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Material weakening due to corrosion in hardened bearing steels

R.H. Vegter
SKF Engineering & Research Centre, Nieuwegein, The Netherlands, erik.vegter@skf.com

M. Ersson
SKF AB, Gothenburg, Sweden

Bo Han
SKF Co. Ltd, Shanghai, China

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Material weakening due to corrosion in hardened bearing steels

International workshop on the environmental damage in structural materials under static load/cyclic loads at ambient temperatures

Cork, Ireland, June 1st, 2016

R.H. Vegter, M. Ersson, B. Han, S. Echeverri Restrepo

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Content of the presentation

1. Introduction
2. Materials used in ball/roller bearings
3. Very high cycle fatigue in bearings
4. Corrosion exposure tests
5. RCF tests with corrosion
6. Hydrogen effects and RCF
7. Atomistic simulation of H in bearing steel
8. Conclusions

1

Introduction

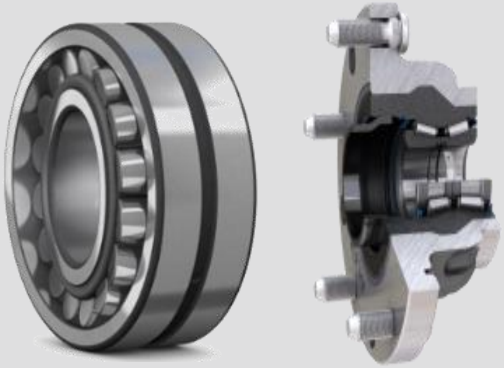
SKF – a truly global company

Established	1907
Sales 2015	SEK 75,997 million
Employees	46,635
Production sites	around 115 in 29 countries
SKF presence	in over 130 countries
Distributors/dealers	17,000 locations
Global certificates	ISO 14001 OHSAS 18001 certification ISO 50001

Two value propositions

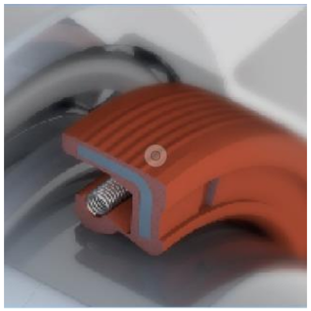
Rotating equipment performance

Product



SKF technology areas

Bearings
and units



Seals

Services

Lubrication
systems

Mechatronics

Where is a bearing used for ?

Bearings are machine elements that are designed for

- Reduction of friction
- Transfer of load
- Guidance of moving parts



Our solutions are everywhere




2

Materials used in ball/roller bearings

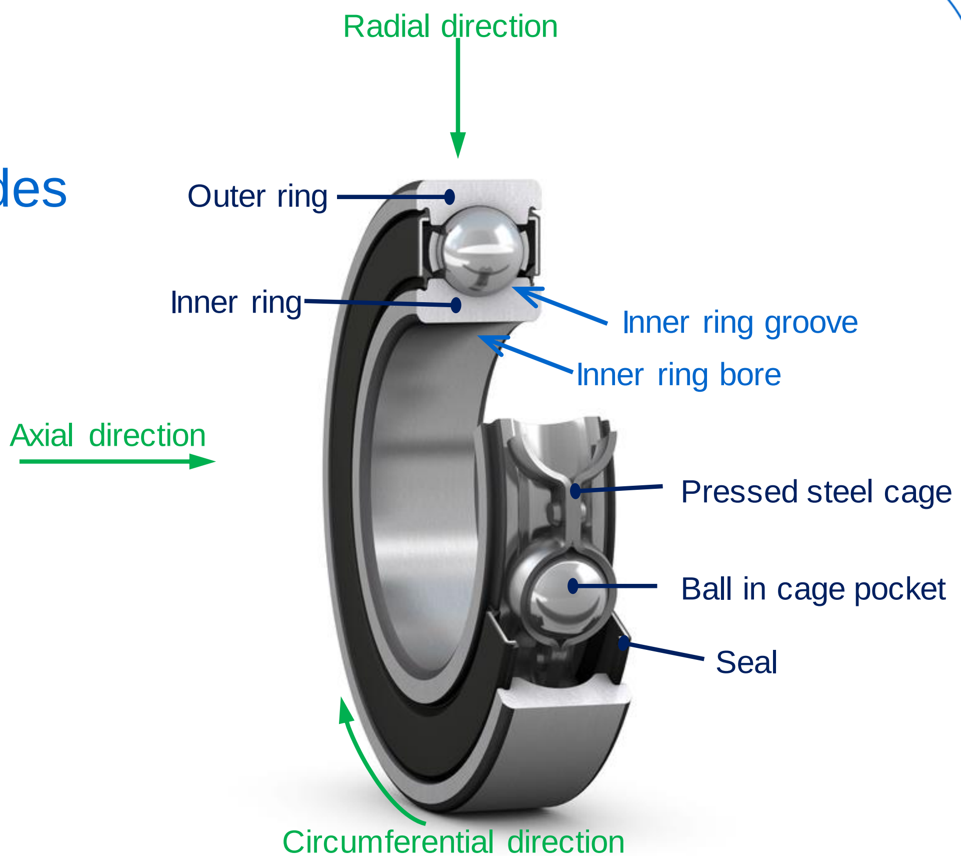
Materials used in bearings

Inner ring/Outer ring
- bearing steel : many steel grades

Rolling elements
- bearing steel / ceramics

Cage
- steel / polymer / bronze

Seals
- steel / rubber



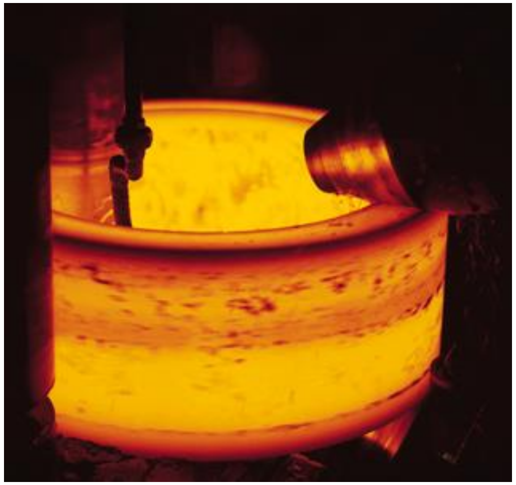
Production steps

Soft Annealed material:

- Cutting/turning from bar/tube
- Forming
- Heat treatment

Hardened rolling elements finishing operations

- Grinding
- Polishing
- Tumbling



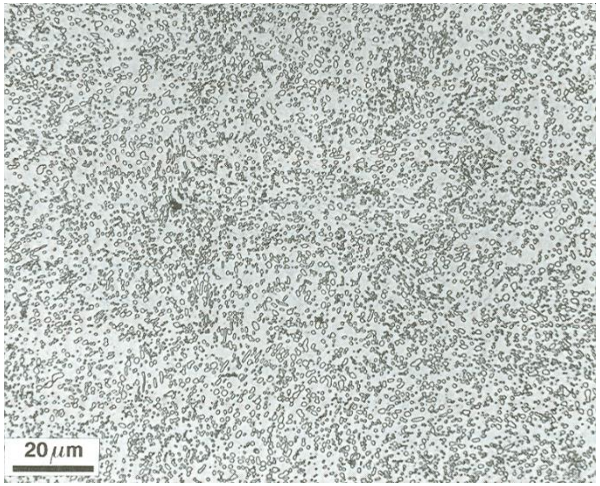
Thermal processing of bearing steel

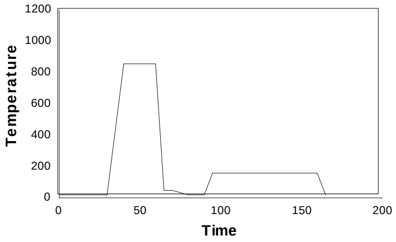
Standard heat treatment

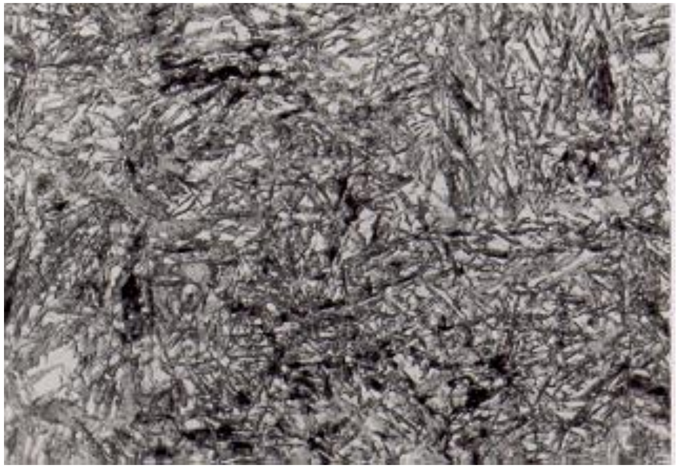
- austenitising
- tempering

This results in

- martensite
- bainite
- different stability classes
- variation in retained austenite
- thermodynamic instability





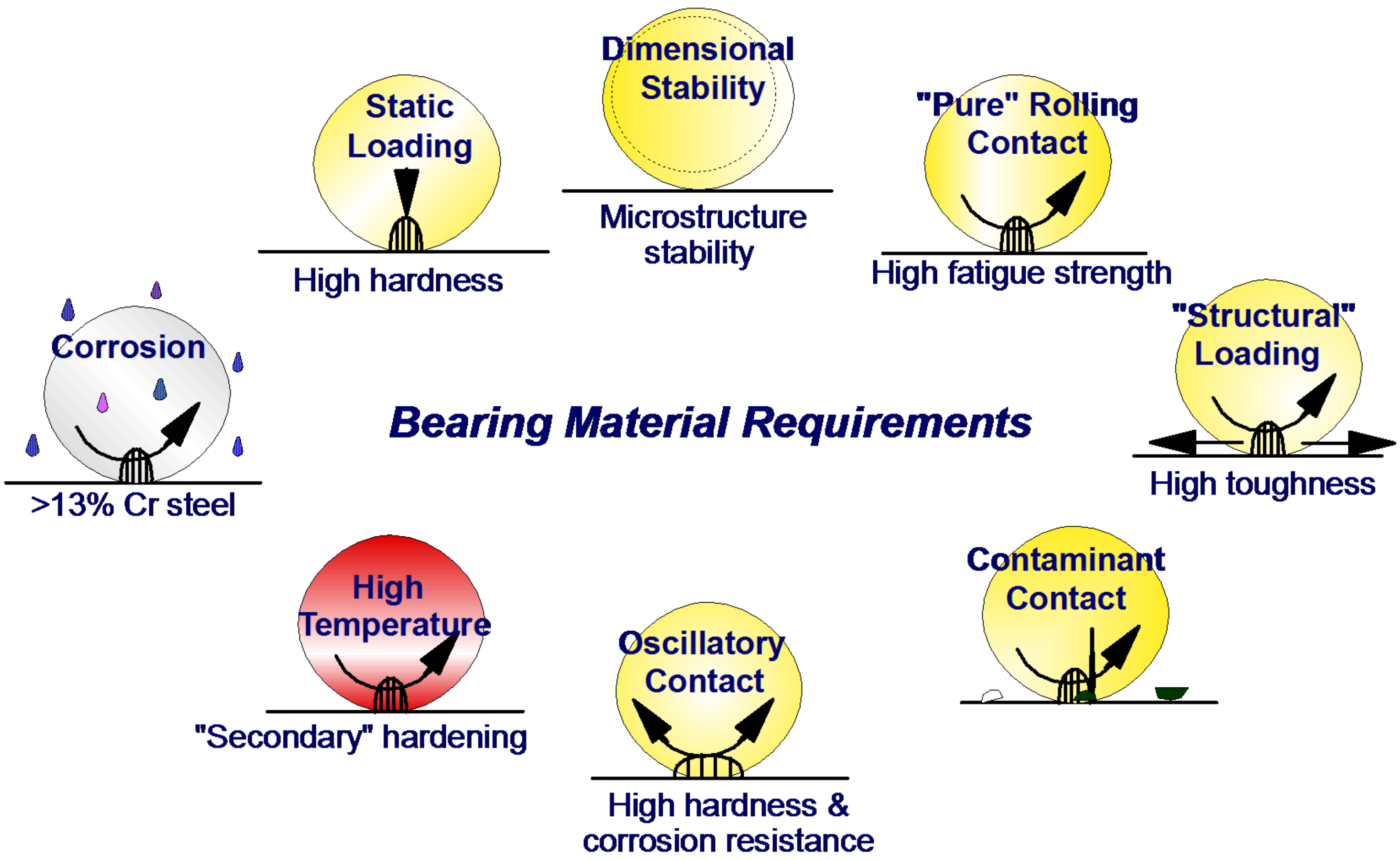


Composition of SKF grade 3 bearing steel (ASTM 52100, 100Cr6)

