Towards a Physics Based Foundation for the Estimation of Bearings RUL

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ABSTRACT

Rolling element bearing (REB) prognosis is the process of forecasting the remaining operational life, future condition, or probability of failure based on the acquired condition monitoring data. One of the common reasons for rolling element bearings failure is the rolling contact fatigue (RCF). Complete understanding of the fatigue process is critical for estimation of the bearing remaining useful life (RUL) and allows planning maintenance actions. In the current work, it is assumed that the spall generation, on the surface of the raceway, is a result of RCF. However, after the first spall formation, the bearing might be fully operational for millions of cycles. Thus, for the estimation of the bearing RUL it is also important to understand the damage propagation process. The proposed method of RUL prediction is separated into two steps: diagnostics and prognostics. The diagnostics includes characterization of the defect in terms of location, type, and extent. The prognostics includes estimation of the defect propagation as a function of time, using its characterization derived from the diagnostics step. It is expected that results of the current study will provide an estimation of the bearing's RUL: from first spall formation to the unoperational bearing. The spall generation process, as a result of RCF, is modeled based on continuum damage mechanics with representation of material grain structure and implemented using a Finite Element software. The results of the model are in a good agreement with published theoretical and experimental data. The paper also includes a discussion on the ongoing research and the methodology that will be implemented as part of it.

1. INTRODUCTION

Machinery diagnosis and prognosis is the forecast of the remaining operational life, future condition, or probability of reliable operation. It includes using the characterization of the machine or part of it, and its operational conditions, e.g. load estimation, in order to forecast the initiation and propagation of the defect as a function of time. A reliable prognostic can significantly reduce maintenance cost and workload, increase availability and enhance safety of the machine or its components.

One of the basic mechanical parts in rotating machines is the rolling element bearing. Bearings are used to allow relative motion between the shaft and the housing under conditions of mutual loading. Since bearings are widely used, their failure is a topic of great interest. One of the common causes of REB failure is rolling contact fatigue (RCF). Cyclic rolling contact with the rolling element (ball, cylinder, etc.) produces local damage that accumulates in the raceway of the bearing, initiating microcracks. The growth and coalescence of multiple microcracks forms a longer crack that propagates toward the surface. Once the crack reaches the surface, a spall is generated. Generally, the existing bearing life models, such as presented herein and other publications (Arakere et al., 2009, Harris & Kotzalas, 2006, Raje et al., 2009, Slack & Sadeghi, 2010, Warhadpande et al., 2012), relate to the time or load cycles required for a small spall formation and do not describe the subsequent damage propagation process. However, the REB failure is a two-stage process: damage initiation, i.e. spall generation; and damage propagation, i.e. spall growth. It is important to understand the damage propagation process, because after the first spall formation, the bearing might be fully operational for more than millions of cycles (Bolander et al., 2009, Branch et al., 2013, Marble & Morton, 2006, Morales-Espejel & Gabelli, 2015, Rosado et al., 2009).

The first part of the paper presents a concise introduction and description of a finite element (FE) based model for the analysis of the spall generation during the RCF process, with an emphasis on the microstructure and the damage evolution in the material. The current investigation will suggest a method for the damage initiation model assembly, towards a realistic representation of the grain topology and microscopic failure, using standard FE software tools. After the assembly of the model, several simulations of the spall generation were carried out and the results of the fatigue lives were found to be well represented as a two-parameter Weibull distribution. Finally, a comparison was made between the results that were obtained from the current work and previous publications. A full description of the model can be found in the paper published by Gazizulin, Klein and Bortman (2017).

Prediction of the damage propagation in the REB, after the first spall generation, is not an easy task. The main difficulties in prognosis of the propagation stage necessitate the deep understanding of the damage mechanisms, the stochastic nature of the spall propagation process and its modeling (Kotzalas & Harris, 2001, Li et al., 1999, Qiu et al., 2002). The main goal of the future research is to develop a physics-based prognostic method for the spall propagation in the REB by using a similar method as in damage initiation model. The achievement of the main goal, which is calculation of RUL for REBs, depends on the implementation of the research objectives and suggested methodology that are described and discussed in the second part of the paper.

