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In-situ neutron diffraction and crystal plasticity finite element modeling to study the kinematic stability of retained austenite in bearing steels☆

Rohit Voothaluru[a,*], Vikram Bedekar[a], Qingge Xie[b], Alexandru D. Stoica[b], R. Scott Hyde[a], Ke An[b]

[a] The Timken Company, North Canton, OH 44720, USA
[b] Chemical and Engineering Materials Division, Spallation Neutron Source, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA

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ABSTRACT

This work integrates in-situ neutron diffraction and crystal plasticity finite element modeling to study the kinematic stability of retained austenite in high carbon bearing steels. The presence of a kinematically metastable retained austenite in bearing steels can significantly affect the macro-mechanical and micro-mechanical material response. Mechanical characterization of metastable austenite is a critical component in accurately capturing the micro-mechanical behavior under typical application loads. Traditional mechanical characterization techniques are unable to discretely quantify the micro-mechanical response of the austenite, and as a result, the computational predictions rely heavily on trial and error or qualitative descriptions of the austenite phase. In order to overcome this, in the present work, we use in-situ neutron diffraction of a uniaxial tension test of an A485 Grade 1 bearing steel specimen. The mechanical response determined from the neutron diffraction analysis was incorporated into a hybrid crystal plasticity finite element model that accounts for the martensite's crystal plasticity and the stress-assisted transformation from austenite to martensite in bearing steels. The modeling response was used to estimate the single crystal elastic constants of the austenite and martensite phases. The results show that using in-situ neutron diffraction, coupled with a crystal plasticity model, can successfully predict both the micro-mechanical and macro-mechanical responses of bearing steels while accounting for the martensitic transformation of the retained austenite.

1. Introduction

High-carbon steels with microstructures composed of tempered martensite, retained austenite (RA) and carbides are prevalent in rolling element bearing applications. It is well known that the presence of retained austenite enhances ductility through the transformation-induced plasticity effect (TRIP). This phenomenon has been studied in detail by Voskamp [1], who examined the effect of load and loading cycles on the gradual decomposition of retained austenite and its subsequent effects on induced residual stress. Voskamp observed that the maximum transformation of retained austenite occurs subsurface, followed by maximum compressive stress at the corresponding depth. Voskamp et al. [2] later found that retained austenite transformation is a very sensitive parameter during contact fatigue and could play a major role in the elastic shakedown, steady state and instability stages of service life.

Since the TRIP effect enables retained austenite to increase ductility, several studies have been conducted on enhancing the retained austenite kinematic stability. Garcia-Mateo and Caballero [3] postulated that to maximize the benefits of retained austenite, its stability should neither be too high nor too low. They hypothesized that retained austenite with relatively low stability transforms too early in service life, causing the beneficial effects of TRIP transformation to remain unrealized. It was further stated that the presence of highly stable retained austenite at necking does not enhance ductility.

Bakshi et al. [4] developed a nanostructured bainitic steel by accelerating carbon migration into retained austenite and found that wear resistance during rolling/sliding conditions can be increased by increasing the retained austenite's stability. The study found that its stability depends not only on the amount of %C dissolved in the austenite, but also its size. Further, Xie et al. [5] conducted an in-situ EBSD study on austempered steel to understand the influence of size and shape on

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* Corresponding author.
E-mail address: rohit.voothaluru@timken.com (R. Voothaluru).

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retained austenite stability. They found that film-like retained austenite transformed at a higher strain than the granular form. They created high-stability retained austenite by dissolving additional carbon and found that the retained austenite with higher stability gradually transformed through strain-induced martensitic transformation, which increased the work hardening index and delayed necking. Thus, it is well established that the mechanical stability of retained austenite is highly dependent upon chemistry (mainly its %C content), size and shape.

Blondé et al. [6] and Jimenez-Melero et al. [7] conducted very detailed thermo-mechanical studies of retained austenite stability using in-situ synchrotron radiations on TRIP and 52100 bearing steels. The authors reported the influence of temperature and load on retained austenite during uniaxial tensile testing. Their study on bearing steels was conducted on only one load (295 MPa). A study on bearing steels using continuous loading has never been conducted, and since strain partitioning between the different constituents of steel also plays a role [8], such a study will enhance the body of knowledge that could be directly applied in industrial applications.

In order to quantify the rolling contact fatigue life of bearing components, it is imperative to understand the onset, steady state and complete transformation of retained austenite. While there is consensus regarding the beneficial effects of stable retained austenite in the service life of a bearing, the extent of this kinematic stability is yet to be qualified or quantified. A case in point is the fact that most of the tensile tests conducted in the prior research are limited to bulk samples with two or more dependent variables. Most of these studies assume that the strains in the retained austenite phase were identical to the macroscopically measured strains in the bulk. There is limited understanding of the actual stress and strain values at the onset of retained austenite transformation for bearing steels. Due to the lack of data with regards to the single crystal elastic constants of the austenite and martensite phases, most of the analytical and computational modeling of bearing steels is based upon continuum formulations using effective stress and strain data from the bulk macroscopic volumes of the bearing steel specimens.