Bearing steel is Iron (Fe) containing :

Elem.	C	Si	Mn	Cr	Ni	Mo	S	P	O	Ti	Ca
Min. (wt%)	0.95	0.15	0.25	1.35							
Max. (wt%)	1.10	0.35	0.45	1.65	0.25	0.10	0.015	0.025	15 ppm	30 ppm	10 ppm

Bearing Material Requirements

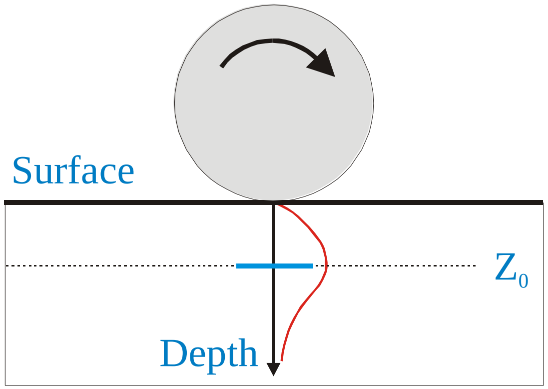


3

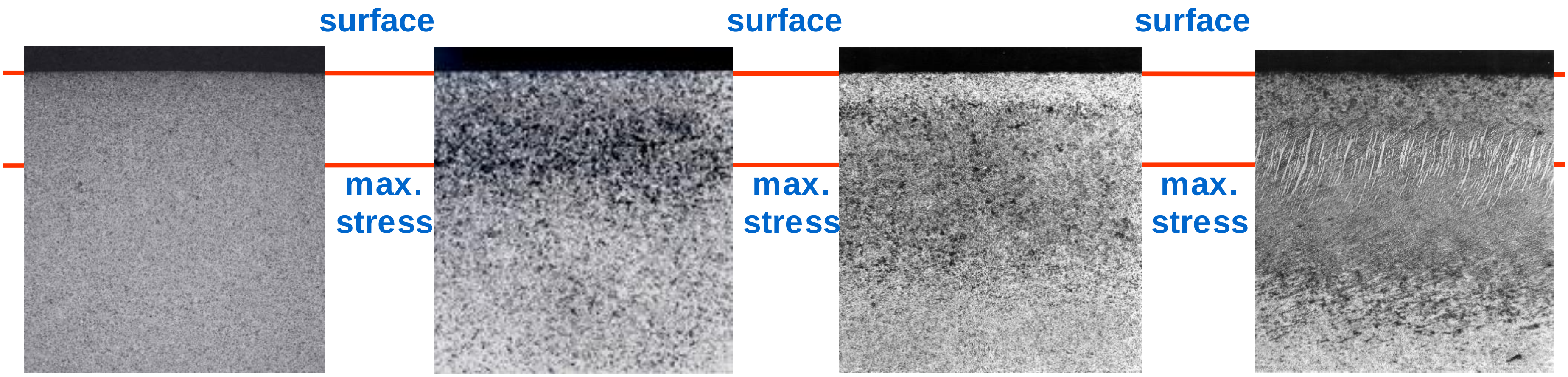
Very high cycle fatigue in bearings

Fatigue development in bearing components

- Bearings require resistance to *Very* High Cycle Fatigue ($>10^{10}$ revolutions)
- Loads are up to 4 GPa
- Load distribution is described by the Hertzian stress profile



Material response in sub-surface region



New | **10 Million revolutions** | **63 Million revolutions** | **660 Million revolutions**

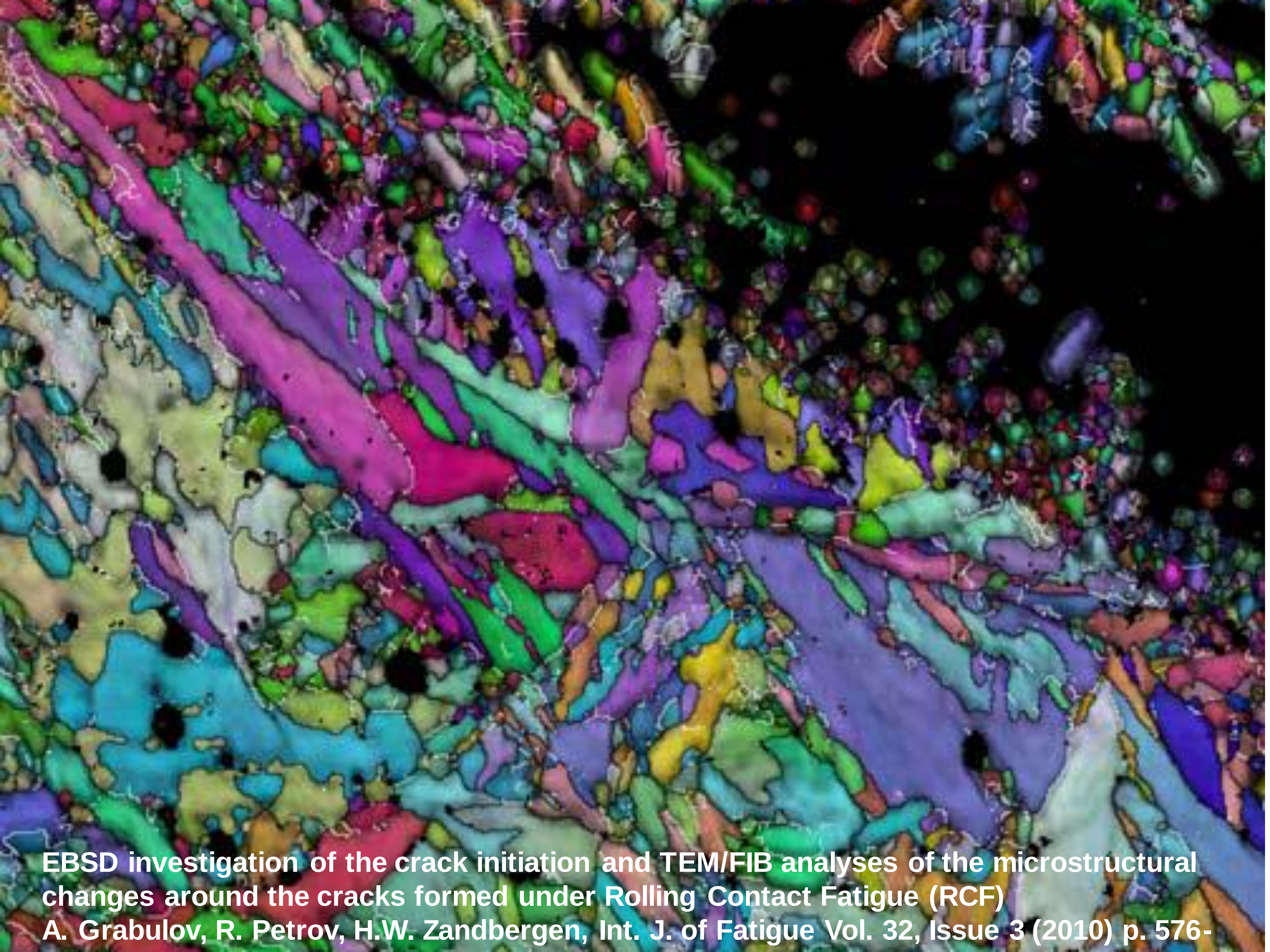
- Deep groove ball bearing 6309
- Contact pressure 3700 Mpa
- Outer ring temperature 53 °C

Various contributions to microstructure alterations due to thermal and mechanical exposure

Localized fatigue damage development

Fatigue damage initiating non-metallic inclusion

Tapered roller bearing, tested 3x nominal life under 1.8 GPa contact pressure



EBSD investigation of the crack initiation and TEM/FIB analyses of the microstructural changes around the cracks formed under Rolling Contact Fatigue (RCF)
A. Grabulov, R. Petrov, H.W. Zandbergen, Int. J. of Fatigue Vol. 32, Issue 3 (2010) p. 576-

Premature failure initiated by corrosion

In some applications, bearings fatigue develops faster than expected.
Premature failures are characterized by multiple crack initiation points and cracks that are decorated with the ‘White-Etching Areas’.

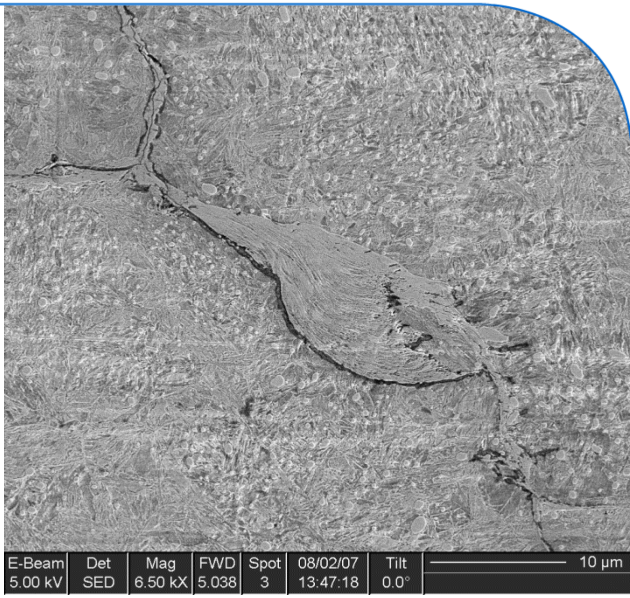
Hypothesis:

One cause of White-Etching Cracks can be material weakening due to corrosion

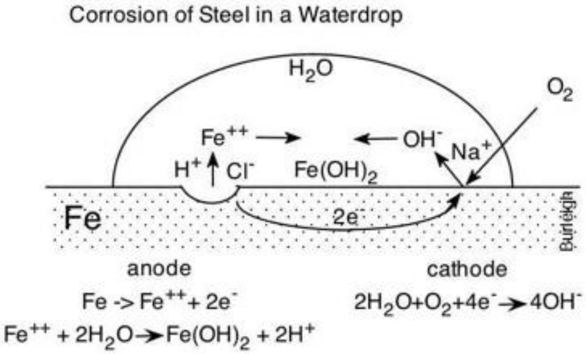
Prerequisites:

- Corrosion can occur in bearings.
- Hydrogen is generated by corrosion.
- Hydrogen diffuses into steel.
- Hydrogen weakens steel and can form white-etching cracks.

Understanding the mechanism of corrosion induced white-etching crack formation is the aim of the work.



