

Microstructural Contact Mechanics Finite Element Modeling Used to Study the Effect of Coating Induced Residual Stresses on Bearing Failure Mechanisms

Robert V. Petrach, David Schall, Qian Zou, Gary Barber, Randy Gu, and Laila Guessous
Oakland University

ABSTRACT

Coatings have the potential to improve bearing tribological performance. However, every coating application process and material combination may create different residual stresses and coating microstructures, and their effect on bearing fatigue and wear performance is unclear. The aim of this work is to investigate coating induced residual stress effects on bearing failure indicators using a microstructural contact mechanics (MSCM) finite element (FE) model. The MSCM FE model consists of a two-dimensional FE model of a coated bearing surface under sliding contact where individual grains are represented by FE domains. Interactions between FE domains are represented using contact element pairs. Unique to this layered rolling contact FE model is the use of polycrystalline material models to represent realistic bearing and coating microstructural behavior. The MSCM FE model was compared to a second non-microstructural contact mechanics (non-MSCM) model. Results show tensile residual stresses induced by the coating have a negative impact on the bearing performance indicated by the increase in subsurface localized plastic strains. The non-MSCM models predict higher amounts of plastic strain in relation to the MSCM models. One of the key benefits of the MSCM model over the non-MSCM model is the ability to predict crack growth and gap distance. The MSCM models show an increase coating crack gap distances due to tensile coating residual stresses. A detailed discussion of these results and the overall value of the developed model's methods and considerations are presented in this work.

CITATION: Petrach, R., Schall, D., Zou, Q., Barber, G. et al., "Microstructural Contact Mechanics Finite Element Modeling Used to Study the Effect of Coating Induced Residual Stresses on Bearing Failure Mechanisms," *SAE Int. J. Mater. Manf.* 7(3):2014, doi:10.4271/2014-01-1018.

INTRODUCTION

Intergranular related failures, such as micropitting and spalling, are fundamental failures for roller bearings and studying this phenomenon for different applications, manufacturing processes, and use of materials is of great interest. One method to minimize intergranular related failures and extend the life of bearing systems is to apply a coating to the contacting surfaces [1], [2], [3]. A number of researchers have studied the effects of specific coatings and processes on tribological performance and resistance to failure. Attempts have been made to correlate structural properties of hard surface coatings to their environmental resistance for various applications [4]. In a separate study, an investigation of the microstructural features of deposited wear-resistant titanium nitride coatings, showed that residual stresses vary due to processing and coating application methods in turn affecting the performance of the bearing itself [5]. Residual stresses induced by the coating or coating process can create localized increases in stress and strain. These observations further emphasize the demand for a better understanding of processing effects on bearing performance and highlight the

present interest in providing an understanding of the effects of coating residual stress and microstructure on failure mechanics. Many of these important effects are not currently represented in models of layered bearing sliding contacts.

In 2008, Nikas presents two works which show development of fundamental two-dimensional FE models of coated surfaces in rolling contact [6], [7]. The parameters chosen for study include coating thickness, elastic modulus, Coulomb friction, and endurance limit of the coated substrate. Nikas's fundamental models are realistic in that actual geometrical solids are used to model the rolling contact load distribution. However, the aim of these works was to present a comprehensive study of very fundamental modeling of layered rolling contact which could then be expanded to include additional elements of consideration by future research. Because of this these models are very simplified. Coating and substrate materials are modeled of homogeneous layers in which each material layer is considered an isotropic medium. Also, Nikas makes note of the paramount importance of other works which studied more complex phenomena, such as the effects of coating residual stress, but this is not considered in these simplified models.

The absence of these key components in Nikas's models greatly limits the application of such methods to bearing related failures.

The work presented in the present study expands on Nikas' work by including intergranular interactions. The idea that microstructure affects bearing life and wear performance has been a commonly accepted fact for many years [8], [9], [10], [11]. Recently, interest in the study of the microstructural features of coatings and how these features affect the wear resistance and bearing performance has increased [5]. For example rolling contact fatigue (RCF) itself is recognized as a microstructural problem in which much of the scatter and data variation observed in RCF test results has been attributed to variations in material microstructures [10]. The time-intensive nature of testing methods for RCF have lead to the development of finite element (FE) modeling methods for more efficient study of microstructural effects [12], [13], [14]. Examples include the work of Warhadpande in which the bearing's material microstructure was considered [12], [15]. Cohesive contact elements linking adjacent FE granular domains were used to simulate realistic microstructural behavior. This type of MSCM FE modeling has aided in understanding intergranular related bearing failures, such as spalling pattern formation. These types of microstructural FE models of bearing materials themselves are still rare, and use of these techniques to model coated bearing surfaces is even rarer.

