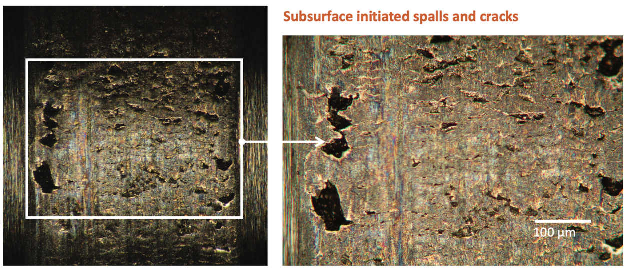

Figure 10: *Lubricant A post-test inspection*

The serial sectioning analysis confirmed this. Seven consecutive slices taken at 0.1 mm intervals across the wear track revealed multiple microstructural anomalies: white etching areas, white etching cracks, surface-initiated cracks, and even dark etching areas,

Lube-Tech
PUBLISHED BY LUBE: THE EUROPEAN LUBRICANTS INDUSTRY MAGAZINE
No.159 page 7

which indicate altered phases of steel. Several of the cracks made contact with the surface and would almost certainly have developed into full spalls had the test continued. These findings align with existing literature on WEC formation, particularly under the influence of electrical current and hydrogen diffusion.

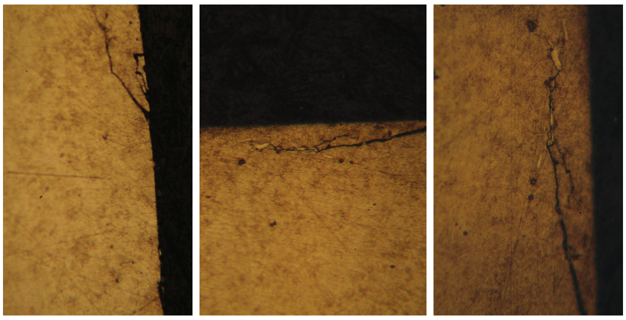

Figure 11: *Lubricant A cross sectioning analysis*

In contrast, Lubricant B, the prototype containing the copper-based additive, demonstrated remarkable stability throughout the test. Vibration levels remained low and consistent, with no spikes or warning trends. Friction remained slightly lower than Lubricant A, indicating effective surface interaction and lubrication film maintenance even under high stress and temperature conditions.

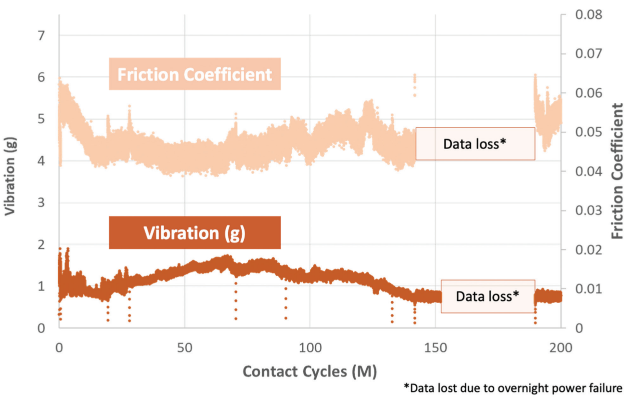

Figure 12: *Lubricant B performance data*

Upon completion of the full test cycle, the roller lubricated with Lubricant B was examined. Surface microscopy showed a smooth wear track, free from pitting, scarring, or delamination. Only minor directional striations in the sliding direction were visible—normal in rolling-sliding contacts and not indicative of failure. More importantly, no subsurface damage was observed during serial sectioning. All seven slices across the wear track revealed structurally intact steel: no WEAs, no white etching cracks, no evidence of hydrogen embrittlement or subsurface material transformation. The roller surface was essentially unaffected by the high contact load, sliding motion, elevated temperature, and continuous electrical current.

