

## BACKGROUND

- The presence of hydrogen in the microstructure of steel bearings exacerbates catastrophic failure in extreme load applications such as wind turbine gearboxes & compressors for hydrogen fuel cells.
- This results from hydrogen embrittlement (HE) and in rolling-contact-fatigue is often associated with the formation of detrimental sub-surface cracking known as White-Etching Cracks (WECs).
- This early failure is halting investment in these renewables due to the added maintenance costs.
- Presently no theory can “explain the effects of hydrogen in bearing steels” and no understanding exists for predicting and preventing hydrogen damage.



Fig. 1. (a) RCF Test Rig set-up, (b) Bearing balls and raceway after test and TDS, (c) Deep spall in race tested in argon.

## AIMS:

- To investigate the influence of lubricant environments on premature bearing failure due to the development of cracks in AISI 52100 steel.
- To explore how test atmosphere and the anti-wear additive, Zinc Dialkyldithiophosphate (ZDDP), help to reduce the effects of HE and compare the results with those found when using a perfluorinated lubricant.

## HYDROGEN CONTENT AND FATIGUE LIFE

- Rolling Contact Fatigue (RCF) tests were run to determine Fatigue Life.
- Thermal Desorption Spectroscopy (TDS) (Denshi-Kagaku TDS1200) was employed to measure hydrogen content in race/balls after RCF tests.

Table 1: Initial Results - Hydrogen Content & Fatigue Life

Atm. / Lub.	CONTENT OF HYDROGEN		FATIGUE LIFE	
	IN DISK PPM	IN BALL PPM	FAILURE	CYCLES
Ar / PAO <sub>32</sub>	0.283	0.226	On disk	9,310,000
Air / PAO <sub>32</sub>	0.322	0.171	On disk	11,830,000
H <sub>2</sub> / PAO <sub>32</sub>	0.406	0.672	On ball	6,600,600
H <sub>2</sub> / PAO <sub>32</sub> +ZDDP	0.163	0.0731	None	2,700,000
Air / Fomblin Grease	-	-	None	100,000,000 +

## OPTICAL MICROGRAPHS OF RACE WEAR TRACKS

- Optical microscopy was used to characterize the wear tracks and quantify the surface defects.

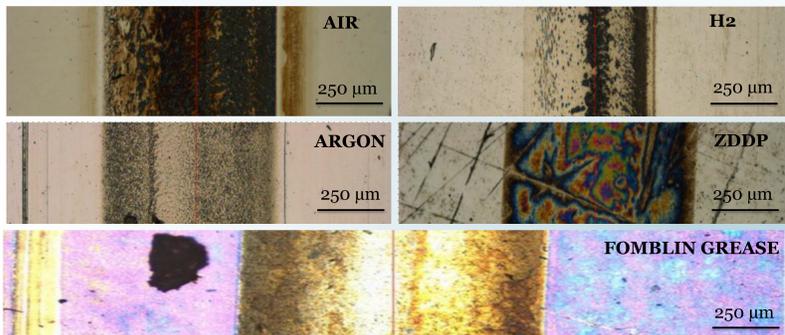


Fig. 2. Optical micrographs of raceway wear scars after testing under the conditions indicated

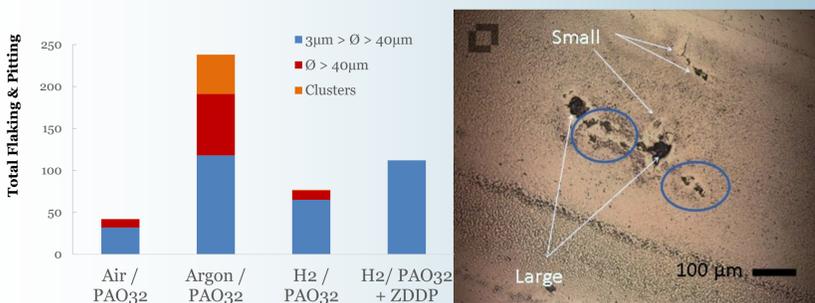


Fig. 3. Surface Defect Analysis: (a) Results. (b) Areas of pitting and flaking: small flaking ( $3\mu\text{m} < \phi < 40\mu\text{m}$ ), large flaking ( $\phi > 40\mu\text{m}$ ) and clusters (circled) group of 4+ small pits in an area of  $100\mu\text{m}$  diameter

## ALICONA – PROFILES OF RACE WEAR TRACK

- Wear tracks widths, depths and profiles were measured using Alicona profilometry to compare volume loss and roughness of the wear scars.