2. DAMAGE INITIATION

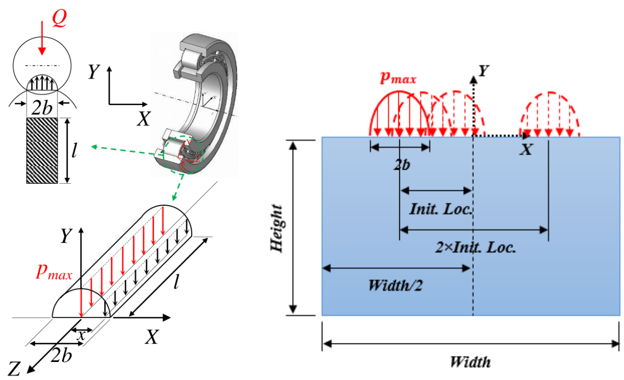
This section presents assembly and application of the damage initiation model for an ideal line contact, by using with the damage accumulation model for different grain topologies. The procedure of the model assembly includes three stages: contact loading, microstructure formation, and damage modeling. The contact between the raceway and the roller represented by the classic Hertzian solution (Harris & Kotzalas, 2006, Jackson & Green, 2005, Timoshenko & Goodier, 1984). The microstructure is represented by a Poisson Voronoi tessellation with variations in the material properties. The damage process is simulated using the elastic damage accumulation model, mostly based on the works published by Slack and Sadeghi (2010), and Warhadpande, Sadeghi and Kotzalas (2012). The three analysis stages were implemented using a FE software.

2.1. The Contact Model

While a bearing is loaded, a small contact area between the rolling element and the raceway is generated. The Hertzian solution for an ideal line contact in a cylindrical roller bearing was chosen to represent the contact area and surface traction distribution, as shown in Fig. 1(a). The surface compressive traction distribution $p(x)$ within the line contact area is given by

$$p(x) = p_{\max}\left(1 - \frac{x^2}{b^2}\right)^{1/2} \qquad (1)$$

where $p_{\max}$, b and x are the maximum pressure at the middle of the pressure profile, the half width of the contact area, and the local coordinate, respectively, illustrated in Fig. 1(a). Fig. 1(b) shows an area representing the rolling contact case between the roller and the raceway that was constructed using ABAQUS FE software with a plane-strain assumption. The Hertzian contact is set to be at initial location (Init. Loc.) from which it was advanced in discrete steps, assuming a quasi-static process, to the final position as shown in Fig. Fig. 1(b). The shear stress history $\tau_{xy} / p_{\max}$ was recorded at point beneath the surface during six load cycles; and the results are presented in Fig. 2. More details about the contact modeling can be found in the previously published work (Gazizulin et al., 2015).



a) b)

Figure 1. (a) Cylindrical roller bearing and equivalent model of two cylinders (1), and (b) the area that was used for the simulation of the rolling contact case.

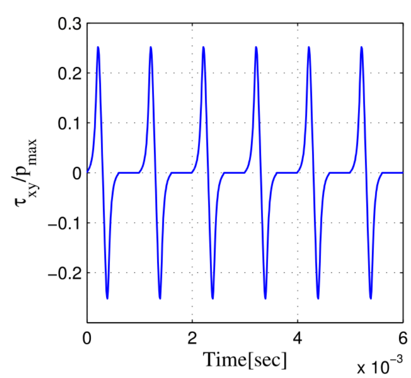


Figure 2. Shear stress history $\tau_{xy} / p_{\max}$ at point beneath the surface.

2.2. Poisson Voronoi Tessellation

Dealing with the system at the micro-scale level requires knowledge of the microstructure of the material and a physical understanding of the microstructural phenomena. The most common bearing steels have a polycrystalline structure (Bhadeshia, 2012) that can be represented by a Poisson-Voronoi tessellation (Meyer et al., 2003, Vena & Gastaldi, 2005, Weinzapfel et al., 2010). An example of the meshed area with a microstructure representation constructed by using ABAQUS FE software is presented in Fig. 3. It is noteworthy to mention that this process is random, so every simulation resulted in a different grain structure.