WEC in Self Aligning Ball Bearing tested with increased hydrogen content



www.corrosionhelp.com

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Corrosion exposure tests

Corrosion exposure tests

Corrosion exposure tests with the objective to

- Obtain controlled corrosion
- Perform SEM analysis of surface corrosion
- Understand corrosion mechanism/surface damage

Controlled corrosion

Corrosion in a climate chamber

Two tests were performed:
Rollers of NU 205 ECP were cleaned and put directly in the climate chamber

Rollers of NU 305 ECP were cleaned and wrapped together using tie-wraps in bunches of 3 rollers. These were also put in the climate chamber

Test conditions

Cyclic corrosion test

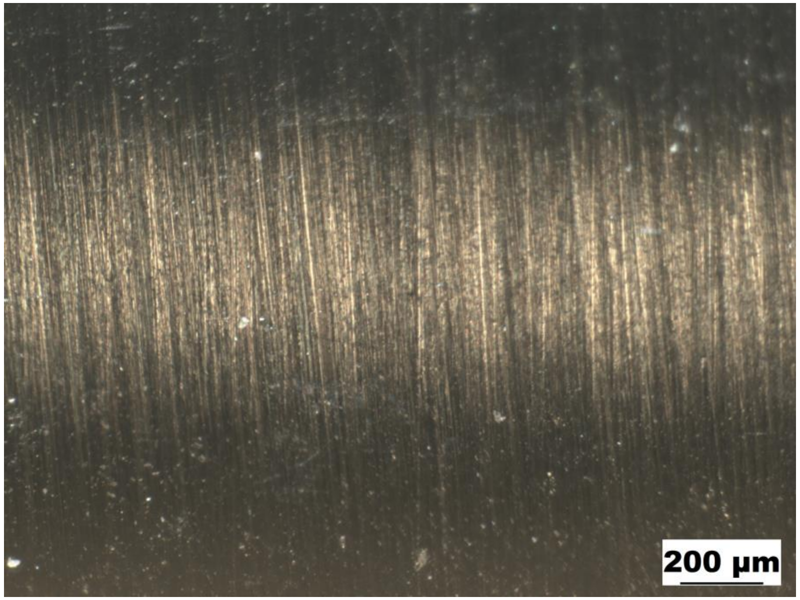
Daily cycle process as follows:

- Increase temperature from 20 ºC to 40 ºC in 1.5 h with a raise in relative humidity from 60 to 98%
- Maintain this warm-humid condition for 4 hours
- Return in 1.5 hours to 20 ºC / 60% RH,
- Maintain the low temperature / dry condition for 17 hours

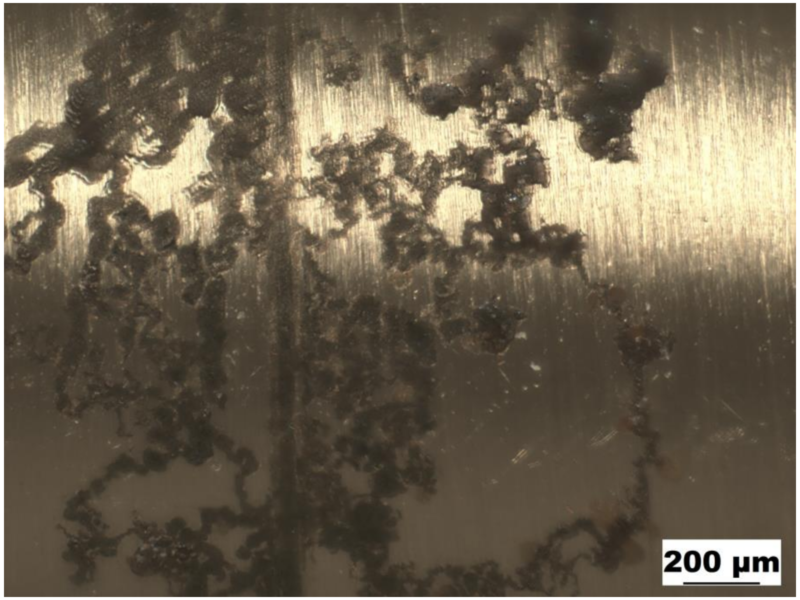
The cycle is repeated, in the present experiment up to 20 days.

3 Rollers tested for 29 cycles in a climate chamber

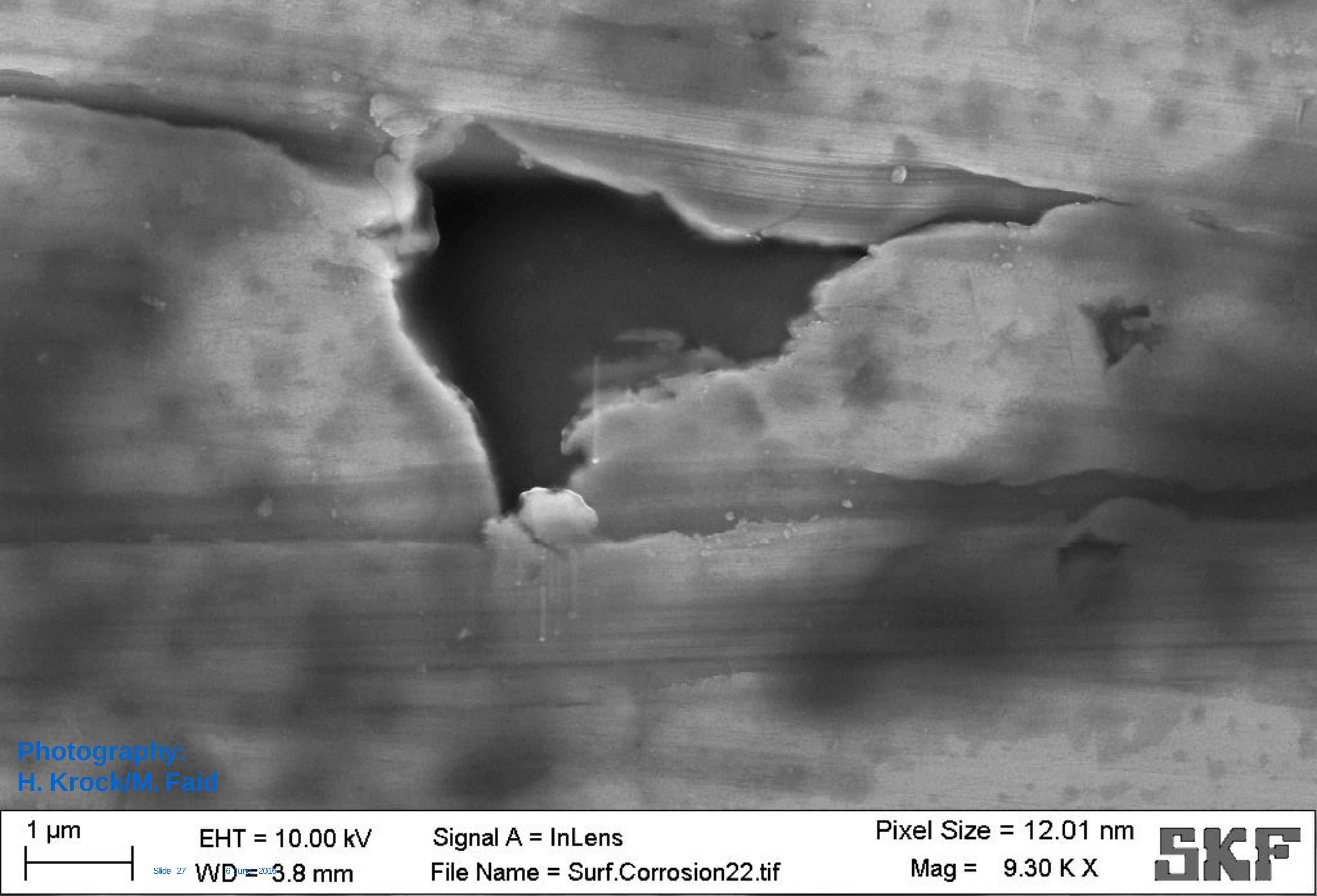
No preservative removal



Cleaned before test



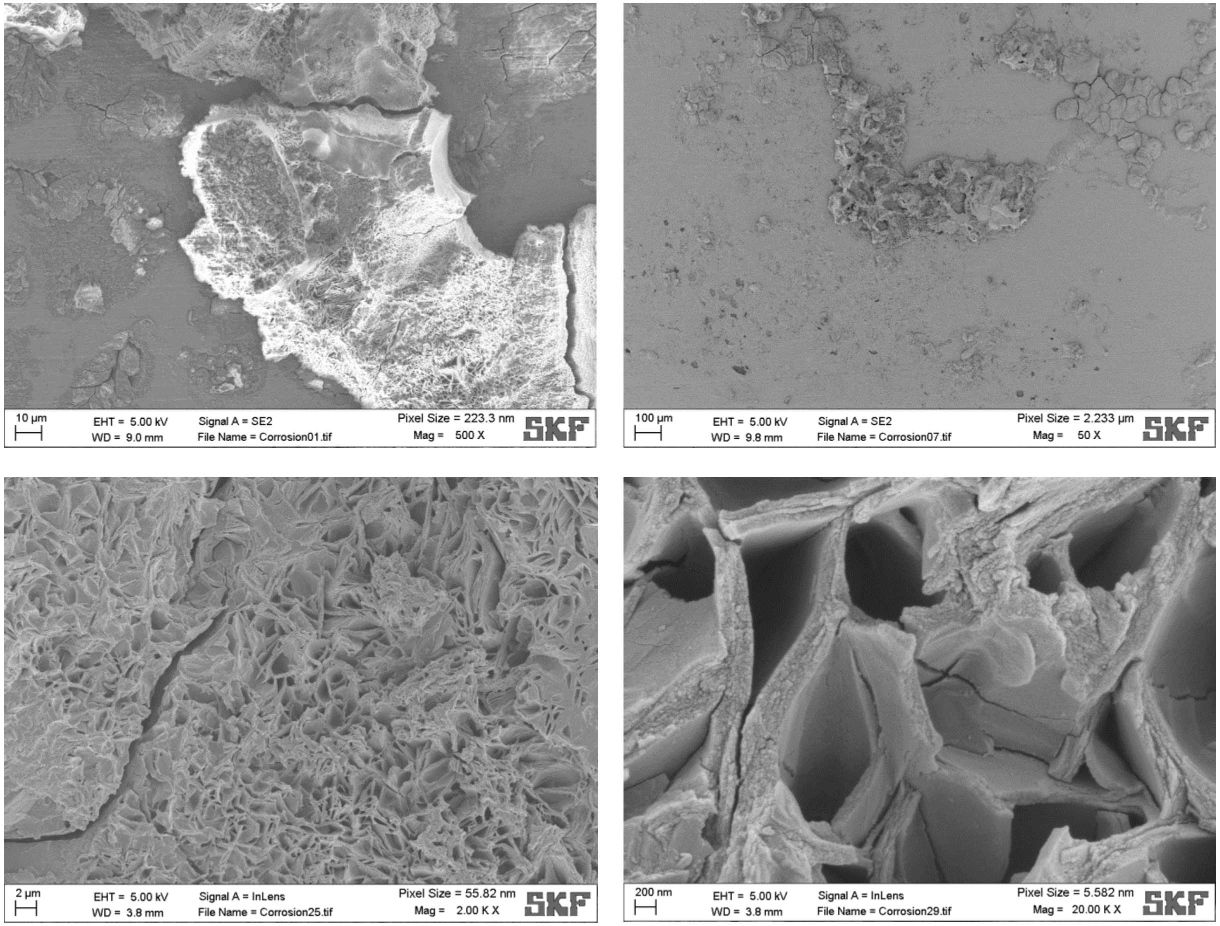
SEM on cleaned rollers exposed in the climate chamber



Photography:
H. Krock/M. Faid

3 Rollers wrapped together in a climate chamber

At the contact of the rollers, crevice corrosion occurs



Photography:
H. Krock/M. Faid

Findings of the exposure tests

Corrosion due to moisture (no salt addition) can be generated in the climate chamber.