The use of computational models to characterize these micro-mechanical responses is incomplete because there are very few accurate material models that can describe the difference in micro-mechanical response between the two individual phases present in bearing steel. The primary reason for the limited data availability in the literature is that retained austenite, being a metastable phase, cannot be studied in a discrete and independent manner without high-end instrumentation such as synchrotron radiation or neutron diffraction. However, the development of and recent advances in neutron sources have greatly enabled discrete studies at the lattice level that can help in understanding the transformation behavior of individual phases during tensile [9], torsion [10] and cyclic fatigue [11] testing. Neutrons penetrate deeper into the substrate, allowing characterization at the subsurface level that cannot be achieved using any other non-destructive techniques. The advantage of neutron diffraction at the Spallation Neutron Source facility is that the data can be acquired in real time without interrupting the tensile test, thus avoiding stress relaxation following the loading cycle. Also, the beam size of the neutrons is in the range of a few millimeters, compared to the micrometer range utilized by a synchrotron source. Using neutron diffraction, austenite transformation can be monitored in real time and in situ, while lattice parameters and the stability of the austenite can be studied simultaneously. Until now, most of the neutron diffraction studies have been performed on TRIP, stainless steel and non-ferrous materials, and little progress has been made on hardened and tempered (58–60 HRc) bearing steels. In this study, a discrete and in-situ analysis of retained austenite transformation is conducted using high-carbon (1% wt) bearing steel and by employing a state-of-the-art engineering neutron diffractometer [10]. The study sheds light on deformation dynamics and transformation behavior based on the lattice strains experienced by the austenite and martensitic planes during continuous loading.

The ubiquity of bearings in industrial applications puts a greater emphasis on studying and understanding the potential micro-mechanical response in material microstructures. To achieve this, there is a need to develop computational models that can accurately model the micro-mechanical response of the individual steel phases. This will help in quantifying the elastic constants of the individual phases viz. retained austenite and martensite in bearing steels. Over the past decade, crystal plasticity finite element (CPFE) models have been successful in predicting micro-mechanical response and also in estimating the fatigue life or relative fatigue life of various polycrystalline microstructures. Recent advances in high-performance computing have helped significantly to enhance the use of CPFE models to predict both the short- and long-term effects of application loads in different representative volumes. Manonukul and Dunne [12] were among the first to use CPFE models to predict low cycle fatigue in nickel alloys. Several groups have developed fatigue initiation parameters (FIP) using CPFE models to facilitate a relative comparison between different application loads [13–15]. Recently, Voothaluru and Liu [16] used CPFE models to predict the micro-mechanical response and also the potential fatigue life of copper [17] and iron microstructures [18]. Alley and Neu [19,20] developed a hybrid crystal plasticity formulation to predict rolling contact fatigue life in high-carbon steels. Alley and Neu found that CPFE models can capture the macro-mechanical response of bearing steels very well. They also found that hybrid crystal plasticity models can accurately capture the effect of retained austenite on the macro-scale material response. Recently, Woo et al. [21,22] used CPFE models to predict the micro-mechanical response of individual ferrite and martensite phases in a dual phase steel. In order to successfully understand and model the micro-mechanical response of bearing steels, there is need to quantify the single crystal elastic constants of the material using CPFE models as they can successfully capture the lattice strain response with good agreement. So far, there has been little progress in the development of quantified material models for CPFE modeling of high-carbon bearing steels that account for transformation-induced plasticity. This is primarily due to the difficulty of mechanically characterizing the kinematically metastable retained austenite. As a result, the majority of the computational models handling bearings in the industry are still heavily reliant on continuum mechanics formulations. Continuum mechanics models and damage mechanics models, while computationally inexpensive, are not capable of accurately capturing the effect of the presence of heterogeneity in microstructures in bearing steels with multiple phase constituents.

In order to address this issue, we present an in-situ neutron diffraction based on an empirically quantified material model for CPFE modeling of multi-phase high-carbon bearing steel. The results of the lattice strain response from in-situ neutron diffraction were used to develop a material model for the bearing steel using CPFE modeling based on a hybrid constitutive formulation that was developed based upon the works of Asaro [23], Turteltaub and Suiker [24], and Alley and Neu [19]. The computational framework and modeling schema follow the works of Voothaluru and Liu [16]. The CPFE model was implemented using a user material subroutine (UMAT) in ABAQUS.

2. In-situ neutron diffraction – experimental details

2.1. Sample characterization

The sample used in the current study is a dogbone specimen of A485 Grade 1 (A485-1) steel, the composition of which is listed in Table 1. The samples were hardened at 850 °C followed by tempering at 180 °C for 1.3 h. The samples were water quenched after hardening. Microstructural characterization was carried out using scanning electron microscopy and was found to be composed of tempered martensite, retained austenite and carbides. The retained austenite content was estimated using X-Ray Diffraction and was found to be 18%. The %C

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