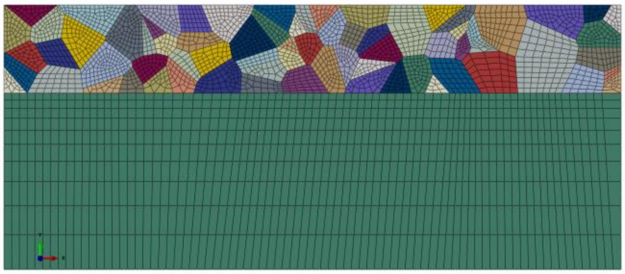


Figure 3. Area with the microstructure representation at the near-surface region. Each color in the area represents a different Young's modulus.

2.3. The Damage Accumulation Model

One microscopic mechanism of RCF damage is the formation and coalescence of microcracks. Continuum damage mechanics (CDM) provides a representation of these microscopic failure mechanisms by the definition of a nondimensional damage variable, D. It is assumed that the damage variable D affects the elastic modulus E of the material as

$$\overline{E} = (1 - D)E \tag{2}$$

where $\overline{E}$ is the damaged elastic modulus. The presence of the damage reduces the material stiffness (Chaboche, 1988, Marble & Morton, 2006). The damage variable D has values ranging from 0, which represents undamaged material, to D_{max}, which represents a completely damaged material, and its maximum value can be 1:

$$0 \le D \le D_{max} \tag{3}$$

The general form of the non-linear equation for damage rate evolution is

$$\frac{dD}{dN} = f(\sigma, D) \tag{4}$$

where N is the number of stress cycles and σ is the critical stress causing the damage. For RCF problems the critical stress is an orthogonal shear stress range $\Delta\tau_{xy}$ (Chen et al., 1991). If the material point undergoes a purely elastic damage, then the damage rate evolution is given by

$$\frac{dD}{dN} = \left[\frac{\Delta\tau_{xy}}{\sigma_r (1 - D)} \right]^m \tag{5}$$

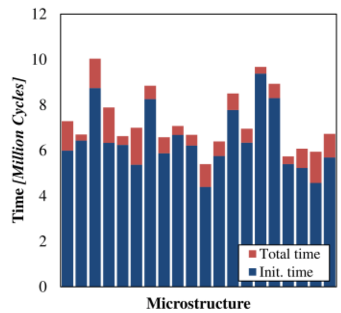
where $\Delta\tau_{xy}$ is the orthogonal shear stress range measured during the load cycles, and σ_r and m are material-dependent parameters that are empirically determined (Slack & Sadeghi, 2010, Warhadpande et al., 2012).

2.4. The Simulation Results

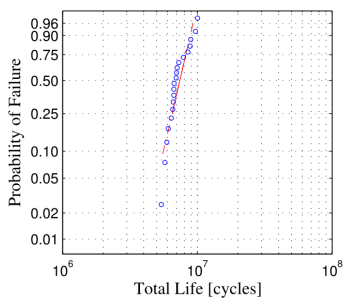
After modeling each of the physical properties and phenomena separately, all three were integrated in order to simulate the damage initiation process. The number of cycles elapsed until the first microcrack is termed the initiation time. Subsequently, the simulation continues via the generation of additional microcracks, which coalesce to form a crack. The crack propagates; and when it reaches the surface, it forms a spall. At this point, when the spall is generated, the simulation stops, defining the total time. More detailed description of the damage model algorithm can be found in (Gazizulin et al., 2017).