Exposure of single rollers leads to pitting corrosion

Rollers in contact show ‘crevice corrosion’

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RCF tests with corrosion

RCF tests with standstill corrosion

Methodology

Obtain controlled (standstill) corrosion of bearing components and then test under realistic bearing test conditions

Objective

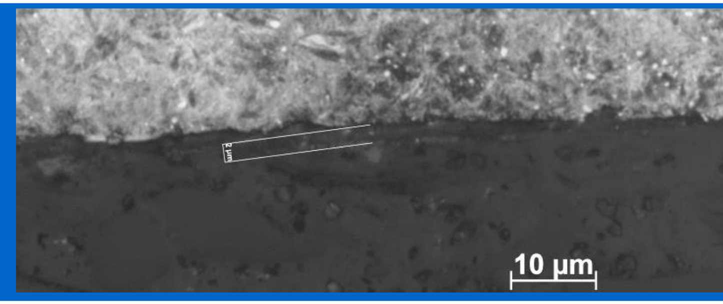
Test should prove (indirectly):

- The harmfulness of corrosion on bearing life
- Generation of white-etching cracks by hydrogen assisted fatigue arising from corrosion conditions

Develop repetitive corrosion method – initial experiments

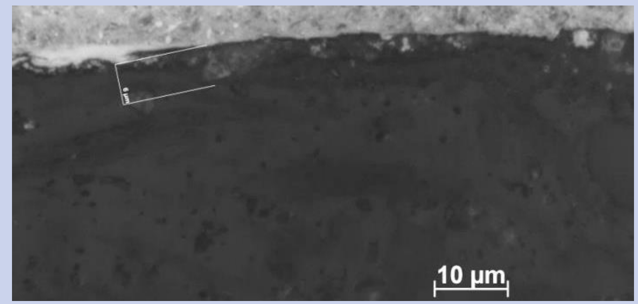
20 µl 1%NaCl,
on each roller/ring contact
Inspect after 1 day

⇒ 2µm



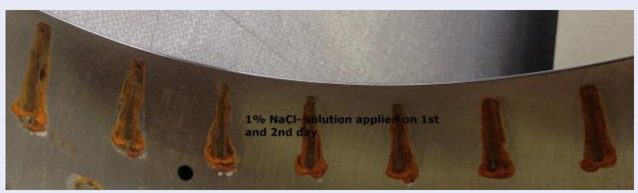
20 µl 1%NaCl on each roller/ring contact
Inspect after 4 days

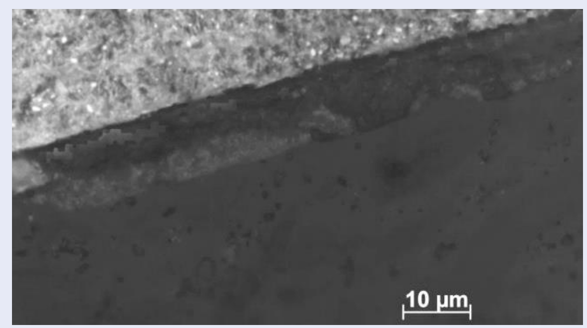
=> 6µm



Day 1 20µl +
20 µl day 2, 1%NaCl on each roller/ring contact
Inspect after 4 days after the first application

=> >10µm





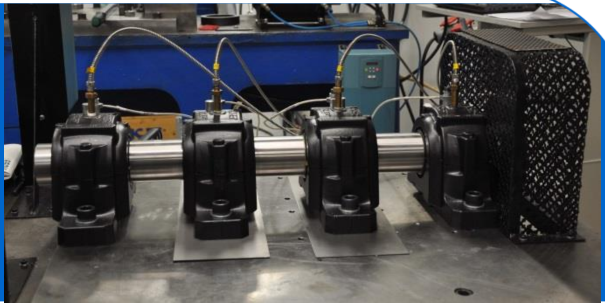
The average of three measurements

Wiped and washed bearing,
No grease or preservative during corrosion process
20 µl of 1 % NaCl- distilled water solution
Vertical position

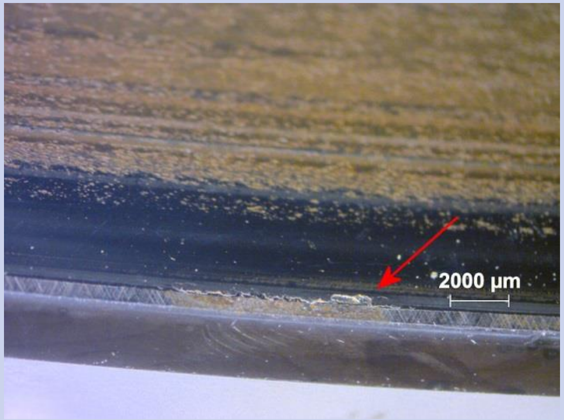
Run the severely corroded bearings as a first try
=> Surface initiated failure mode

Bearing tests in rig

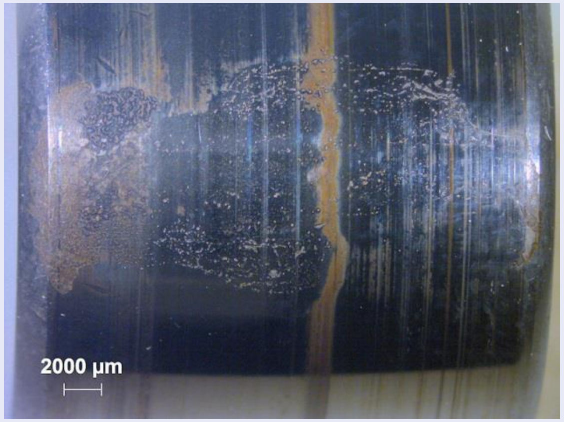
- Failure after about 300-800 hrs
- Similar visible results and no subsurface cracks
- Only one BF found in two investigated bearings

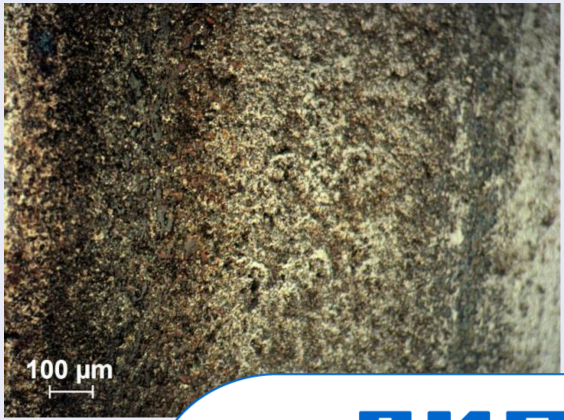


OR



Rollers





Need to develop less aggressive and reproducible corrosion method

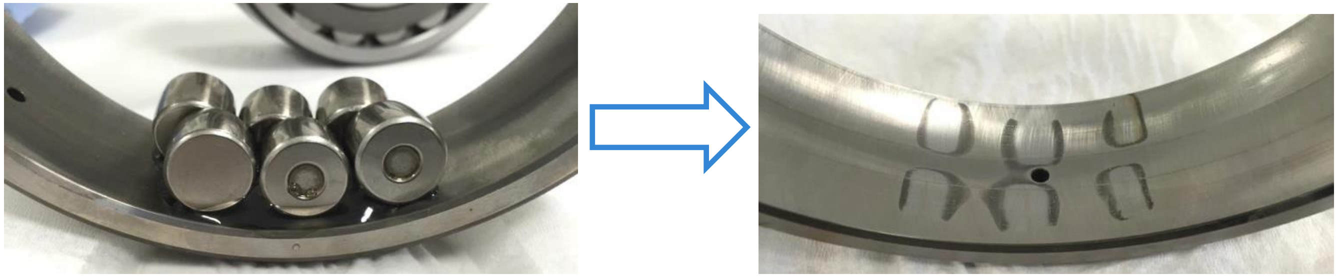
Extensive testing to improve corrosion method to have less corrosion with less oxide

- Preservative removal
- No grease or greased bearing – two different greases mixed with water to have high water level (5000 ppm)
- Water: Several versions of “artificial tap water” (to get not too aggressive but still defined level of ions)
- Amount of extra water at roller/raceway contact
- Bearing in different orientation

All cases : exposure during 14 days

⇒In best cases spot type corrosion could be obtained but not well reproducible. Tests without cage gave indications of influence by cage (by lifting roller elements or possible electrochemical)

⇒Ongoing tests where corrosion without cage influence and rollers placed on raceway

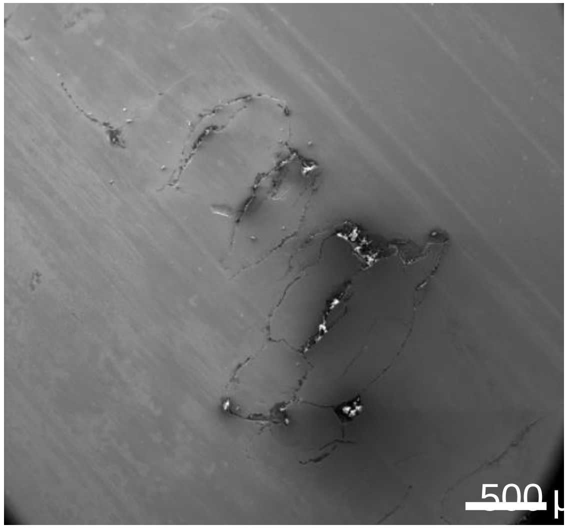


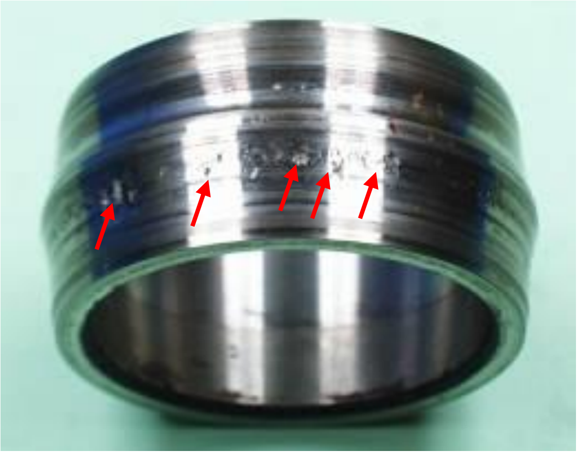
Standstill corrosion tests

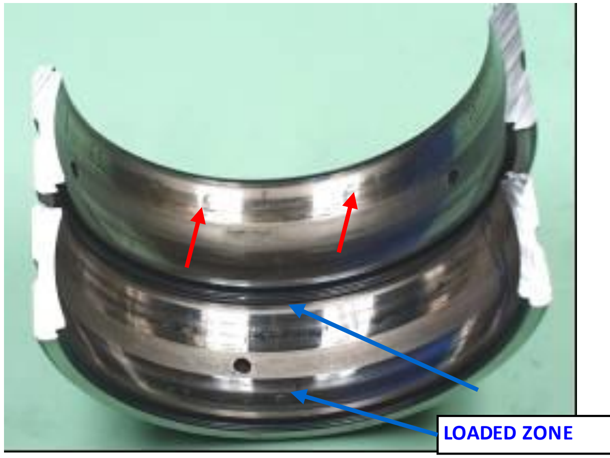
Tested bearing with water in the grease (Shell Nerita HV), standstill corrosion.

- Radial load 10 kN
- Test time 13x120 h with 48 h standstill after each 120 h
- 0.5 ml water was added to the grease at every standstill
- Every second standstill the bearing was re-lubricated

Several failures occurred, microstructural investigations were performed

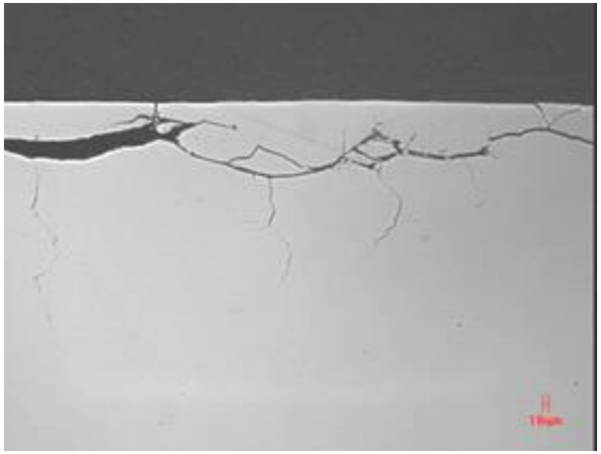


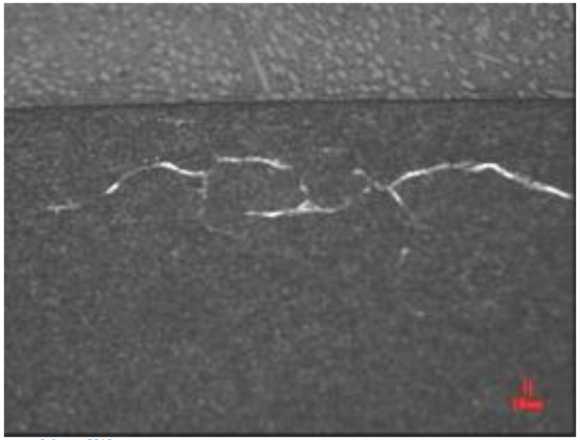




Sub-surface fatigue

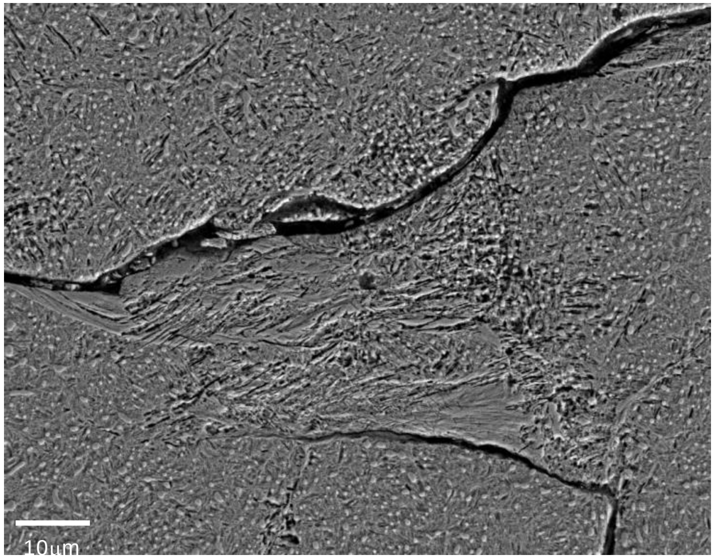
In the bearings with water in grease, accelerated fatigue is observed, leading to extensive cracking with some White-Etching areas around it.