Studying the effects of coating induced residual stress is another key expansion to Nikas's models presented in this study. The study of residual stress effects, as described separately by Khor[16], Camargo[17], and Fortuna[5], has grown in interest and value. Different coating processes combined with different coating materials and substrates can result in very different residual stresses due to thermal expansion mismatches. These residual stress changes have been shown to affect coating performance [16]. Khor, for example, investigated thermal cycling of different zirconium dioxide coatings. Certain coatings and methods that resulting in low residual stresses were shown to improve coating bond strength by as much as five times. The improved bond strength resulted in fewer imperfections.

The aim of this paper is to create a simplified model of sliding bearing contact while capturing the effects of microstructure and residual stresses on bearing contact related failure indicators. This research makes use of MSCM FE techniques to represent the bearing steel granular topography. Due to their tribological benefits and generally low cost, WC-Co coatings applied by thermal spraying techniques are also common to many studies [2], [3], [18]. Because of this, the coating microstructure and properties in this work are modeled after thermally sprayed tungsten carbide with cobalt coatings (WC-12% Co). The model was designed to provide information on the effects of coating residual stress on substrate stress distributions, subsurface localized plastic strains, and surface crack formation while under a simplified rolling contact loading

condition. The FE model used in this research was developed with the intent to be able to study the effects of coating residual stress on intergranular failure via localized plastic strains and cracking of a layered bearing section while under rolling contact. For comparison, a non-microstructural contact mechanics (non-MSCM) model with identical materials properties for the coating and substrate was also developed. In the non-MSCM model the coating and substrate are treated as isotropic media with no crystal grains. Further application of MSCM FE models should allow for ease in changing material microstructures and mechanical properties making this model an efficient tool for to simulating new coating material and process combinations. This flexibility has been the main driving factor for the research presented here.

The following section discusses construction of both the non-MSCM and MSCM FE models, and how the approaches of current FE models can be applied to surface coated materials. The next section describes the design of simulations to study the effects of coating residual stress on stress distributions, subsurface localized plastic strains, and surface crack formation followed by results and discussion.

MODEL DEVELOPMENT AND DEFINITIONS

Two models of layered rolling contacts were developed for this research: a MSCM model and a non-MSCM model. Both models are setup in the same manor. Each model consists of a semi-circular section of a roller element in contact with hard coating layer which is placed over a softer bearing race substrate. The radius of the roller element is 0.5 mm and the coating thickness is 20 μm . Both models apply the same bearing loading and residual stress boundary conditions, as well as display similar finite element definitions. The key difference between these models is the presence or lack of coating and substrate microstructures and contact element pairs to represent realistic granular interactions.

The following subsection describes the material modeling and contact mechanics specific to the MSCM FE model. The subsections to follow describe the finite element definitions and loading conditions which are similar between both models.

Microstructural Contact Mechanics Model

Modeling Material Microstructures

Recent MSCM FE models, as presented by Jalalahmadi [13] and Sadeghi [11], define the granular geometry by applying a method is known as Voronoi tessellations [19]. Voronoi tessellations are an efficient technique to break up a region into smaller polycrystalline geometries. Also results show that anisotropic properties of a polycrystalline material are represented to a good degree of accuracy from models using this type of grain geometry definition [20]. For this research, Voronoi functions in MATLAB® were used to generate grain vertices from a given set of random grain nucleation site coordinates. The generated grain vertices can then be used to

define the boundaries between grains. A more detailed explanation of the Voronoi tessellation technique can be found in works by Okabe and Boots [21].

Ultimately, the grain vertices, grain shape, and size variation greatly depend on the spacing between the randomly generated nucleation sites. For this developed model, the spacing of grain nucleation sites was controlled to give an output of grain vertices that more accurately represents the geometry of bearing steels. Most current finite element polycrystalline grain geometry models make similar consideration to control their grain geometry variation [15], [22], [23], [24]. After generating the grain vertices, this information was converted into a format that can be used in the FE software. The output from MATLAB® is a series of single grain vertices. For crack formation and relative grain sliding to occur, multiple coinciding grain vertices, in which a single vertex belongs to a single grain, are necessary. To format the MATLAB® output, any vertex shared by multiple grains was duplicated and defined to a specific grain. Formatting of the MATLAB® output was continued until each grain was defined as a separate grain area with its own set of grain boundaries and vertices, and the result was then imported into ANSYS®.