Twenty microstructures were constructed and the RCF process was simulated. The values of different coefficients and parameters are presented in (Gazizulin et al., 2017). The results of the fatigue lives and the corresponding Weibull probability plot are presented in Fig. 4. An example of crack initiation and propagation in the microstructure, and the representative spall pattern are presented in Figs. 5 and 7, respectively. As expected, the first microcrack initiated near the location of the maximum orthogonal shear stress, $y = -0.5b$, which corresponds to the experimental results achieved by Chen et al. (1991). From Fig. 4, it can be seen that the RCF process is dominated by the initiation stage, whereas the average duration of the propagation stage is only 12% of the total life. This result is consistent with the results obtained by Slack and Sadeghi (2010) and Warhadpande et al. (2012). The microcracks generated during the RCF simulations and the propagation process show good agreement with experimental observation described by Meyer et al. (2003) and presented in Fig. 6. The general shape of the spall obtained from the simulations is in good agreement with the results presented by Slack and Sadeghi (2010) and Warhadpande et al. (2012), and with experimental spallation (Fig. 7). However, each simulation resulted in a unique spall shape due to different grain topologies and variation in the material properties.

Bearing fatigue lives are stochastic in nature; therefore, it is very common to use the Weibull distribution to describe the fatigue lives of bearings. The results of the total time are displayed on the Weibull probability plot in Fig. 4(b), where the slope, β, is 5.77. According to Harris and Kotzalas (2006), for modern, ultra-clean, vacuum-remelted steels, the values of the Weibull slope should be $0.7 \le \beta \le 3.5$. The achieved slope, $\beta = 5.77$, is outside this range. The difference can be explained by the simplifications in the assumed material properties. In order to summarize the work that has been done here, and to make a comparison with previous publications, Table 1 is presented. It includes the results, Weibull slopes based on the two-parameter Weibull distribution of the current model and previously published works. The achieved slopes, for the initiation and the total time, are very close to the results of most models presented in Table 1.



a)



b)

Figure 4. (a) Fatigue lives of 20 different material microstructures and (b) Weibull probability plot of the total time.

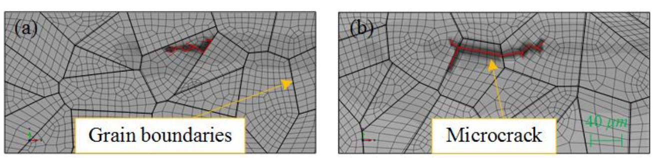


Figure 5. Microcracks generated during two different RCF simulations. Two different microcrack propagation processes are presented: (a) The microcrack stops advancing and (b) it propagates into an adjacent grain.

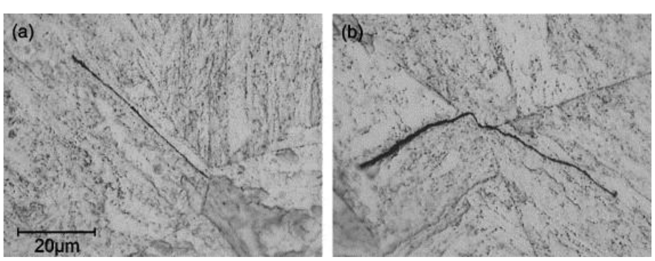
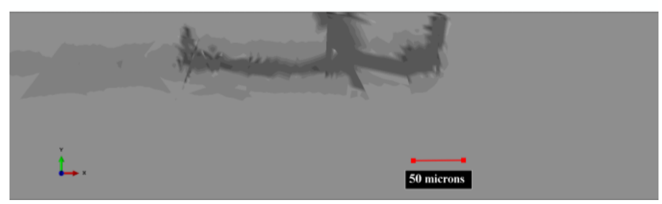


Figure 6. According to Meyer et al. (2003) and other publications (Ahmadi & Zenner, 2005, Andersson, 2005), microcracks initiate and propagate mainly inside the grains.

Table 1. Results of the different RCF models for of the bearing material (AISI 52100 steel) with $p_{max} = 2GPa$. Different assumptions of the models are presented in the column 'Model description', by the following abbreviations: HM - homogenous material, NDS - normally distributed stiffness, ED - elastic damage, EPD - elastic-plastic damage, SSD - spring stiffness damage.