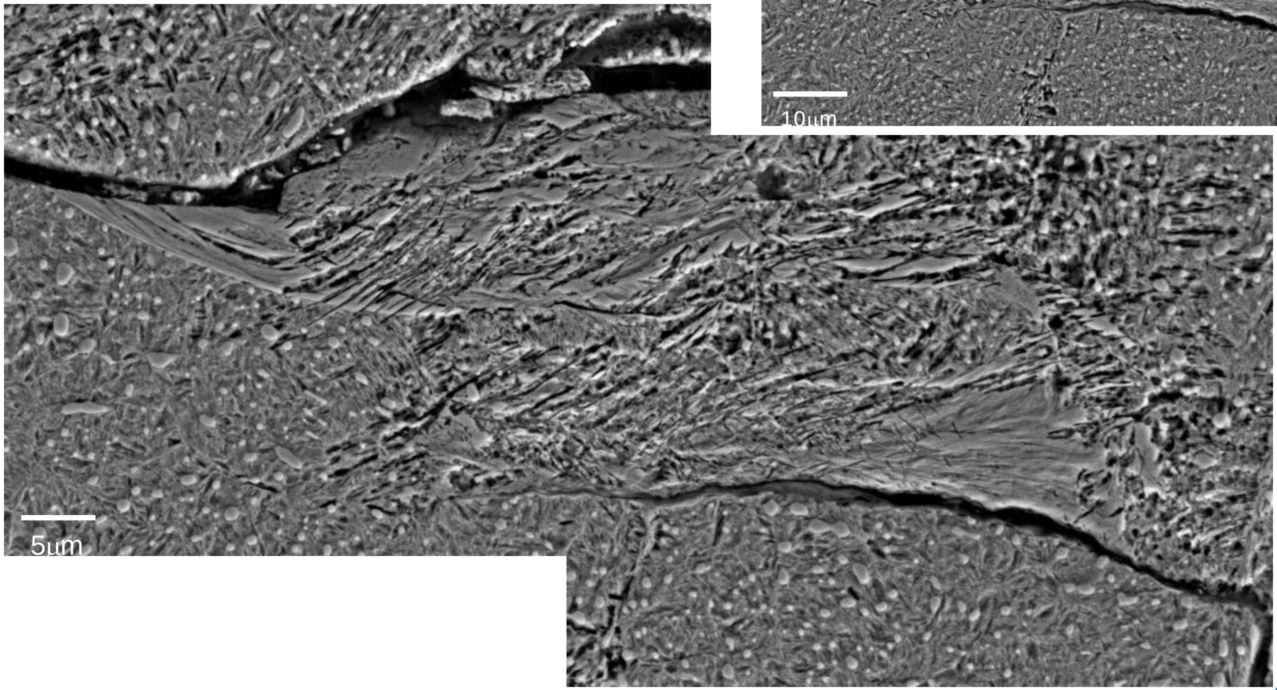




Extensive White-Etching Cracking due to corrosion

Sub-surface WEC in tested bearing with water in grease after standstill corrosion





Low level standstill corrosion

Standstill corrosion experiments
Small size Tapered Roller Bearing

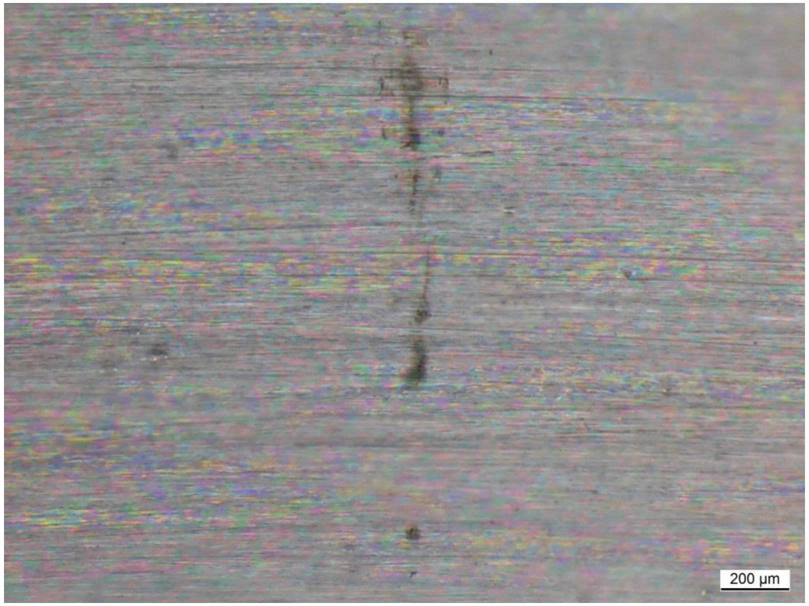
Exposure to 6 standard temperature/humidity cycles

- Increase temperature from 20 ºC to 40 ºC in 1.5 h with a raise in relative humidity from 60 to 98%
- Maintain this warm-humid condition for 4 hours
- Return in 1.5 hours to 20 ºC / 60% RH,
- Maintain the low temperature / dry condition for 17 hours

After standstill corrosion, a Rolling Contact Fatigue test was performed: 2.2 GPa contact pressure on the inner ring for 168 h (8 MRevs), lubricant Mobilgear SHC (Wind turbine oil)

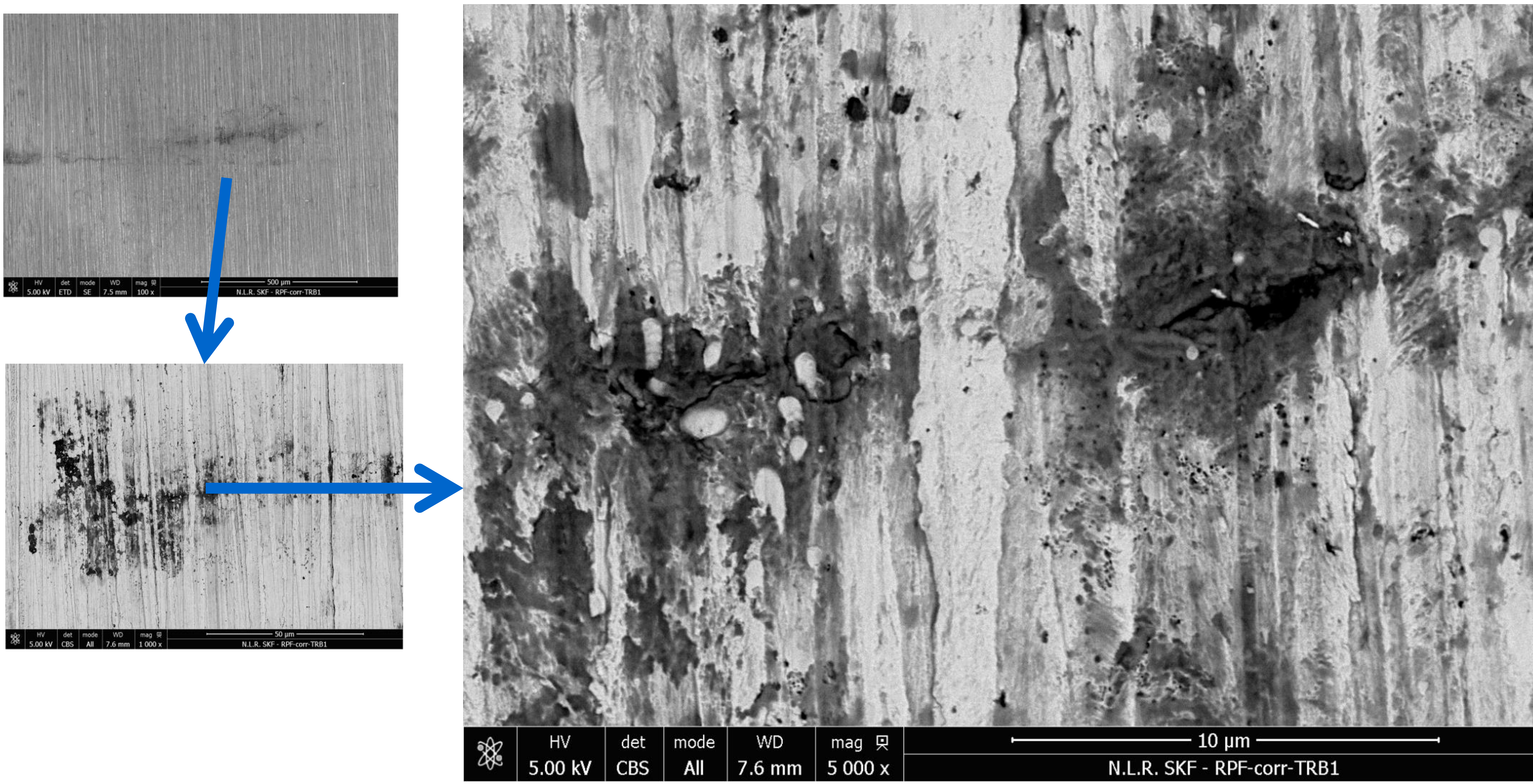
Optical observations

Standstill corrosion marks very difficult to find



Standstill corrosion marks after testing

Cracks become visible, axial direction



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Hydrogen effect on mechanical properties

Hydrogen effect on mechanical properties

Description of charging process

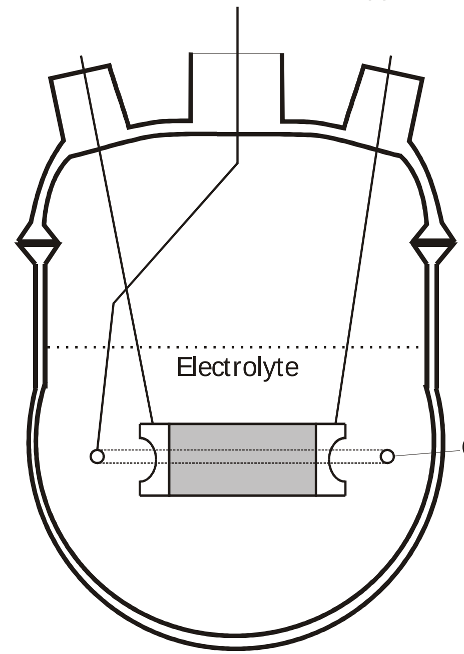
Tensile testing with H-charged samples

RCF testing

Hydrogen charging cell

Design of the hydrogen charging cell

- Glass bulb
- Large anode-cathode distance
- Temperature control
- Internal stirring
- Rings up to 100 mm outer diameter



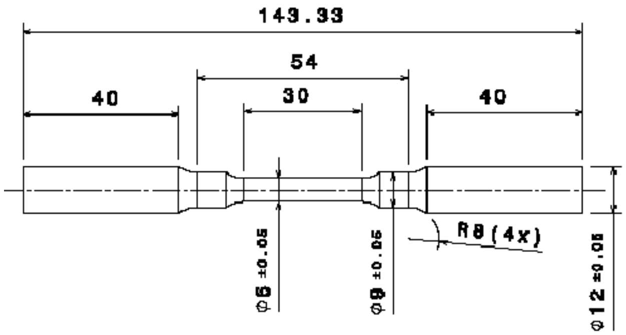
Parameter	Value
Electrolyte	Alkalyne
Temperature	80 ºC
pH	11.5-12 at start
Estimated current density	10 mA/cm^2
Polarity workpiece	negative
Time	24 h

Tensile testing with H-charged samples

Hydrogen is weakening the steel.
To quantify the effect, hydrogen charged tensile testing was performed.

