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# Influence of microstructure on retained austenite and residual stress changes under rolling contact fatigue in mixed lubrication conditions

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A B S T R A C T

The objective of this study was to understand how the near-surface microstructures of bearings are able to resist surface-initiated damage under rolling contact and mixed lubrication conditions. In the study, rolling elements were subjected to case-carburizing treatments to generate different microstructures containing from 20% to 30% retained austenite. The rolling elements, which developed either fine or coarse martensitic microstructures as a result of the heat treatment, were then subjected to rolling contact fatigue (RCF) tests. Those elements with a fine microstructure had nearly three times the life of those with a coarse microstructure. Retained austenite and residual stress were measured both before and after RCF at different depths below the contact surfaces.

In both types of microstructure, rolling contact-induced plastic deformation tended to significantly decrease the near-surface retained austenite content. Rolling contact also tended to produce an increase in compressive residual stresses in the subsurface fine microstructure. In contrast, the residual stress state in the coarse microstructure was changed by RCF from compressive to tensile. Such differences in the residual stress and amount of retained austenite in the microstructure clearly affected the elements' RCF life.

## 1. Introduction

The mechanical engineering components used in demanding applications must be as damage-tolerant as possible with high reliability. In addition to choosing the right combination of design, material and heat treatment for each application, the microstructure of the material must be tailored to resist mechanical damage. Roller bearings are key engineering components of rotating machinery; it is essential that the bearings be highly durable and reliable so they ultimately contribute to uninterrupted operation of the machinery. Investigational studies of how the bearing material's microstructure responds to the mechanical loads of its actual application and the material's resultant lifetime bring direct insights into the design and development of damage-resistant and highly reliable engineering components.

To make bearings more reliable and durable in demanding applications, their microstructure must be tailored to the application conditions [1]. One such case is bearings for wind turbine gear box applications. It has been extensively reported in literature that bearings in this application experience premature damage because of the development of cracks in the bearing steel [2,3]. After studying several field-damaged wind turbine bearings, it was found that case-carburized bearings with large amounts of retained austenite ($> 20\%$) deliver relatively high lifetimes in such applications [4].

In addition, it is well known that the retained austenite in bearing steel affords the steel longer life when wear debris is present in the lubricant [1,5]. The wear debris in bearing lubricants dents the surfaces of the raceways and rollers, and ultimately damages the bearing prematurely [5]. But the means by which the retained austenite and/or microstructural characteristics of case-carburized materials contribute to bearing durability have not been demonstrated.

Several researchers have consistently reproduced the crack damage found in wind turbine gear box bearings using laboratory scale test setups [6–11]. One of the common test conditions in all these investigations is that the bearings (or the steel) were tested under rolling contact fatigue (RCF) in mixed and/or boundary lubrication test conditions. In fact, because of associated low and drastically varying rotational speeds and dynamic loads, bearings of wind turbine gear boxes experience mixed and boundary lubrication conditions [2]. In these lubrication regimes, significant solid-solid contacts or surface asperity contacts exist at the rolling contacts [12]. In concurrence with this finding, in our latest studies of bearings tested under similar lubrication conditions, we observed surface-initiated damage on the rolling contacting surfaces [10,11]. In fact, even in bearings with dented rolling contacting surfaces, the surface damage significantly reduces bearings life [5].

Since high retained austenite in the bearing steel and case-

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carburizing heat treatment of bearing components are known to extend bearing life in these demanding application conditions [1,4,5], we life-tested tapered roller bearings (TRBs) made of case-carburized components in a mixed lubrication regime [13] under thrust load to examine how retained austenite and residual stress would respond to rolling contact fatigue (RCF) loads in the bearings. Case-carburized rolling elements with 20–30% retained austenite were incorporated into the bearings and tested. In addition, the rolling elements were heat treated differently to generate microstructural morphological variations. Two variations were produced: one fine and one coarse. The rolling elements were subjected to retained austenite and residual stress measurements at different depths both before and after RCF testing using X-ray diffraction (XRD), and further investigated by electron microscopy.

Few reports on changes of residual stress and retained austenite in laboratory-scale RCF tests are available in the literature [14,15]. These reports do not demonstrate microstructural changes in detail at different depths under RCF. In contrast to the previously reported results, this study sought to understand the role of microstructural constituents in bearing applications by directly measuring the microstructural changes before and after the bearing tests. Since the microstructural variations were induced only in the rolling elements, just the characterization results from the rollers are discussed in this manuscript. However, the discussed microstructure response to the RCF is found to be applicable to other bearing components as well.