Model	Model description	Init. time Weibull slope	Total time Weibull slope
Raje et al. (2009)	NDS, SSD	-	1.61
Slack and Sadeghi (2010)	HM, ED	7.15	12.54
Jalalahmadi and Sadeghi (2010)	HM, ED	5.11	4.08
	NDS, ED	4.89	3.37
Warhadpande et al. (2012)	HM, ED	4.81	5.13
	HM, EPD 1	4.89	6.52
	HM, EPD 2	4.81	6.58
	NDS, EPD 1	-	4.97
Current model	NDS, ED	4.99	5.77



a)

b)

Figure 7. (a) Spall pattern received from one of the RCF simulations and (b) a section of the spall observed in experimental analysis (Slack & Sadeghi, 2010, Warhadpande et al., 2012).

3. DAMAGE PROPAGATION

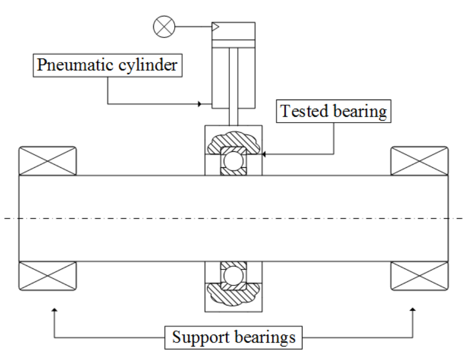
Thus far, a damage initiation model has been presented in order to simulate spall generation process in the REBs. The model is based on physical principles, producing statistically distributed results. However, modeling of the damage initiation process was only the first step toward the estimation of the RUL. After the damage initiation, e.g. spall formation, it propagates until the bearing becomes unoperational. The achievement of the main goal, which is calculation of RUL for REBs, depends on the accomplishment of the research objectives and methodology that will be described in this section.

3.1. Objective 1: Physical Understanding of the Damage Propagation Process

The first objective is the quantitative and qualitative understanding of the damage-driven mechanisms, e.g. plastic strains, residual stresses, etc., of the spall propagation process (Bolander et al., 2009, Branch et al., 2009, Marble & Morton, 2006, Morales-Espejel & Gabelli, 2015). In addition, it is important to acquire knowledge, based on the existing literature and experiments, about the effect of the bearing's features (e.g. hardness, ball mass), operational conditions (e.g. speed, load) on the propagation process and the trend of the spall growth (Arakere et al., 2009, Branch et al., 2013, Morales-Espejel & Gabelli, 2015).

In order to achieve this objective an experimental setup was designed (Fig. 8) and endurance tests were conducted. The tests add an insight about the spall propagation process and can be used for the physical model calibration, i.e. estimation of the model parameters, and later for validation. Examples of the test results are shown in Figs. 9 and 10.

a)



b)

Figure 8. a) The experimental setup for the endurance tests and its b) schematic.

a) b)

Figure 9. a) Artificial defect located in the outer race of the tested bearing. b) The spall that was generated in vicinity of the artificial defect after 55 hours of test run.

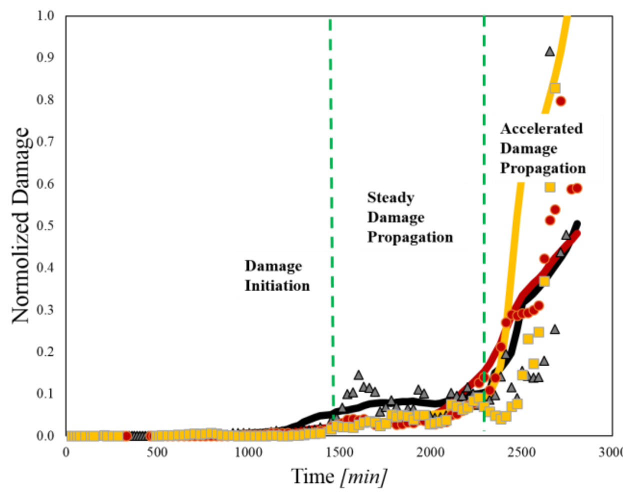


Figure 10. This data illustrates the damage evolution trajectory during the endurance test. Each data point correspond to the vibration measurement during the test.

