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Parametric study on stressed volume and its application to the quantification of rolling contact fatigue performance of heterogeneous material

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ABSTRACT

This research explores the influence of distributed inhomogeneities and surface asperities on the stressed volume of heterogeneous material in contact with a sphere. The recently developed modeling method for solving rough-surface contact problems involving distributed inhomogeneities, incorporated with FFT algorithms and a mesh differential refinement scheme, is utilized. The effective stressed volume, quantitatively described by effective depth, length and width, is investigated to characterize the rolling-contact-fatigue influence zone in heterogeneous material. Furthermore, a parametric study is conducted for the influences of inhomogeneity distribution and surface roughness on volumetric stress integral in order to understand the rolling contact fatigue performance of particle-laden inhomogeneous materials.

1. Introduction

Rotating mechanical components, such as bearings, are widely used in mechanical transmission systems to allow rotary motion and support significant cyclic load. Rolling contact fatigue (RCF) is a main failure mode for bearings and other rotating mechanical components. Many RCF empirical and analytical models have been developed and proposed over the past few decades [1]. The most representative models for predicting RCF life of bearings were proposed by Lundberg and Palmgren [2], Ioannides and Harris [3], Zaretsky [4], which can be categorized as probabilistic engineering models. On the contrary, the models presented in Refs. [5,6] belong to deterministic research models developed based on physical principles and with taking into account the actual mechanics of failure process.

An important concept involved in probabilistic RCF models is stressed volume, whose root can be traced back to the research work by Weibull [7]. The material strength was related to the volume of the material subjected to stress through specific equation in his work. Lundberg and Palmgren [2] further gave the formula definitions for the stressed volumes for point and line contacts, respectively. The stressed volume V was quantified by raceway contact diameter d, the length of the running track l_t and the depth of the critical shear stress z, i.e., $V=dl_tz$, when Hertzian contact theory was applied. The model proposed by Lundberg and Palmgren became the basis of the first ISO standards for bearing life used in the industry [8] and has been extensively used. Nevertheless, Harris and Yu [9] pointed out that the stressed volume utilized by Lundberg and Palmgren to encompass rolling contact fatigue failures does not show the real zone of stress influence. The actual influenced depth should be much larger. Besides, the Lundberg-Palmgren model, as well as the stressed volume, were associated with the stress of a single point rather than the subsurface stress distribution. The integrated effect of subsurface stress distribution on fatigue endurance should be considered, as suggested by Ioannides and Harris [3]. Moreover, the above mentioned stressed volume can only be applied to rolling contact analysis of homogeneous materials.

Materials involved in contact behavior are traditionally assumed to be homogeneous. However, in engineering practice, a second-phase material with different properties can always be observed in the matrix. For instance, large nonmetallic inclusions may be introduced into metal components due to faulty manufactures; fibers, whiskers, or particles are designed to reinforce composite materials to achieve high strength and stiffness. Those second-phase materials, can be termed as inhomogeneities according to the definition of Mura [10], inevitably exist at arbitrary locations in many engineering materials. They can produce disturbances to the elastic field at both the local and global scales. Therefore, the determination of stressed volume for hetero-

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geneous contact must be quantitatively examined in order to better understand the roles played by inhomogeneities in the RCF performance.

The modeling of the influence of inhomogeneities on the elastic field of materials was explored by many research works. The well-known equivalent inclusion method (EIM) proposed innovatively by Eshelby [11,12] was widely used to solve heterogeneous stress field due to the existence of inhomogeneities distributed in a full-space [13–15]. The conventional EIM can only deal with ellipsoidal-shaped inhomogeneities in an infinite medium applied with a uniform load. Nevertheless, taking the advantage of the cuboid inclusion solution proposed by Chiu [16], the EIM can be extended to arbitrarily shaped inhomogeneities [17]. The EIM is further introduced to solve heterogeneous contact problems, which should be analyzed in a half space, with the superposition scheme based on the method of images [18]. Representative work utilizing the improved EIM includes the fast method proposed by Leroux et al. [19] to study the effects of spherical inclusions on the contact pressure distribution and subsurface stress field in an elastic half-space; an efficient approximate numerical method for exploring the influence of distributed non-interpenetrating inhomogeneities on the contact of inhomogeneous materials [20] and RCF life of composite [21]; an updated superposition approach enables higher computational efficiency for partial-slip contact involving materials embedded with inhomogeneities by Wang et al. [22]. The method of images may induce numerical truncation errors for near-surface inclusions. A direct method capable of solving the elastic fields caused by a cuboidal eigenstrain was proposed by Liu et al. [23], and the complete set of integral kernels to express the elastic field caused by eigenstrain was derived. Further, the solution method by Liu et al. [23] was introduced to our recent work [24,25] to study the rough-surface contact problems involving distributed inhomogeneity with arbitrary shapes.