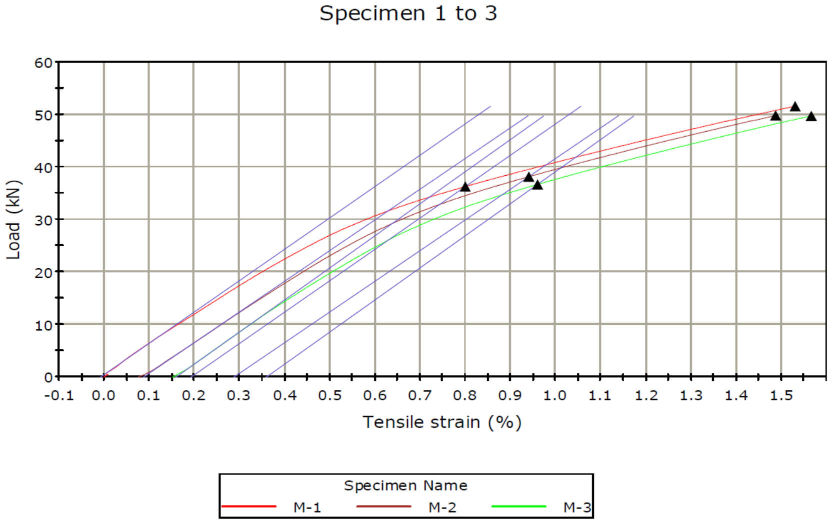
Test set-up

- Charging tensile test bars
- Hydrogen level 4-5 ppm
- Transport to tensile test machine (± 2 hours)
- Tensile test with cross-head speed 0.1-1.0 mm/min

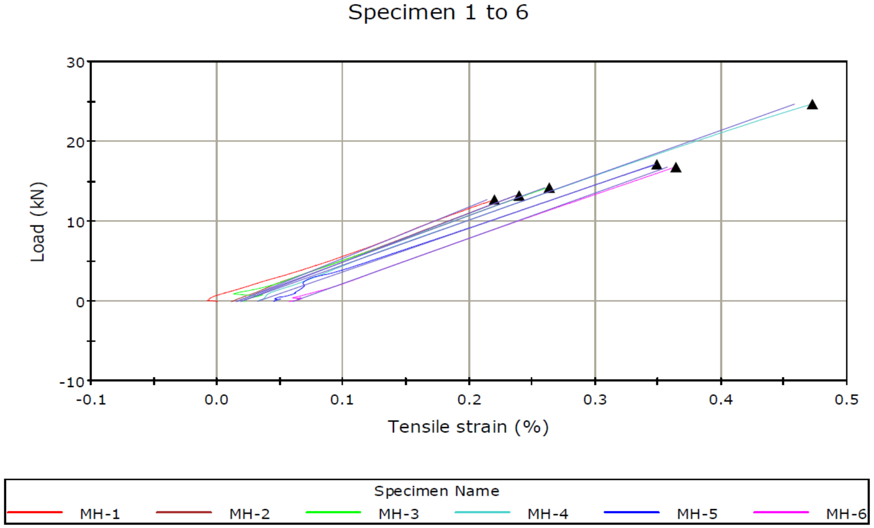


Results of tensile testing

Standard martensite



Hydrogen charged



Elongation : 1.4%

Failure at region of change in diameter

Elongation : max. 0.44%

Failure positioned randomly in straight part of test specimen

Fracture surfaces

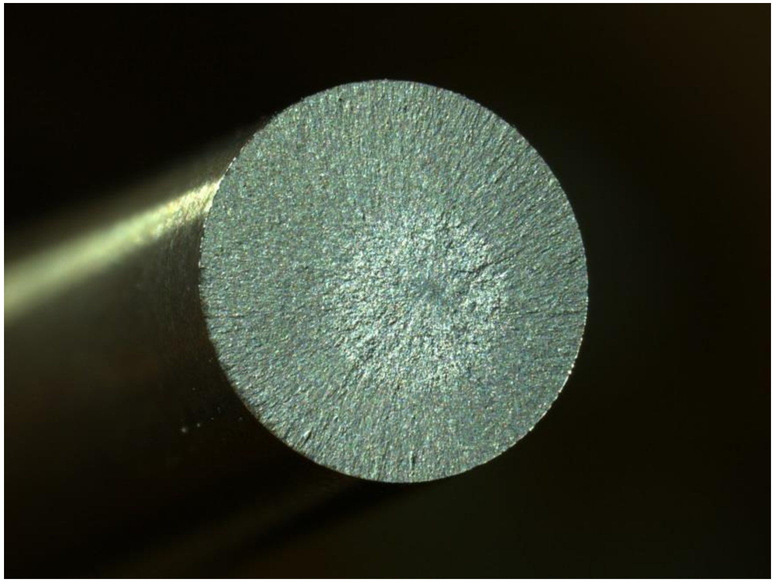
Standard martensitically hardened steel

Crack initiation at surface

Specimen M2

Hydrogen charged martensitically hardened steel

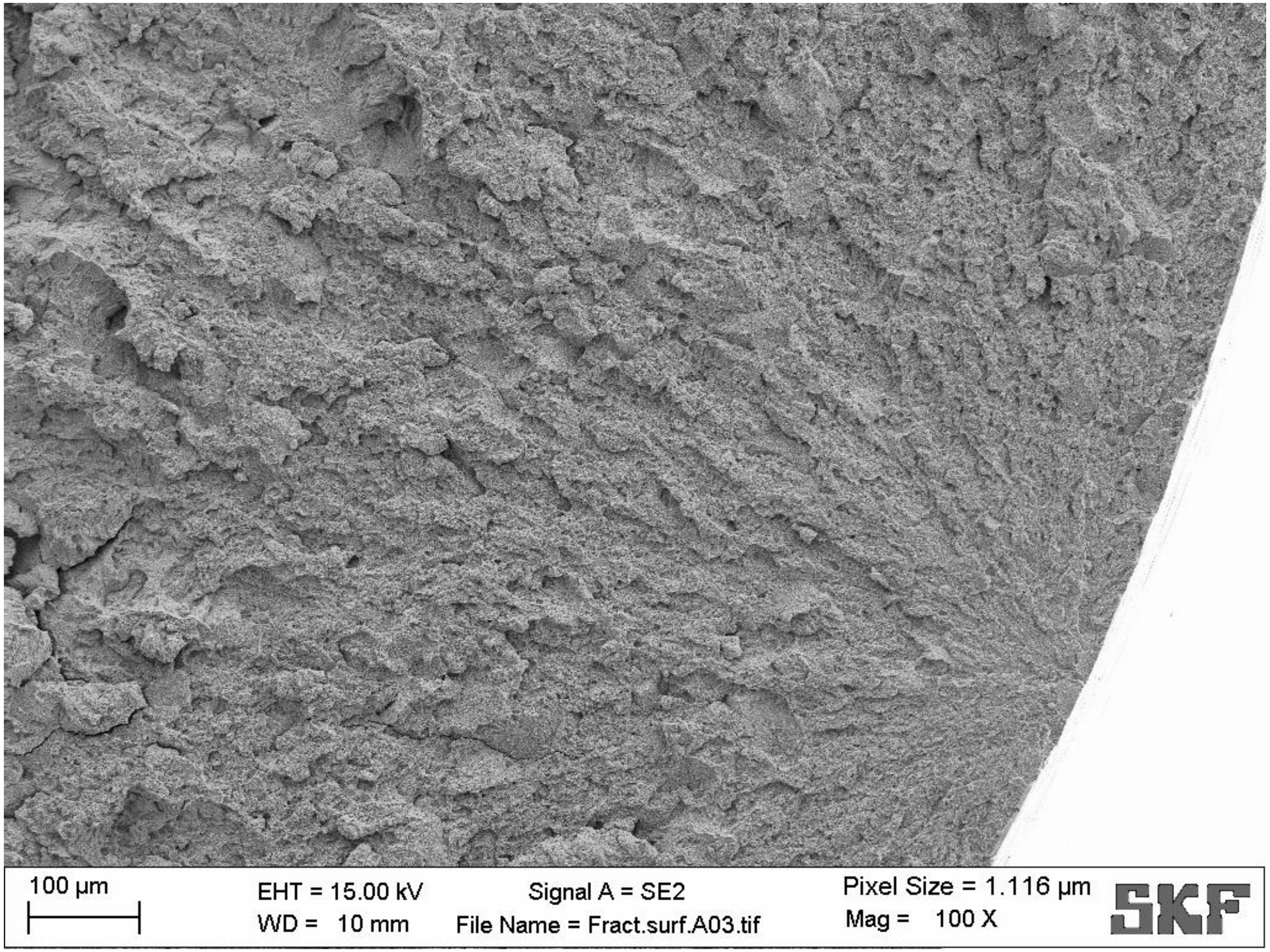
Crack initiation in bulk material



Specimen MH3

Standard martensitically hardened steel

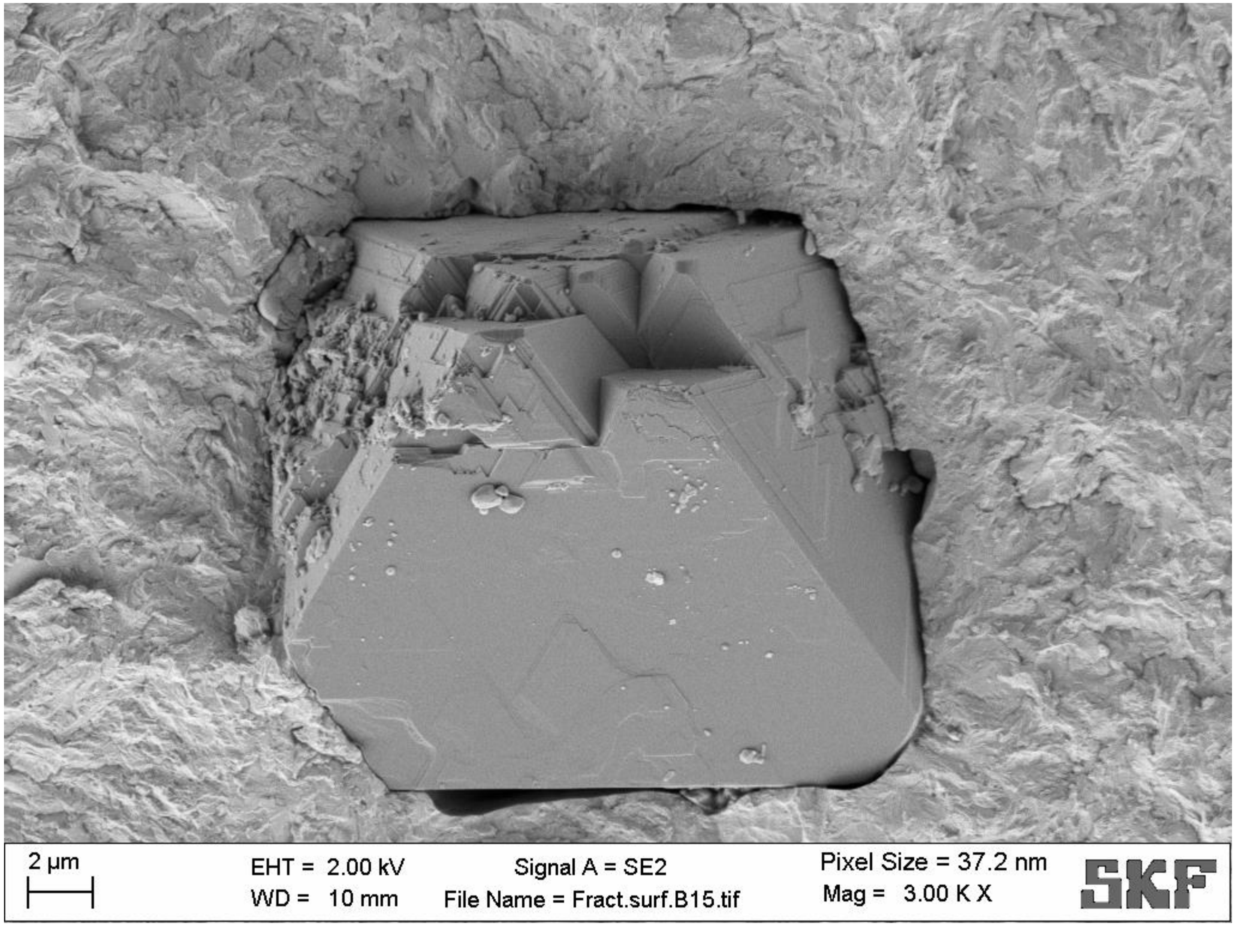
Crack initiation at surface of the test specimen