3.2. Objective 2: Damage Propagation Model

The second objective is the model development to describe and predict the damage propagation process. After the completion of the first objective, we will be able to build a damage model based on physical principles. Next, will be required to assemble a bearing model with a simulated spall. The model will be used, in addition to the estimation of the bearing dynamic response in the presence of defect, for evaluation of the developed stress/strain fields. A dynamic model of a faulty ball bearing has been recently developed by Kogan et al. (2015). It was verified and validated by comparing its results to analytical solution and empirical test results. The dynamic model enables a better understanding of the physical behavior of the faulted bearings. The results of this model and stress/strain analysis will be used as an input to the damage model which can be implemented by using a FE software. The damage and the bearing models will be integrated to simulate the spall propagation process. Accomplishment of this objective, will provide a mean estimated damage trajectory. However, the damage propagation is a stochastic process. Hence, the results will have some degree of uncertainty. Which brings us to the next objective, discussed in the next subsection.

3.3. Objective 3: Stochastic Nature of the Damage Growth Process

The propagation of the spall in the REB is a highly variable process. Even under well controlled experimental conditions, using allegedly identical bearings, the results of the endurance tests will be different (Rosado et al., 2009). In the RUL estimation the uncertainties and their propagation have to be taken into account. Thus, the third objective of the research, and probably the most challenging, is the description/modeling of the stochastic nature of the damage propagation. One of the common methods for dealing with the challenge is by using diagnostic condition indicators in the early stages of the damage in order to monitor its propagation, e.g. oil debris, vibration level, etc. An example of a diagnostic indicator time history based on vibration data is shown in Fig. 10. Also, in our laboratory we have a diagnostic tool for the spall width measurement via time domain analysis of the acceleration signature (Kogan et al., 2016). The data from diagnostic indicators will be used for the estimation of the damage model parameters by the trend identification of the spall propagation process. Afterward, using the adjusted model parameters to the specific spall propagation process in the damage model, the RUL will be estimated. It is important to understand, that the measured data will be dispersed around the trend with some variance. Thus, in addition to the RUL estimation, its distribution should be determined. The RUL process estimation is schematically illustrated in Fig. 11. The accomplishment of this goal will complement the development of the physics-based prognostic method.

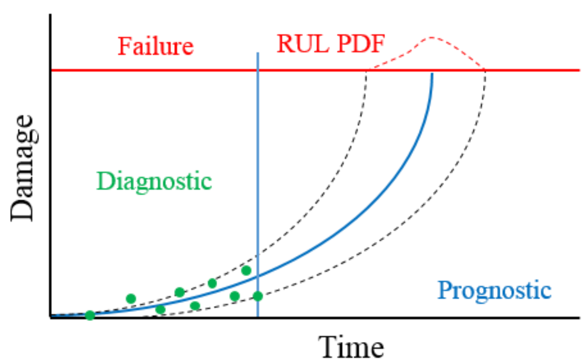


Figure 11. Bearing prognosis: first the damage propagation process is monitored, the model parameters are estimated and the RUL is calculated.

4. METHODOLOGY

The proposed methodology for the development of the prognostic method is based on a combination of physics-based models, diagnostic methods and experiments. This approach consists from procedures and techniques which described below. The spall initiation process, described previously in this paper, was successfully implemented and verified using the FE software ABAQUS. The propagation process also might be implemented in a similar way by including the input of the bearing geometry with embedded spall. The FE and dynamic models (Kogan et al., 2015) of the bearing can yield the dynamic response, stress and strain histories of the spalled bearing, that later can be used as input for the damage propagation model. Furthermore, the spalled bearing model might be used for the validation of the diagnostic method for the damage severity estimation.