The RCF performance of an engineering material is greatly effected by arbitrarily distributed non-metallic inhomogeneities [26]. Moreover, the consideration of surface roughness surely increases the complexity when solving elastic field disturbance for heterogeneous materials. In our recent work [25], a mesh differential refinement scheme, consist of independent surface, source, and target computational domains, was developed to enhance computation efficiency and flexibility. After that, a numerical solution method, incorporating with 3D fast Fourier transform (FFT) techniques and the mesh differential refinement scheme, was proposed for solving the contact with a smooth or rough surface involving distributed inhomogeneities [24]. The method was then introduced to predict the RCF lives of composite materials taking the benefit of the dual-beam focus ion beam scanning electron microscopy (FIB/SEM) technique [27]. In the present study, however, the recently developed numerical method is employed to quantify the stressed volume for identifying the influence scope of contact loading on a heterogeneous material, which is critical for the computation domain determination with considering inhomogeneity effect. Further, the focus is given to the parametric study on the effect of distributed inhomogeneities and surface asperities on the volumetric stress integral of materials. The obtained result is expected to be beneficial to better understanding the influences of non-metallic particles and surface characteristics on the RCF lives of rotating mechanical components.

2. Analytical procedure

The employed numerical solution method for predicting the RCF lives of heterogeneous material under a rolling contact load was developed in our recent work [27], which is briefly summarized here for clarity. The selected computation domain is numerically discretized firstly. The mesh differential refinement scheme [25], as demonstrated in Fig. 1, is integrated for the present solution method. The solution method is composed of two parts, i.e., numerical solution for rough-surface heterogeneous contact and RCF prediction model based on the computation result of the former part. Fig. 1 gives the basic flowchart of the numerical solution. Four main steps are involved to determine the disturbance in the elastic field caused by subsurface inhomogeneities and surface asperities. They are:

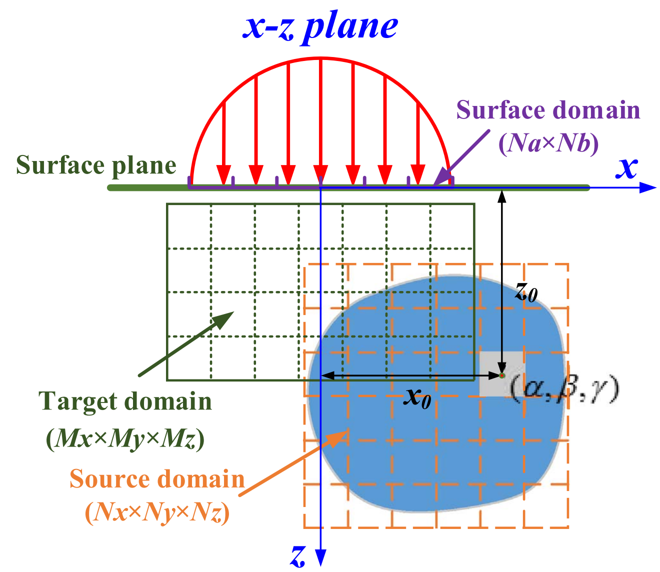

Fig. 1. Numerical discretization of computation domain and the mesh differential refinement scheme.

1) Solving the surface pressure for rough-surface contact. A system of contact equations and inequalities used for describing load balance, surface deflection, contact body gap and contact compatibility is solved for the elemental pressures on contact surface. The conjugate gradient method (CGM) [28] is employed for fast solutions based on homogeneous-contact assumption. Readers may find more details in Ref. [28].
2) Solving the elastic field induced by surface pressure. FFT algorithms, including a 2D discrete convolution and fast Fourier transform (2D DC-FFT) algorithm and a 2D layer-by-layer FFT algorithm [29], are introduced to accelerate the computation of surface deflection and stress distribution beneath the surface, respectively. The influence coefficients relating surface deformation and subsurface stress to surface traction are demonstrated in detailed in Refs. [30,31].
3) Determination of the eigenstrains distributed in equivalent inclusions. The numerical EIM developed in our recent work [24] is implemented on all elementary inhomogeneities under consideration to compute the eigenstrains within the inclusions, which can equivalently replace the influence caused by inhomogeneities. A iterative scheme with stress or strain components represented in terms of Dundurs parameters [32] is adopted to implement the numerical EIM.
4) Calculating the surface displacement caused by eigenstrains. The explicit solutions for the surface deformation produced by subsurface equivalent inclusions are given in Ref. [33]. A 2D DC-FFT algorithm can be applied between the subsurface domain enclosing all the inclusions under consideration and surface computational area in a way of layer-by-layer. The obtained surface deflection are then used to update the contact surface geometry.

The above four steps constitute a loop, which stops when the eigenstrain-surface deformation interactive process gets convergent (Fig. 2). The elastic field caused by distributed inhomogeneities and surface asperities can be solved by the direct analytical method proposed by Liu et al. [23]. Full 3D FFT algorithms can be incorporated