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Failure analysis and thermochemical surface engineering of bearings for wind turbine drivetrains

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Abstract: Roller element bearings inside the drivetrain of a wind turbine are exposed to highly dynamic loads that can for instance originate from the wind field, the rotor, the drivetrain itself or the generator. This can lead to premature failure of these components and consequently to high economic maintenance costs. The mechanism behind the premature failures is not well understood but is associated with the formation of so called white etching cracks (WECs). Complementary microscopic techniques were used to analyse failed bearings and to characterize the morphology of white etching cracks. Deep nitriding was studied as a potential remedy to failures associated with WECs. Performance of nitrided rollers was evaluated by rolling contact fatigue testing under conditions known to provoke WEC failure.

Key words: white etching cracks; bearings; wind turbine drivetrain; nitriding; rolling contact fatigue

1 Introduction

Recently failure modes of wind turbine bearings have been described, characterized by flaking or radial inward going axial cracks, sometimes in combination with spalling on the bearings' raceway. These failure modes are associated with the occurrence of so called white etching cracks (WECs), named after the white etching areas (WEAs) bordering the cracks (cf. Fig. 1a). The failure cannot be predicted by classical lifetime models nor be explained by classical rolling contact fatigue mechanisms. Failures associated with these WECs can be found in bearings made of martensitic or bainitic through-hardened as well as case hardened (carburized) steels. The flaking or axial cracks can lead to premature failure and is found in all bearing types, irrespective of the supplier. The failure modes occur in applications with dynamic load conditions, for example in the wind turbine drivetrain or the automotive industry.^[1-8]

There are various hypotheses for the origin of WEC failure and theories of WEC formation, some pointing at purely transient loading conditions, while others consid-

er the presence of hydrogen as the main cause. None of them are so far generally accepted and a better understanding of the mechanisms is needed for more accurate lifetime prediction models and to develop potential remedies for premature failure.

Both surface initiated fatigue and sub-surface initiated fatigue is hindered by compressive residual stresses^[9, 10]. A potential remedy to WEC failure is deep nitriding which introduces nano-scale alloying element nitrides and an associated compressive residual stresses profile beyond the depth of WEC formation and beyond the typical depth of maximum shear stress (up to 900 μm)^[11]. Since the treatment is usually conducted in the ferrite rather than the austenite state, contrary to case hardening by carburizing, subsequent quenching is not necessary and a minimum of distortion results, giving excellent dimensional control.

2 Failure analysis of field components

Various types of failed roller bearings from different positions inside the wind turbine drivetrain were investigated by the complementary use of both conventional techniques as reflected light microscopy (RLM), scan-

ning (SEM) and transmission (TEM) electron microscopy as well as electron backscatter diffraction (EBSD) and ion channelling contrast imaging (ICCI). The gap between RLM and SEM (providing a good overview over the crack morphology) and TEM (providing very detailed information but from a very limited part of the sample) could be fulfilled by the use of EBSD and IC-

CI. For example, by ICCI homogeneous regions were observed showing a striation type pattern consisting of linear features related to the progress of the position of the crack (cf. Fig. 1b). It is likely that these lines are residual traces of a cyclic opening and closing of the crack, similar to the mechanisms of WEA formation proposed by Vegter and Slycke^[5].