Calibration and Validation of the spalled bearing model can be implemented by comparing the simulations results with the data extracted from endurance tests. For example, a diagnostic method for the defect severity estimation (fault size, vibration level, etc.) can be implemented during the first stages of the tests. The results obtained by the diagnostic method can be used for the estimation of the damage model parameters and their uncertainties. Then, the integration of the prognostic and the diagnostic methods, has the potential for the online estimation of the RUL including probability distribution of the result. Fig. 12 illustrates the integration of different steps described above for the REB's RUL estimation.

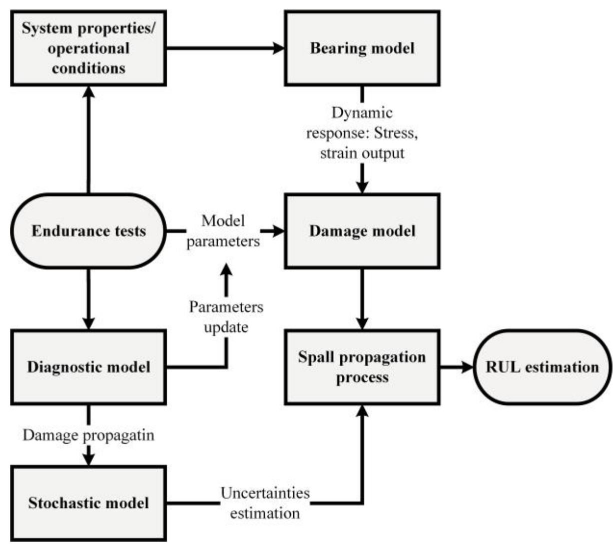


Figure 12. Research flow chart describing the steps toward the development of the RUL model.

5. SUMMARY AND CONCLUSIONS

A process has been presented for developing and implementing a damage initiation model representing spall generation in REB during RCF. The procedure of the model assembly comprises three stages: contact, microstructure, and damage modeling. The contact is modeled using the Hertz solution; the microstructure is represented by a Poisson Voronoi tessellation; and the damage accumulation model is based on CDM. Model implementation was carried out using standard tools of the FE software, i.e., meshing process, damage representation, etc. The spall patterns achieved from the simulation are in a good agreement with previously published work and what has been observed experimentally. As well, the results indicate that the spall generation is dominated by the initiation stage. The resulting Weibull slopes were similar to those achieved in previous works, but larger than the typical values for modern bearings. This could be a result of the simplifying assumptions made in relation to the material behavior. The paper also suggests a methodology for the REB's RUL estimation. It includes understanding and implementation of different steps: endurance tests, physical understanding of the spall propagation process and its stochastic nature, damage and bearing modeling, etc.. Eventually, accomplishment of these steps will help to build a prognostic tool.

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Dr. Renata Klein received her B.Sc. in Physics and Ph.D. in the field of Signal Processing from the Technion, Israel Institute of Technology. In the first 17 years of her professional career, she worked in ADA-Rafael, the Israeli Armament Development Authority, where she managed the Vibration Analysis department. In the decade that followed, she focused on development of vibration based health management systems for machinery. She invented and managed the development of vibration based diagnostics and prognostics systems that are used successfully in combat helicopters of the Israeli Air Force, in UAVs and in jet engines. Renata is a lecturer in the faculty of Aerospace Engineering of the Technion, and in the faculty of Mechanical Engineering in Ben Gurion University of the Negev. In the recent years, Renata is the CEO and owner of R.K. Diagnostics, providing R&D services and algorithms to companies who wish to integrate Machinery health management and prognostics capabilities in their products.

Prof. Jacob Bortmann joined the academic faculty of Ben-Gurion University of the Negev in September 2010 as a full Professor. Prof. Bortman spent thirty years in the Israel Air Force (IAF), retiring with rank of Brigadier General. His areas of research in the Dept. of Mechanical Engineering include: Health usage monitoring systems (HUMS); Conditioned based maintenance (CBM); Usage and fatigue damage survey; Finite Element Method; and Composite materials.