## 2. Materials and methods

### 2.1. Bearing test parameters

Two different microstructures were obtained in the rolling elements and subjected to RCF loads by assembling them into separate bearings. To test these rollers in severe conditions (higher contact stresses), the test was modified to load the rolling elements higher than the load they were designed for. The test was modified by assembling fewer rollers per bearing. Because of the reduced number of rolling elements, post-RCF test examinations of the bearings revealed that at least one rolling element per bearing was damaged. This damage caused an increase in vibration from the bearing, which consequently stopped the test. The bearing tests were conducted in ISO VG68 mineral oil [13]. The applied contact stress on the rolling elements was around 2.2 GPa, and the test temperature was set around 80 °C. Surface roughness details of the bearing components were measured using a stylus gauge (Talysurf). The average surface roughness ($R_a$) of the raceways and rollers was about 100 nm. Averages of vertical distances between highest (peaks) and lowest (valleys) points measured on different rollers (called $R_z$) are around 950 nm; maximums of these vertical distances ($R_t$) measured on the different rollers are around 1.2 µm. Typical surface topographies on the rolling elements can be seen in SEM images, Fig. S1 of the supporting material. The bearings were rotated at a speed of 3500 rpm. Under these test conditions, calculated central and minimum lubricant film thicknesses (as per the Hamrock & Dowson equation [12]) were 166 nm and 123 nm respectively. Effect of the test temperature (oil inlet temperature) was considered in the lubricant film thickness calculation. These film thicknesses and the $R_a$ values at the rolling contact resulted in a lambda value (film thickness ratio) of 0.8–1.1. When lambda values in this range are obtained, a mixed or boundary lubrication condition exists [12] at the rolling contact.

### 2.2. Rolling element material and heat treatment

The rollers were made of a modified AISI 8620 grade steel with a composition (in wt%) of C: 0.2, Mn: 0.95, P: .013, S: 0.014, Si: 0.28, Cr: 0.72, Ni: 0.35, Mo: 0.1, Cu: 0.1, and Al: 0.02. As described in reference [16], fine and coarse microstructures were obtained by conducting the case-carburizing heat treatment in two different ways. As discussed in detail by Krauss in reference [16], a coarse microstructure morphology was obtained by carburizing at $> 950$ °C followed by quenching. A finer microstructure was obtained by repeating the reheating step on the carburized rollers, followed by quenching. The ranges of temperature and time were similar to those used by Krauss [16]. After the quench steps, all the rolling elements were tempered at 200 °C for 2 h.

### 2.3. Materials characterization

Materials were characterized by optical microscopy and scanning electron microscopy (SEM). Retained austenite and residual stress at different depths in the rolling elements were measured using XRD, as described in the ASTM standards [17,18]. A Proto Labs manufacturing XRD system (LXRD) having Cr K-α radiation, made for dedicated retained austenite and residual stress measurements, was used. Residual stress was measured in the direction tangential to the rolling contact surface ($\sigma_{11}$). The rollers were etched electrochemically to the required depth before conducting the XRD. Micro-hardness across the case region was measured using a Clark Instrument micro-hardness tester with a load of 500 g. The SEM used in this study was a FEI Versa 3D Dual Beam SEM equipped with scanning ion microscopy (SIM) and with focused ion beam (FIB) milling, scanning transmission electron microscopy (STEM) capabilities. In addition, the FEI Tecnai F30 TEM (300 kV) was used to characterize the microstructural damage. The TEM samples at the desired locations were prepared using the FIB technique.

## 3. Results

### 3.1. Microstructure and hardness characterization of the rolling elements

Figs. 1a and 1b, respectively, show optical metallographs of the coarse and fine martensite microstructures taken from the case regions of the rollers. The metallographs show a martensite phase (dark areas) in the retained austenite matrix (bright). As can be seen from the images, the martensite phase and RA islands are significantly coarser in Fig. 1a than in Fig. 1b. This difference can easily be seen in the respective SEM images shown in Fig. 1c (coarse) and 1d (fine). In the coarse microstructure, the RA islands are 2–10 µm in size, whereas in the fine microstructure, the RA islands are in the sub-micron range. In addition, careful observation of Fig. 1d, the fine martensite, shows nano-sized particles in the microstructure. These particles are iron carbides that were formed in the case region during the reheating and reaustenitizing steps [16].

To characterize the hardness differences between the two microstructures, Vickers micro-hardness was measured across the case regions. The obtained Vickers hardness numbers were converted into Rockwell hardness (HRC) and are shown in Fig. 2. As can be assessed from Fig. 2, the micro-hardness is nearly same for both the microstructures. In addition, prior austenite grain sizes were measured in both microstructures by deeply etching the prior austenite grain boundaries. Etching was done with a solution of aqueous picric acid plus 2% of wetting agent (sodium tridecylbenzene sulfonate). Metallographs of the etched grain boundaries are shown in Fig. 3a and 3b. The coarse microstructure's grain sizes ranged from 20 to 60 µm (Fig. 3a) and the fine microstructure's grain sizes ranged from 30 to 40 µm (Fig. 3b).

### 3.2. Bearing life results

The rolling elements with the coarse and fine microstructures were then fitted into different bearings and tested until damage occurred. A Weibull plot of the life test results is shown in Fig. 4. As can be seen in Fig. 4, the bearings fitted with the rollers containing a fine microstructure exhibited nearly three times longer life than the bearings with the rollers containing a coarse microstructure. The Weibull slope is nearly same for both kinds of microstructures, suggesting the same