Hydrogen charged martensitically hardened steel

Chemical (EDS) analysis of crack initiating inclusion:

- Al 24 wt%
- Mg 11 wt%
- O 64 wt%



Bearing tests

Tested bearings under high hydrogen content conditions

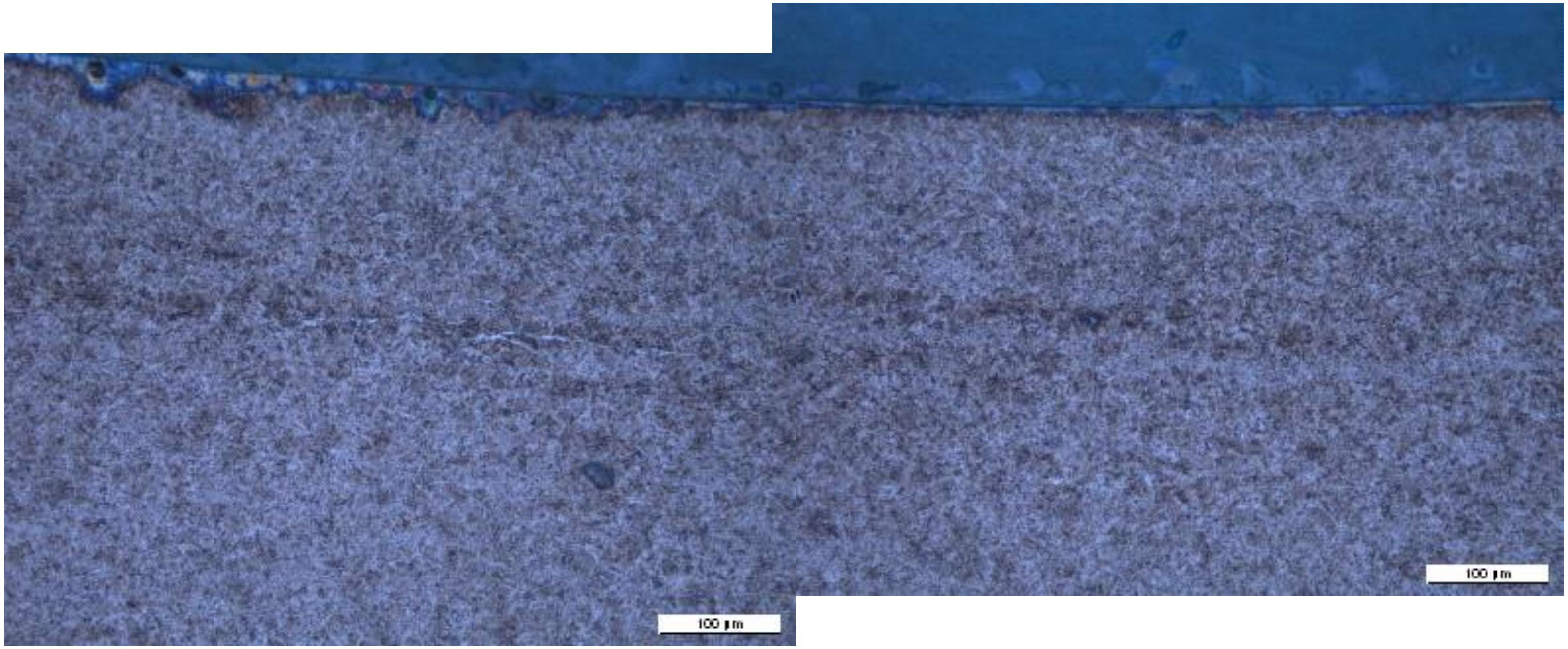
Bearing number	Contact pressure (GPa)	Temperature (°C)	Number of revolutions
1	2.8	83	$5.2 \cdot 10^6$
2	1.6	83	$5.2 \cdot 10^6$
3	2.0	83	$5.2 \cdot 10^7$

Tests do not lead to failure, but were stopped

Microstructure investigations show damage in sub-surface

Subsurface microstructure bearing 1

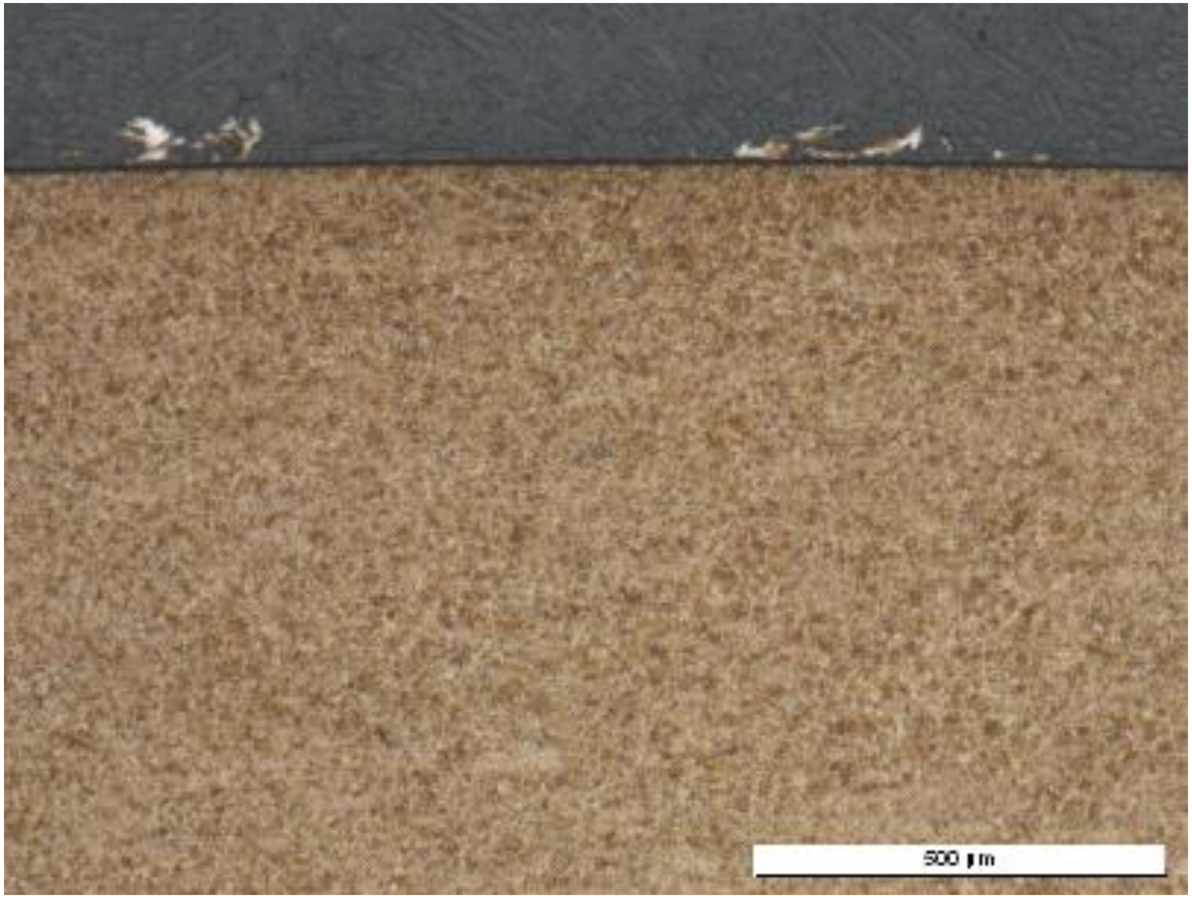
Microstructure of bearing 1, tested for $5.2 \cdot 10^6$ revolutions at 2.8 GPa and 83 °C



Bearing running time in this test is << nominal life

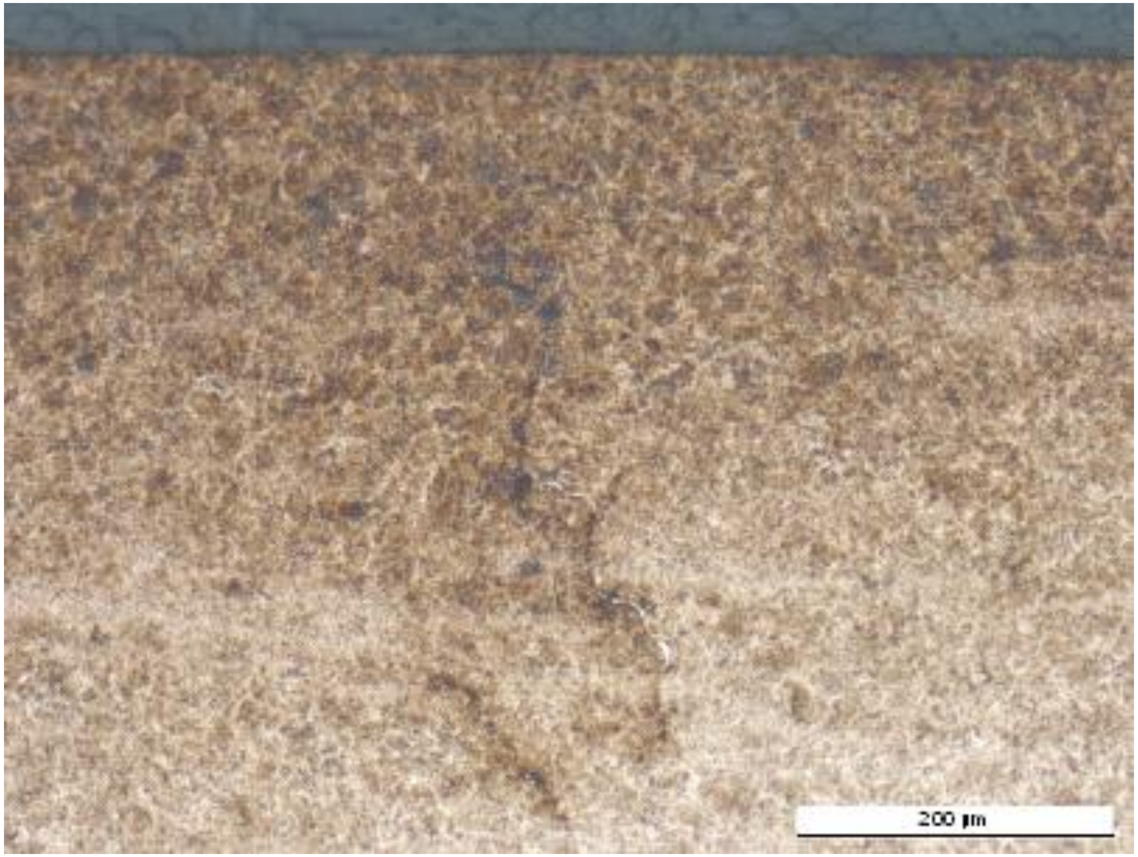
Subsurface microstructure bearing 2

Microstructure of bearing 2, tested for $5.2 \cdot 10^6$ revolutions at 1.6 GPa and 83 °C



Subsurface microstructure bearing 3

Microstructure of bearing 3, tested for $5.2 \cdot 10^7$ revolutions at 2.0 GPa and 83 °C



Hydrogen-induced weakening of bearing steel

Hydrogen promotes formation of more and more mobile crystal point defects:

- Accelerated iron self-diffusion and dislocation climb
- Promotes the creep-like fatigue damage process
- More plastic damage accumulation (WEA)
- Earlier crack initiation
- Increased crack growth rate
- Reduced bearing life

7

Atomistic simulation of H in bearing steel

Hydrogen concentration in the microstructure

Literature shows the presence of hydrogen at non-metallic inclusions.