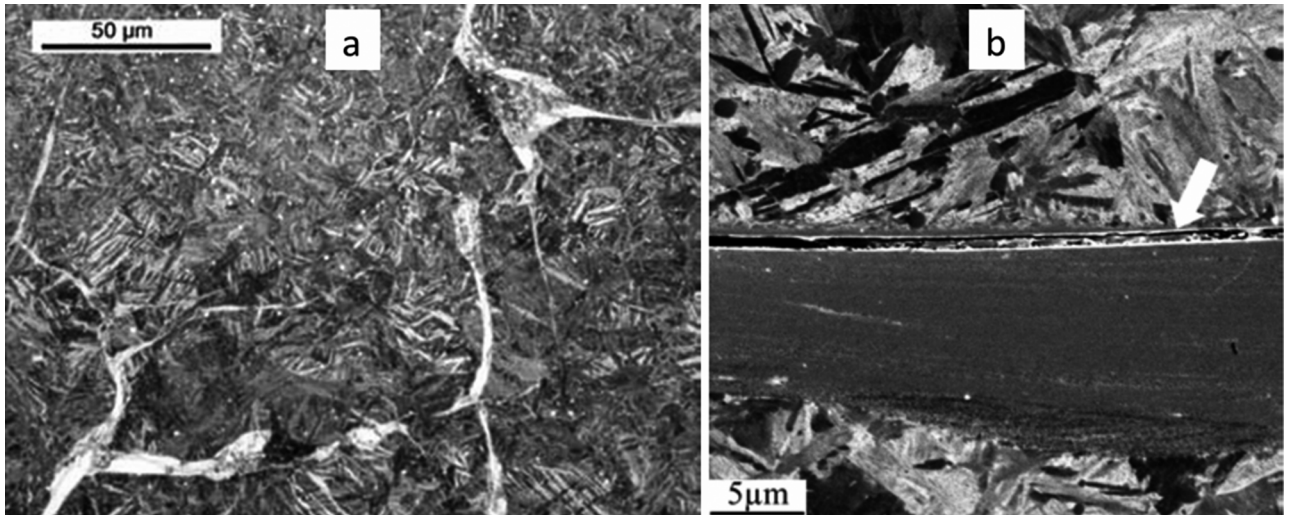


Fig. 1 a) RLM image of a WEC network, etched by nital to reveal the white etching area bordering the cracks^[12], b) ICCI image of a WEC showing the homogeneous WEA bordering the crack indicated by the arrow. Inside the WEA a striation pattern is visible^[12]

3 Nitriding as a potential remedy to WEC failure

Nitriding experiments were conducted on four different commercial nitriding steels to study the influence of different alloying concepts, prior heat treatments and nitriding parameters on the case properties. Initial experiments conducted in a thermobalance were used to determine the temperature and nitrogen potential necessary to achieve a case with the desired properties, i. e. a deep diffusion zone, no or only a thin, non-porous compound layer and a shallow decrease in the hardness profile. The effect of a temperature boost, a higher nitrogen potential boost on the mass uptake as well as the nitrided case depth and compound layer were investigated. Up-scaled experiments were conducted in a semi-industrial furnace. Special attention was given to the formation of grain boundary carbides/ nitrides, which are suspected to be potential crack initiation sites. Two dif-

ferent approaches were studied to prevent grain-boundary carbide/nitride formation by carbon removal from the case: oxynitriding (oxygen added to the nitriding atmosphere) and prior heat treatment in a reducing atmosphere.

The best case properties were achieved by nitriding for 100 hours at 530 °C and a gas flow of 1l/min NH₃. The hardness-depth distributions achieved by nitriding under these conditions are displayed in Fig. 2a. The highest surface hardness was observed for aluminium-alloyed grades 34CrAlNi7 and 34CrAlMo5, while a maximum nitriding depth of 800 μm was observed for a 15CrMoV5-9 steel. On nitriding 15CrMoV5-9 and 31CrMoV9 samples developed a distinct 7 μm thick non-porous compound layer at the surface (cf. Fig. 2b). In 34CrAlNi7 and 34CrAlMo5 samples, a less well-defined layer formed at the surface with nitride branches reaching deeper into the material (about 35 μm); also this nitride “layer” is free of porosities and cracks. The formation of grain boundary nitrides/ carbides was observed

in all steel grades. Oxynitriding showed no significant effect, but prior heat treatment in a reducing atmosphere showed promising results to avoid the formation of grain boundary nitrides/ carbides.