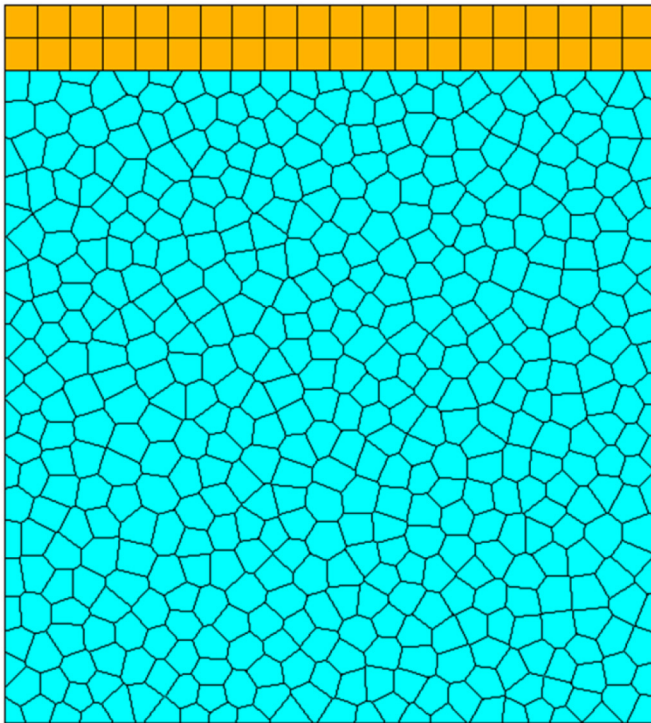


Figure 1. ANSYS® model of granular coating and bearing substrate microstructures.

Voronoi tessellations are appropriate for creating random polycrystalline structures similar to that of bearing steel materials. However, WC-Co coatings generally display a very block or tile like microstructure [5], [18], which would make use of Voronoi tessellations not appropriate. Because of this, specific characteristics as described in Stewart's, Usmani's, and Zhu's works were used to accurately model and represent a WC-12%Co thermal sprayed coating [1], [3], [25], [26]. The average

grain diameter of the bearing substrate is about 10 μm . Typical thickness for this type of coating is 20 μm . By accounting for these characteristics, a coating microstructure was constructed on the top surface of the granular bearing substrate. Figure 1 shows the final ANSYS® model with the granular bearing substrate geometry and tile like coating microstructure defined.

Contact Mechanics Definitions

To simulate microstructural interactions contact element pairs were defined along each grain boundary. This is component to the MSCM model which allows for intergranular failure, such as grain sliding and separation, to be simulated. A script was developed to automatically generate all the contact element pairs. These contact element pairs were defined in ANSYS® using the bonded style contact elements. This particular bonded style means that each contact pair acts like a set of flexible springs along the grain boundary, as shown in Figure 2. These springs can be represented as a normal and a tangential set of springs, which in turn account for the normal resistance (crack opening) and tangential resistance (grain sliding) type of grain interactions. With this contact element style the contact opening stiffness, or resistance to grain fracture, as well as the internal friction between grains can be controlled.

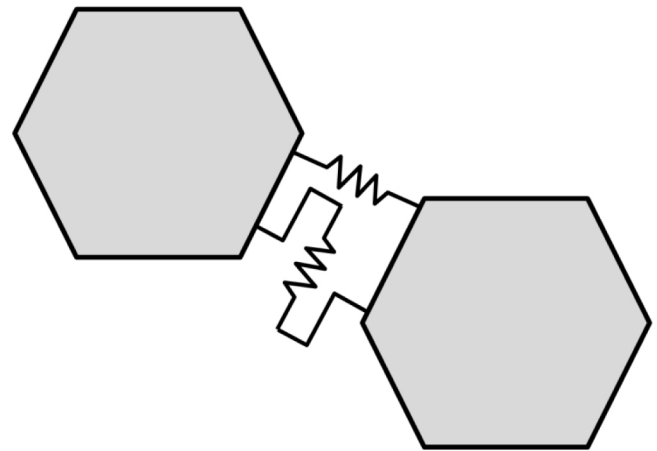


Figure 2. Representation of bonded style contact element pair. This shows the normal and tangential springs that represent the cracking and grain sliding resistance respectively.

For defining the contact parameters for the bearing material, research from Sfantos was used. This research shows that internal friction can play a critical role in the rate of crack propagation [27]. The internal friction coefficient chosen for this study was 0.4, which is consistent with that from Sadeghi and Jalalahmadi [11], [13], [28]. WC-Co coatings should have less tangential resistance to intergranular failure than the steel substrate since these coating materials are more prone to shear according to Ahmed's research [2]. The coating material has an internal friction coefficient of 0.1. Understanding of appropriate values for the cohesive normal spring stiffness, referred to as the contact opening stiffness in ANSYS®, is lacking from current granular material models. This is largely due to the difficulty with coupling systems to focus on the