Fatigue life is shown to be reduced by hydrogen

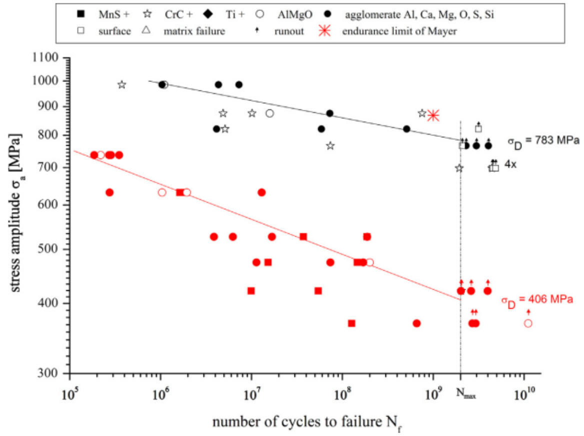
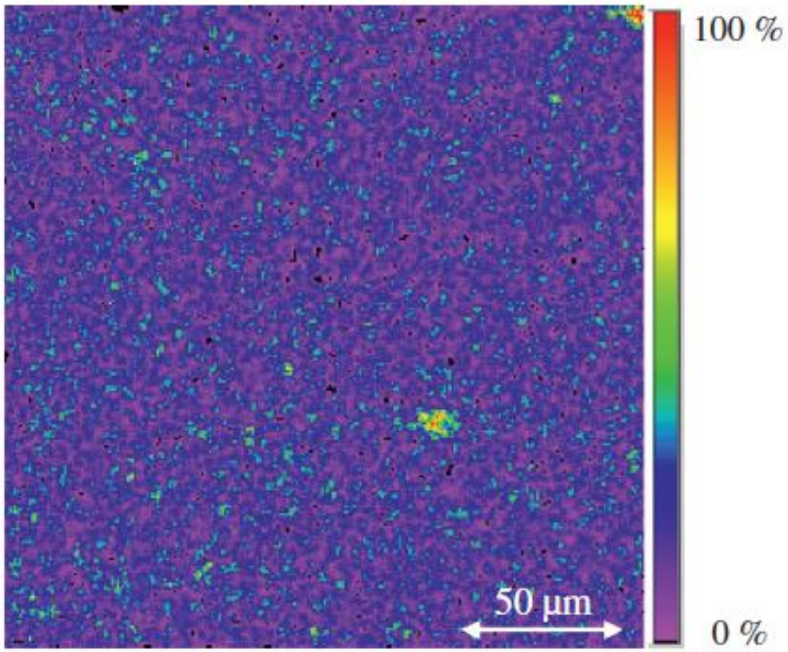


Fig. 10. S–N diagrams of the bainitic conditions including curves for 50% failure probability, $R = -1$, black: uncharged, 0.6 ppm hydrogen, red: charged to 3 ppm hydrogen. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



T. Karsch, H. Bomas, H.-W. Zoch, S. Mändl, ‘Influence of hydrogen content and microstructure on the fatigue behaviour of steel SAE 52100 in the VHCF regime’ International Journal of Fatigue 60(2014) 74-89

DFT calculations of V_xC_y and Fe

Trapping of hydrogen in microstructure features

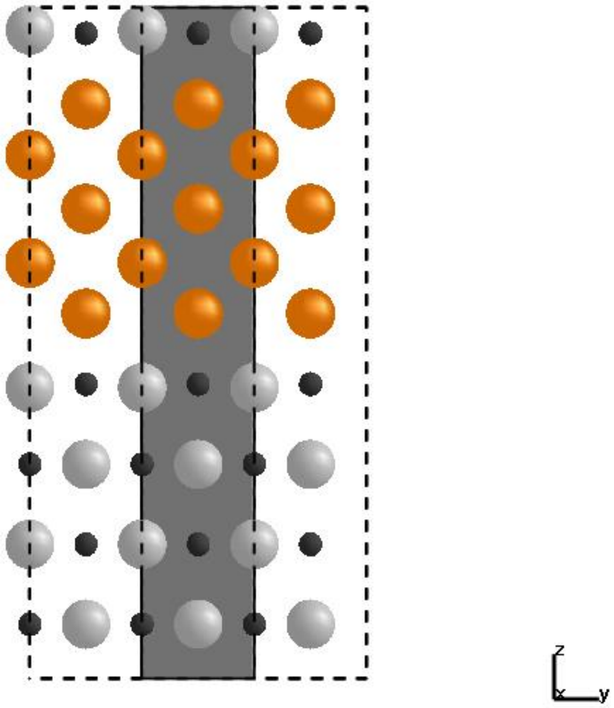
Calculations are performed to investigate the trapping in:

- Grain boundaries
- Interfaces of precipitates
- Inside precipitates

The objective of the work is to understand the relative importance of the various microstructure features and their trapping capacity.

DFT calculations of V_xC_y and Fe

- Trapping of H
  - At the GBs
    - **Pure**
    - H in octahedral position
    - H in tetrahedral position
  - Inside the Precipitates



DFT calculations of V_xC_y and Fe

- Trapping of H
  - At the GBs
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    - H in tetrahedral position
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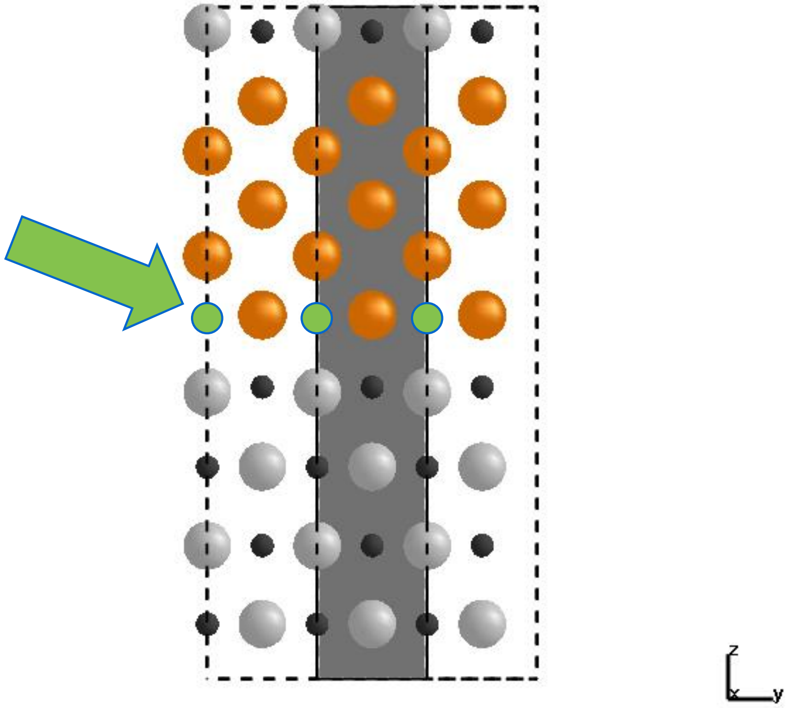

DFT calculations of V_xC_y and Fe

- Trapping of H
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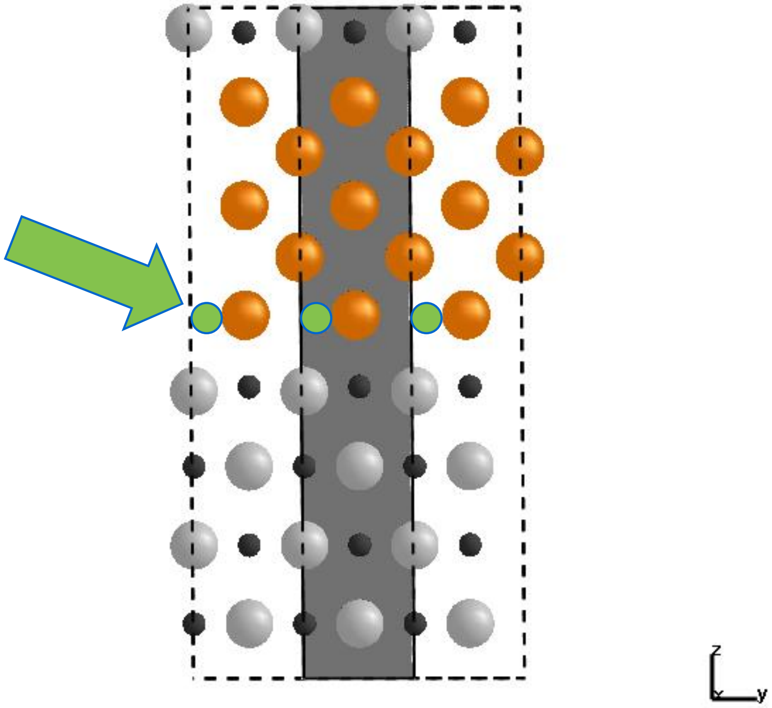
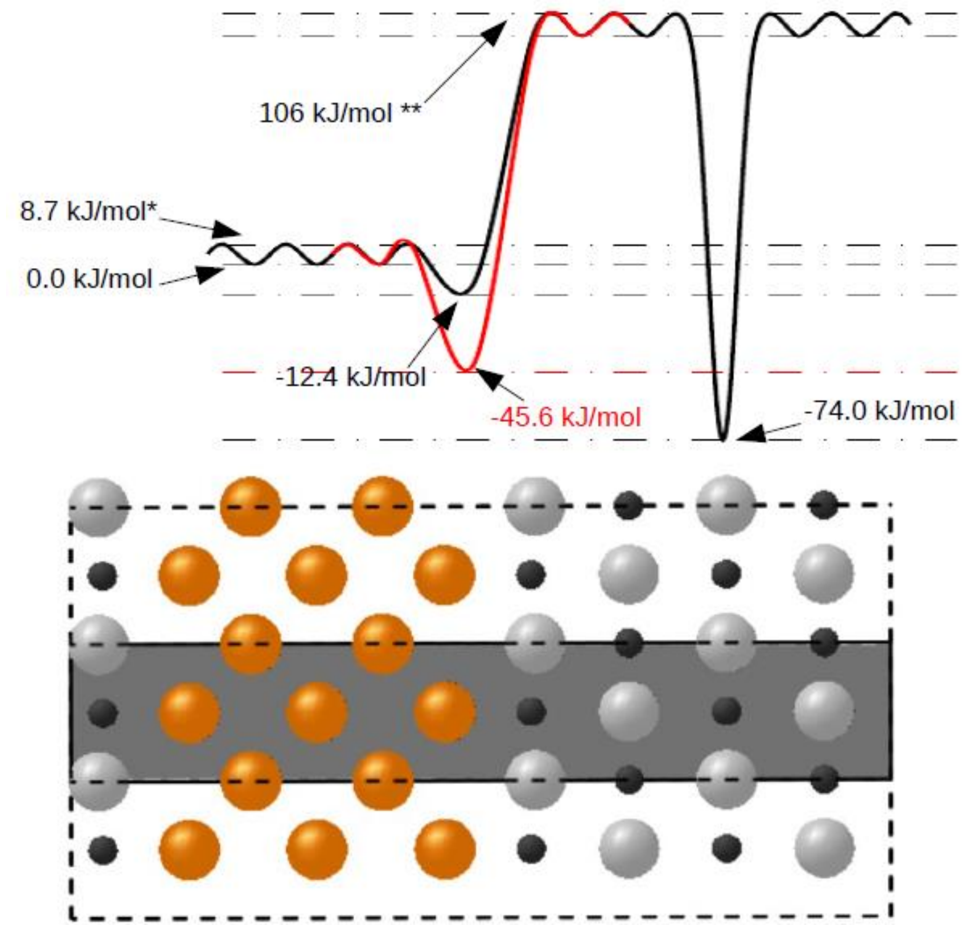


Fe-VC interfaces

Energy landscape of Fe-VC interface shows trapping at interface



*Di Stefano, D., Mrovec, M., & Elsässer, C. (2015). Physical Review B, 92(22), 224301.
**Kawakami, K., & Matsumiya, T. (2012). ISIJ International, 52(9), 1693–1697.

Result of DFT calculations

Main focus is to understand the material structure with trapping sites:

- Character
- Number
- Efficiency/release rate

Knowledge of traps and hydrogen behavior will be supporting steel development for rolling contact fatigue applications

Further work is required for other non-metallic inclusions to prove the hydrogen attraction to the various microstructure features

8

Summary and Conclusions

Summary

The presentation showed

- Very high cycle fatigue in bearings
- Standstill corrosion exposure tests
- RCF tests with corrosion
- Hydrogen effects and RCF
- Atomistic simulation of H in bearing steel

Conclusions

It has been shown that:

- standstill corrosion, also barely visible, causes cracks and failures in bearing steel.
- Standstill corrosion can lead to cracks that show white-etching areas
- Hydrogen weakening of the bearing steel leads to early failure
- DFT simulations and experiments reported in literature show that non-metallic features in the microstructure attract hydrogen

The connection between standstill corrosion and the increase of the hydrogen content in bearing steel needs to be further quantified.

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Steuart Horton, Ingemar Strandell, Kenred Stadler, Hans Krock, Mohammed Faid, Thore Lund, Amra Cenanovic, Rob Geelen, Tim Hattenberg (NLR) and Pelle Matson contributed in various ways to this work.