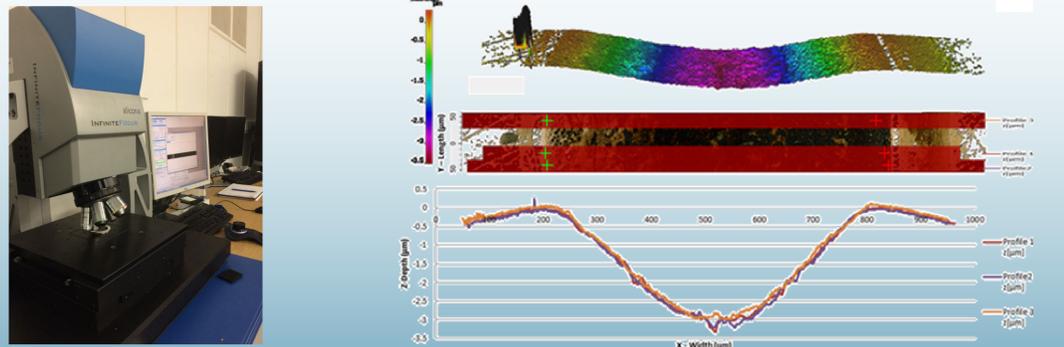


Fig. 4. (a) ALICONA Optical Profilometry apparatus (b) Alicona scans across the wear tracks.

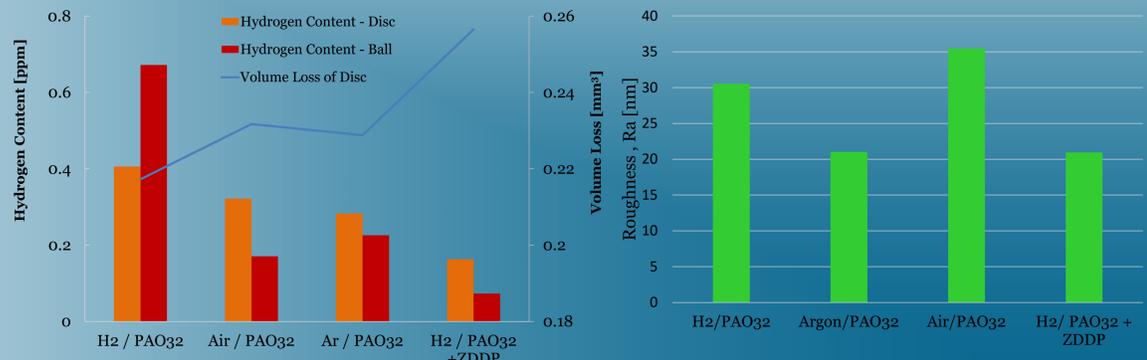


Fig. 5. (a) Total volume loss in the disc and hydrogen content of disc and ball (b) Average wear track roughness, Ra, after testing in various environments

## MICRO-CT SCANNING & SECTIONING

- The viability of Micro-CT Scanning as a new technique to find and characterise WECs was investigated and compared with traditional sectioning methods.

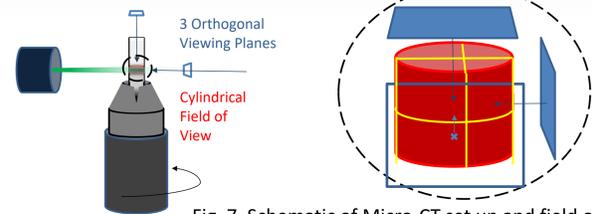


Fig. 7. Schematic of Micro-CT set up and field of View

- Scan/Sectioning locations were chosen based on regions with high population of surface defects and/or thick carbon deposits.

- Specimens ground to < 1mm thick cross-section to minimise noise from x-ray transmission through steel.

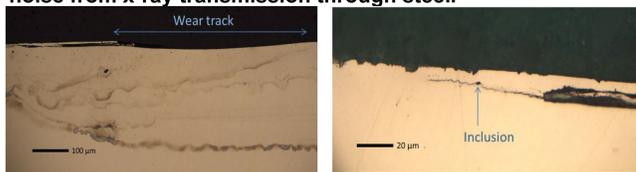


Fig. 8: Optical micrographs of sectioned and polished specimen tested in an argon atmosphere (a) Crack propagating under wear lips adjacent to the wear track (b) crack tip and influence of inclusion.