The 15CrMoV5-9 and 34CrAlNi7 steel grades were chosen for RCF testing and nitrided under the conditions mentioned above. However the samples were not heat

treated in a reducing atmosphere prior to nitriding. Non-destructive synchrotron X-ray diffraction stress analysis in energy-dispersive diffraction mode was applied in both axial and hoop direction to investigate the build-up and stress distribution of compressive residual stresses. In the first 100 μm accessible with this measurement technique, compressive stresses of about 500 MPa were observed.

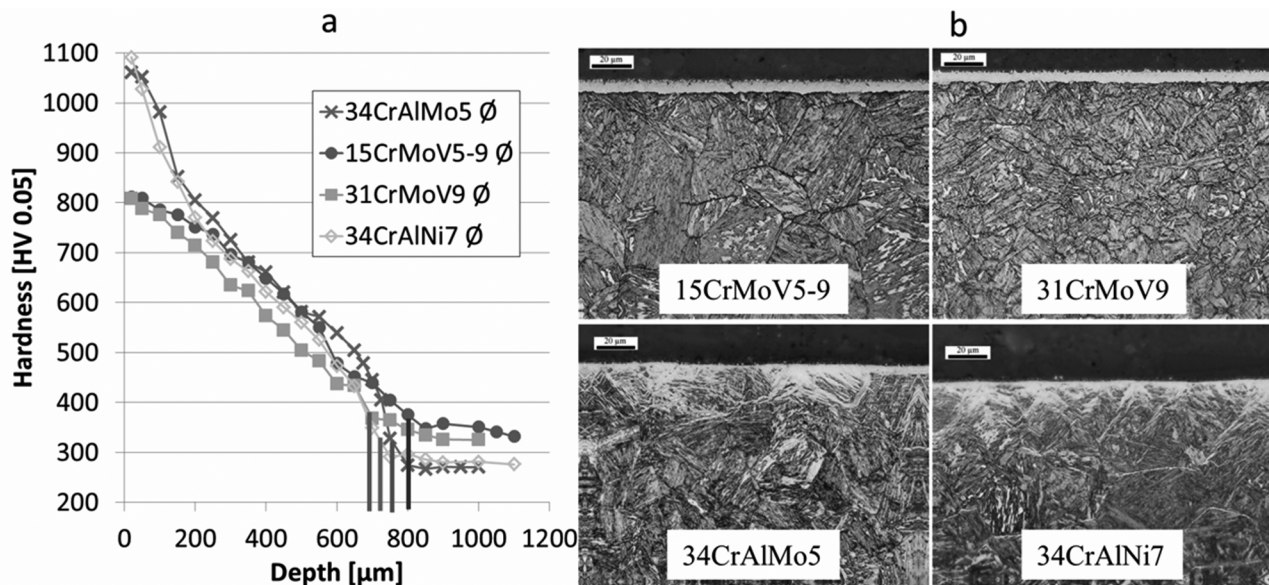


Fig. 2 a) Hardness profiles of the four different steel grades after nitriding (100h at 530 $^{\circ}\text{C}$, 1 l/min NH_3), average of the two sample sides; vertical lines mark the nitriding depths; b) nitral etched cross sections of the samples, scale bar is 20 μm , in the 15CrMoV5-9 and 31CrMoV9 a white compound layer is visible, in the 34CrAlMo5 and 34CrAlNi7 samples a white phase at the surface with branches into deeper regions can be observed

4 Rolling contact fatigue testing of surface engineered components

Rollers made from 15CrMoV5-9 and 34CrAlNi7 were chosen for rolling contact fatigue testing under conditions that are known to provoke WEC formation in a standard 100Cr6 through hardened steel^[13]. During the reference tests performed on 100Cr6 rollers many butterflies (crack-wings at non-metallic inclusions) formed in the sub-surface region (cf. Fig. 3a). In contrast, in both nitrided steel grades no WEC networks or butterflies were observed. Furthermore no crack initiation was observed at those grain boundaries that were considered potentially weakened by the presence of carbides/nitrides. The distinct compound layer that developed at

the surface of the 15CrMoV5-9 rollers, showed no cracking or debonding from the matrix (cf. Fig. 3b). On the other hand, in the 34CrAlNi7 rollers cracking and spalling occurred near the surface, in the region where branches of iron nitride reach deeper into the material (cf. Fig. 3c).