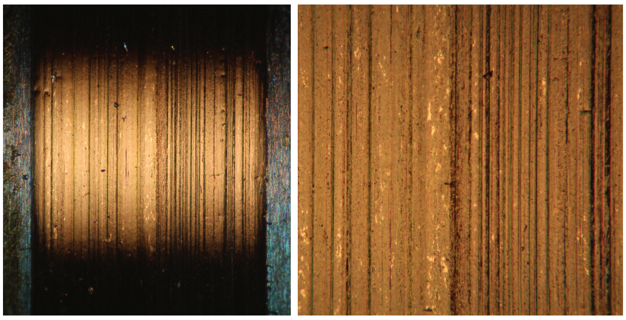

Figure 13: *Lubricant B post-test inspection*

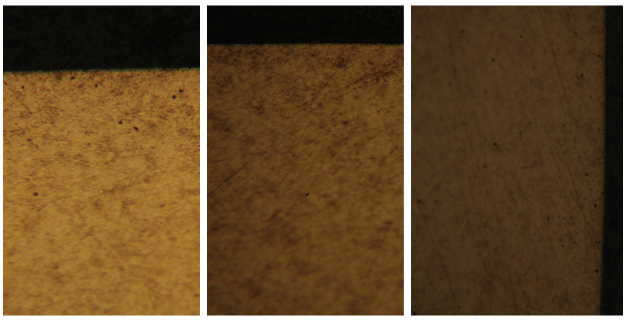

Figure 14: *Lubricant B cross sectioning analysis*

This stark difference in performance strongly supports the hypothesis that the copper additive actively intervenes in the wear mechanism, not simply by forming a protective tribofilm, but by disrupting the electrochemical and thermally driven pathways that normally lead to hydrogen generation and diffusion.

By forming a conductive, low-shear film across the surface, the copper salt reduces the likelihood of electron bombardment and lubricant degradation at the friction interface. This in turn suppresses the formation of free hydrogen ions and blocks their absorption into the steel—effectively halting the cascade of events that leads to methane formation, intergranular pressure, and crack propagation. Additionally, copper's high electrical conductivity appears to provide a preferential path for electrical current, diverting it away from high-resistance entry into the bearing surface, which further reduces hydrogen ingress driven by electrical potential.

When these results are compared to published WEC testing datasets—such as those by Gould et al. (2021)—the copper-based prototype outperforms even high-end commercial wind turbine oils tested under similar mechanical and electrical conditions. In tests using 250 mA DC currents and comparable Hertzian pressures, many commercial oils succumb to WEC formation well before the 200 million cycle mark. The fact that Lubricant B completed the entire test without a single crack, pit, or microstructural anomaly is not just promising—it represents a step-change in how lubricant formulations might address WECs in the field.

The broader implications

By rethinking wear as a system-level phenomenon driven by mechanical, electrical, and chemical factors, and by targeting the common root—hydrogen activity—we can design lubricants that prevent damage before it begins.

The novel lubricant additive based on oil-soluble copper salts is able to tackle three key contributors to WEC formation:

1. **Mechanical pressure and flash temperature** – Copper ions help form a soft, ductile film on surface asperities, effectively increasing the real area of contact and reducing pressure spikes. This lowers local temperatures, which helps avoid the electron emissions that lead to hydrogen formation.
2. **Hydrogen generation and diffusion** – Copper is much less reactive than iron and will not release hydrogen when exposed to frictional heat or stray electrons. Moreover, the copper film forms a barrier that inhibits hydrogen from diffusing into the steel.
3. **Electrically induced wear** – Copper's excellent conductivity allows stray currents to pass over the surface with minimal resistance, preventing the high-energy pathways that would otherwise drive hydrogen deeper into the bearing material.

The additive also has "self-healing" properties. Copper ions can embed into the iron lattice and repair emerging wear features, contributing to the formation of a stable tribofilm that actively resists degradation. For operators of wind farms, locomotives, or heavy industrial equipment, this could mean dramatically extended service intervals, lower failure rates, and fewer catastrophic shutdowns. For lubricant formulators, it opens new avenues for innovation using non-traditional additive chemistries. Of course, further testing is needed. Measuring hydrogen concentration changes in steel over time will help confirm the proposed mechanism, and field validation will be essential to prove the additive's effectiveness at scale. But the early signs are promising.

The message is clear: by understanding the true drivers of wear, we can go beyond resisting failure—we can design lubricants that actively prevent it.

ingramtribology.com
neol.world

References

Hosenfeldt, T., Bugiel, C., Leimann, D.-O., Loos, J., Luther, R., Merk, D., et al. (2024). White etching cracks - position paper of the German society for Tribology. doi:10.13140/RG.2.2.27783.41121

Mamykin S, Ingram M, Alieva L and Privalova V (2025) Preventing electrically induced subsurface initiated pitting failures (incl. WSF, WEC, WEA) with copper based lubricant additives. Front. Mech. Eng. 11:1585472. doi: 10.3389/fmech.2025.1585472