Lubricant Effects on White Etching Cracking Failures in Thrust Bearing Rig Tests

April 26, 2017

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White Etching Cracking (WEC) is a sub-surface bearing failure occurring under fatigue load

- Cracking occurs near grain boundaries
- "Root cause" is highly debated

Why is it a problem?

- Reported to cause ~60% of wind turbine high speed bearing failure
- Initial & intermediate extensive WEC fatigue damage all happens below surface without warning!
  - Once WEC damage erupts to surface - it's too late!
  - Most WEC damage causes complete component failure requiring extensive €/$ repair
Objectives

- This paper presents experimental results explaining the intersection of critical factors that cause WEC.
- A model on the mechanism of WEC failure will be proposed.

Unusual factors that combine causing WEC

**Lubrication Regime**
- Boundary/ Mixed Lubrication
- Load/ Loading Type
- Speed (Sliding/Rolling)
- Lubricant Viscosity
- Surface Roughness

**Tribological Contact**
- Hertzian Contact Stress
- % of Surface Exposed to Contact
- Additives Chemistry or Tribofilms
- Slip / Friction energy
- Decomposition of water/lubricant
- Electrical field / current flow

**Subsurface**
- Hydrogen (Embrittlement)
- Subsurface Stress
- Residual Stress
- Carbide, Austenite, Chrome, Vanadium
- Defects/ Dislocations

WEC
### FE8 Results – Lubricant Variations

<table>
<thead>
<tr>
<th>Failure Mode</th>
<th>Additive Pack (Metal/No Metals)</th>
<th>Viscosity (ISO 68/320)</th>
<th>API Base Oil Group I (min) / IV (syn)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WEC</td>
<td>Bad</td>
<td>High</td>
<td>I</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Low</td>
<td>IV</td>
</tr>
<tr>
<td>No WEC</td>
<td>Good</td>
<td>High</td>
<td>I</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Low</td>
<td>IV</td>
</tr>
</tbody>
</table>

WEC failure mode of FE8 is affected by additive type
- No effect of Base Oil Type
- No effect of Lubricant Viscosity
  - Higher viscosity delays, but does not prevent WEC

**Certain metal containing lubricant additives cause WEC**
White Etching Cracking – Impact of Lubricant Components

FE8 test results with stepwise controlled assembly of poor performing WEC oil.

Test duration:

- **<120 hours**
  - Early Failure (WEC)
- **200 hours**
  - Late Failure (non-WEC)
- **624 hours**

<table>
<thead>
<tr>
<th>Result</th>
<th>&lt;120 hours</th>
<th>200 hours</th>
<th>624 hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zinc DithioPhosphate</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Phosphate (Ashless)</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Na sulfonate (High TBN)</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Ca sulfonate (High TBN)</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

- Ashless phosphates do not generate WEC
- Ca and Na sulfonates independently do not generate WEC

Zinc phosphate and/or the combination of overbased Ca & Na alkyl sulfonates cause **WEC**
MTM-SLIM Tests – Friction vs. Film Formation

MTM SLIM ‘Switching Oil’ Expt: 
non-WEC Oil Followed by WEC Oil

MTM-SLIM 'Switching Oil' Expt: 
WEC Oil Followed by non-WEC Oil

Tribofilms govern friction response →
Non-WEC Oil cannot remove the tribofilms formed by the WEC Oil
### Impact of Film Formation on WEC – FE8 Switching Tests

#### FE8 Test

<table>
<thead>
<tr>
<th>Switching oil tests Single oil tests</th>
<th>Non-WEC Oil</th>
<th>624 hours</th>
<th>Pass</th>
</tr>
</thead>
<tbody>
<tr>
<td>WEC Oil</td>
<td></td>
<td>110 hours</td>
<td>Fail</td>
</tr>
<tr>
<td>WEC 20 hours then Non-WEC Oil</td>
<td></td>
<td>94 hours</td>
<td>Fail</td>
</tr>
<tr>
<td>Non-WEC Oil 20 hours then WEC Oil</td>
<td></td>
<td>125 hours</td>
<td>Fail</td>
</tr>
</tbody>
</table>

- FE8 bearings tested for 20 hours with WEC Oil failed by WEC even after switching to a Non-WEC oil
- WEC initiates as short as 20 hours

A **Non-WEC oil cannot relieve the damage caused by a WEC Oil**
Crack initiation observed at a depth of 100 - 120 μm (shear maximum)

Friction intensifies subsurface stresses resulting in WEC

High friction induced stress alone cannot cause WEC

WEC can occur with increasing lubricant induced sub-surface stress

WEC Mechanism - Sub-surface Stress

Hertzian Contact

Load

Subsurface Stress

Contact Pressure

Sub-Surface Stress

WEC Failure at ~106 um Depth

100-120 μm

SEM Image

Initiation Sites

FE8 roller - test with WEC Oil stopped at 40hrs
WEC Mechanism – Hydrogen Ingress

- Rollers of the modified Four Ball Tester (FBT) were analyzed in Thermal Desorption Spectroscopy (TDS).
- Greater trapped hydrogen concentrations observed in WEC failed rollers versus rollers with no WEC.
- More hydrogen observed than can be explained by the presence of tribofilm.

**TDS Results on FBT Rollers**

**High sub-surface H concentration correlates with WEC failure**
Simulation confirms the highest concentration of hydrogen is just below the roller contact.
WEC Sub-surface Conditions

WEC initiates in regions of overlapping high H concentration and elevated shear stress

Overlap of stress and hydrogen conc. fields \rightarrow\ crack initiations

100-120 µm

> Critical Stress

> Critical H Concentration

Tribofilm

Hydrogen field

Stress field
Summary

- A Non-WEC oil can be formulated to avoid WEC
- A Non-WEC oil cannot remove the WEC forming tribofilm or mitigate sub-surface damage
- ZDDP and/or the combination of Ca & Na alkyl sulfonates contribute to formation of WEC-critical tribofilm which trap water
- Tribofilms can form and initiate WEC as short as 20 hours in the FE8 test
- Sub-surface dark spots in the maximum shear plane were found
- Harmful tribofilm can increase sub-surface stress (high friction) and enhance hydrogen diffusion below the contact allowing for WEC initiation
Thin Tribofilm: good oil – low water

Bearing

100-120 µm

- Tribofilm provides cushion
- Slight deformation
- Sub-surface Stress
Thick Tribofilm: WEC Oil

- Entrained Water
- Water breaks
- Hydrogen diffusion
- Initiation site
- Sub-surface Stress
- 100-120 µm

Tribofilm provides cushion

Slight deformation
We propose, water ingress as the source of hydrogen, trapped in the Tribofilm

- 50 x higher water content in WEC Oil
- WEC Oil has hygroscopic additives

WEC Oil was saturated with heavy water (D$_2$O); FE8 test was conducted; parts evaluated with TDS; Clear evidence of deuterium (D) found in FE8 roller

The only path for D to be here was the D$_2$O from WEC Oil
Thank You

Together We Move The World