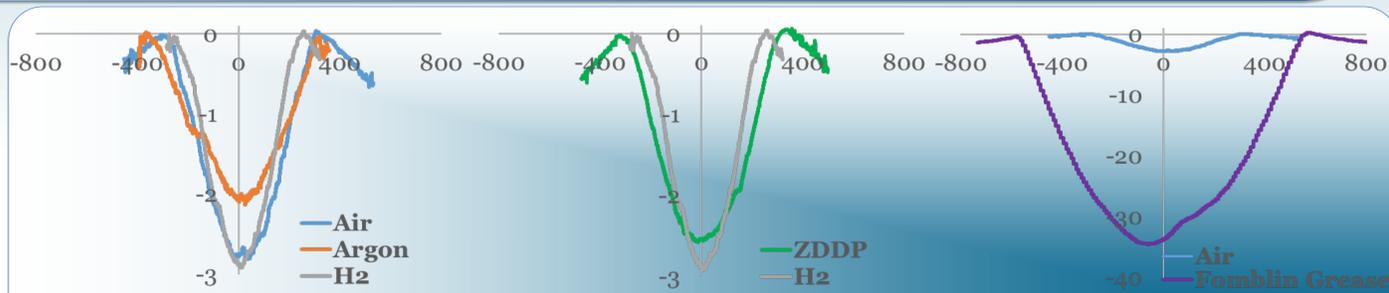


Fig. 6. Averaged wear track profiles under various test conditions. (a) PAO samples (b) Effect of ZDDP on wear scars produced in hydrogen environment (c) Wear tracks after testing in PAO and a perfluorinated fomblin grease in an air environment

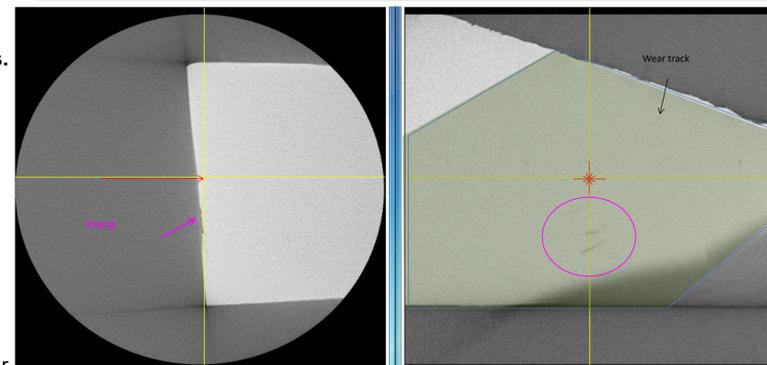


Fig. 9. CT scanned images, showing the sub-surface in two orthogonal viewing planes, of a heavily flaked region of the race tested in Argon.

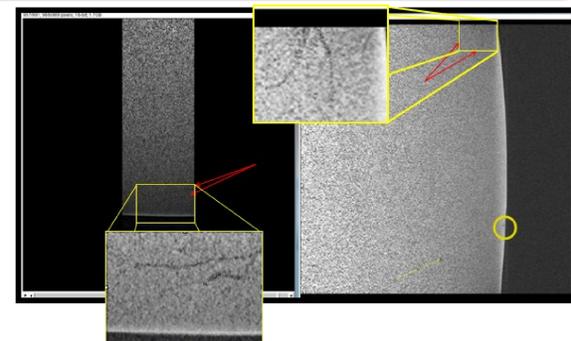


Fig. 10. Micro-CT scans of ball tested in H<sub>2</sub> atmosphere and PAO lubricant highlighting, in two orthogonal planes, a multi-pathed crack propagating parallel to surface

## CONCLUSIONS & FUTURE WORK

- In non-hydrogen environments, the physical decomposition of the lubricant under heat and pressure is a primary cause of HE.
- For non-additized PAO, atmospheres promoting the formation of oxidative films (i.e. air) reduce wear and asperity contact, and help prevent further hydrogen decomposition.
- Inert atmospheres (i.e. Ar) promote surface distress (severe flaking/spalling), friction and fatigue.
- HE can also be prevented through thick protective chemical tribofilms formed on the metal surface by the additives (i.e. anti-wear ZDDP) acting as a barrier to hydrogen generation and permeation.
- The use of lubricants that do not contain hydrogen (such as Fomblin grease) avoided HE related wear and dramatically increased fatigue life.
- Micro-CT as a non-destructive technique for investigating WECs gives a reasonable crack depiction of the 3D crack morphology.
- To help avoid the problems associated with the high density of steel (such as noise) and the long duration of the scanning the next step is to utilize monochromatic synchrotron that offer more coherent light sources and much faster imaging.