5 Conclusions

Complementary use of microscopic techniques can fill the gap between a good overview over the crack morphology achieved by RLM and SEM and the very local detailed picture of the WEA morphology achieved by TEM. ICCI (in combination with EBSD) provides a new means to investigate the WEC, and especially the WEA morphology.

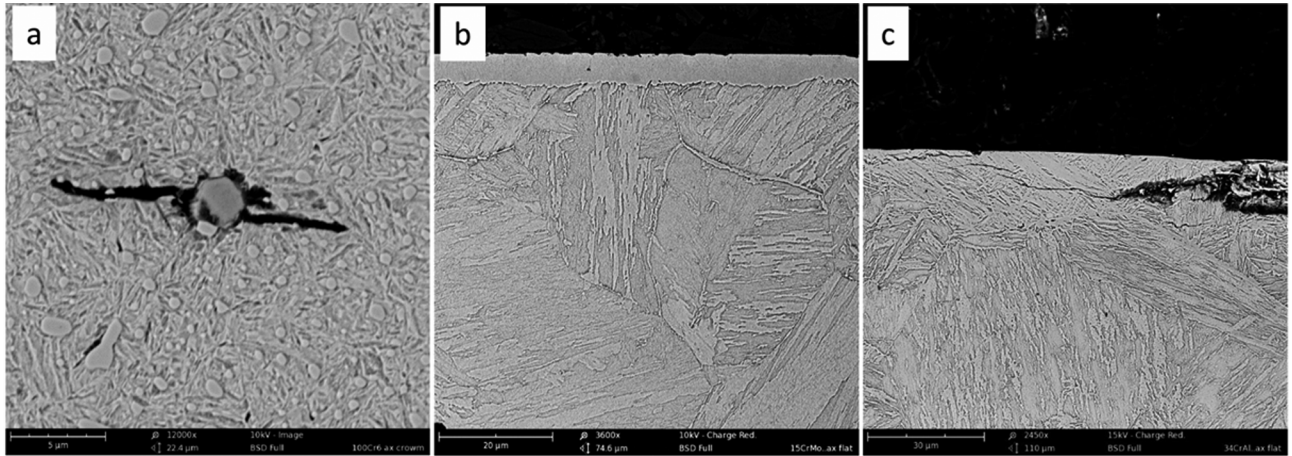


Fig. 3 SEM pictures of nital etched cross sections of RCF tested rollers: a) Crack wings forming at a non-metallic inclusion in the 100Cr6 rollers, b) Case of the 15CrMoV5-9 with the still attached non-porous compound layer and without any crack formation, c) Example of surface cracks and spallation in 34CrAlNi7 rollers

By deep nitriding, a nitriding depth approximately covering the depth of WEC formation can be achieved, without the formation of a thick porous compound layer. A hardness gradient developed and the build-up of compressive stresses in the case was confirmed. Prior heat treatment in reducing atmosphere showed promising results to prevent grain boundary carbide/ nitride formation.

After RCF testing no WEC or butterflies were found in the 15CrMoV5-9 and 34CrAlNi7 under conditions where 100Cr6 samples showed butterfly or even WEC formation in prior studies. Surface cracks and spallation were found in RCF tested 34CrAlNi7 rollers. Optimising the combination of alloy selection and nitriding parameters the near-surface morphology forming during nitriding can be tailored to potentially avoid crack formation. In this respect 15CrMoV5-9 rollers showed no debonding of the compound layer upon RCF testing, nor did cracks develop in grain-boundary nitrides/carbides. Under the applied test conditions, a thin non-porous compound layer and grain boundary nitrides/ carbides did not act as crack initiation sites as initially anticipated. Further testing is necessary to eventually evaluate the performance of nitrided components and their applicability as a

WEC failure remedy.

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