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A review of rolling contact fatigue behavior of silicon nitride focusing on testing practices and crack propagation analysis

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ABSTRACT

Experimental and numerical analyses of the lifetime and crack propagation behavior of silicon nitrides under rolling contact fatigue (RCF) loading are surveyed. Intercomparison of four major test methods for RCF, namely balls-on-flat (BOF), balls-on-rod (BOR), two-roller, and four-ball configurations, are performed. The differences in the implications of the test results between the first three methods, are explored by using a test specimen made of material from the same production batch. With an understanding of the differences, the influences of variables such as the state of lubrication and surface roughness on RCF behavior is discussed. The influence of mechanical properties of test materials is also discussed in chronological order to trace the history of trends in the material development of silicon nitrides. Crack growth models based on observation results of propagation from an artificially induced crack, semi-elliptical or partial ring crack, are comparatively discussed along with the results of numerical analysis for more simplified initial crack models. An observational study of propagation behavior from a natural flaw is also addressed. Finally, future work to improve the reliability of ceramic bearings is discussed.

1. Introduction

More than two decades have passed since ceramic elements were put to practical use in bearings. Hybrid ball bearings, made of steel raceways combined with silicon nitride balls, have come into use in some machinery such as wind power generators [1] and machine tools [2]. Silicon nitride rolling elements have distinct advantages over steel ones in such applications. For example, the superior insulation capability of silicon nitride prevents electric pitting, resulting in a longer lifetime of bearings, hence contributing to long-term maintenance-free operation in a wind power generation system. The reduced centrifugal forces stemming from their light weight enable suppression of the temperature increase, thereby contributing to the improvement of machining accuracy in a machine tool. These advantages could be exploited for rolling bearings in new generation vehicles such as electric vehicles (EV) and fuel cell vehicles (FCV), and even those in rotorcraft [3,4], where a reduction in weight is one of their vital factors. The usage of silicon nitride is, however, extremely limited compared to the overwhelming market size of bearing steel. To further expand the application of silicon nitride to rolling elements, an understanding of their rolling contact fatigue (RCF) behavior and precise lifetime prediction methodology is necessary as well as cost reductions in manufacturing processes such as near-net-shape sintering and precision machining to produce a finish without any remaining subsurface damage. To estimate the lifetime of bearings, RCF test data of materials should be analyzed by a probabilistic approach and an accumulation of significant amount of fatigue test data is therefore required. Attention should be paid, however, to the fact that the physics in RCF tests are not identical to those in actual rolling elements of bearings, because all phenomena found in ball bearings cannot be reproduced perfectly in the fatigue tests due to the inevitable differences in conditions such as loading configuration and lubrication from those in real bearings. Nevertheless RCF data has been emphasized in understanding the material behavior in long-term use of real bearings. In the steel ball bearings community, the well-established Lundberg-Palmgren theory and its derivatives have been widely used in the analysis of an incomparably large amount of data on lifetime. Comparative reviews of those theories and the analysis results thereof were made by Zaretsky [5,6] and analytical and empirical fatigue models were compiled by Sadeghi [7].

Meanwhile, the pioneering research work on application of glass ceramics to bearings by Zaretsky was carried out more than 50 years ago [8]. Silicon nitride, manufactured by hot-pressing or flame spray, was first applied to floating bearings by Dee [9]. In the 1970s and the 1980s, hot-pressed or reaction-bonded silicon nitride was tested in anticipation of its use in bearings for the main spindle having a high DN, the product of the spindle diameter (D) and the number of revolution per minute (N), in a machine tool [10–13]. Those materials did not always have superior RCF performance compared to bearing steel. Under some conditions,

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contradictory behaviors were observed between hot-pressed materials. In 1975, Zaretsky pointed out that RCF performance is influenced by the presence of impurities at grain boundaries as well as the surface finish of specimens through comparison between hot-pressed silicon nitride manufactured in early 1970s and state-of-the-art materials at that point [14]. Comprehensive survey on the studies on silicon nitride for bearings up to the late 1980s was also provided by his review [15].

In the late 1980s, applying hot isostatic pressed (HIP) silicon nitride to rolling elements were started and literature on those investigations appeared in the early 1990s [16,17]. Investigations of hybrid bearings for aircraft gas turbine engine, where high reliability is of primary importance, was fully launched and presumably studies of the RCF behavior of silicon nitride were commenced. Fundamental research on crack propagation behavior during an RCF test was carried out using various types of test configurations from the late 1980s to the early 2000s [18] along with the evaluation of full scale ceramic bearings life. Even though there were a couple of national projects for ceramic material development [19,20], where the improvement of wear resistance was one of their goals, applying silicon nitride to rolling elements was unfortunately not listed explicitly as the purpose of those projects.

Around the year 2000, with the expansion in the range of use of hybrid bearings for turbochargers [21] and hard disk drives [22], the need for standardization of the bearings were growing significantly in the industry, especially in bearing manufacturers in the US. The first industrial standard on ceramic bearings is ASTM F2094/F2094M-14 [23], "Standard Specification for Silicon Nitride Bearing Balls." Exceptionally in this standard, however, the specifications of balls and those of ceramic materials, which should have been issued in a separate standard, are consolidated. In the subsequent standardization activity in the International Organization for Standardization (ISO), a material standard ISO 26602 [24] and a product standard ISO 3290-2 [25] were issued separately in 2009. To complement these standards, a test method for rolling contact fatigue of silicon nitride was specified by ISO 14628:2012 [26] on the basis of preceding research results, including those by the author of this review [27,28].

In 2005, Zaretsky comprehensively reviewed the history of ceramic bearings since 1970 [29]. The influence of materials for rolling elements on the life of bearings was compared between all-steel rolling element bearings and hybrid ones. Literature on rolling contact fatigue from the 70's to 90's were referenced in the review. A good deal of data on bearing lives seem to have been accumulated in the private sector, such as major bearings manufacturers, and there are some associated reports [21,22,30–33]. All of the data are not, however, open to the general public and there is still an insufficiency of RCF data of ceramics. The lack of a standardized test method of RCF even for bearing steel might have had no small effect on the slow accumulation of experimental data on RCF compared to other mechanical properties of ceramics such as strength, fracture toughness and elastic modulus. The aforementioned ISO standard for a RCF test method [26] is expected to make a significant contribution to improving the rate of data accumulation.

In this paper, an important point concerning design to improve the performance of ceramic bearings is highlighted by reorganizing varied information about the behavior of silicon nitride under rolling contact, focusing on experimental analysis thereof. Research on RCF can be classified roughly into two groups; an experimental analysis of life with a probabilistic method and an analysis of crack propagation behavior from an artificially induced or a natural initial flaw. There are many reports discussing the RCF life under various experimental conditions assuming operating conditions in real bearings. As for the crack propagation analysis, observational studies are predominant and associated numerical analyses on the stress intensity factor K have provided in-depth understanding of propagation mechanism by computation using three-dimensional finite elements. In the following, the features of major testing methods will be listed and to clarify differences between them, a comparison of test results using the same test materials will be shown. With such an understanding of the differences, the influences of variables such as the state of lubrication and surface roughness on RCF behavior will be discussed. Then the relationship between RCF behavior and mechanical properties of test materials will be reviewed by tracing the history of trends in material development of silicon nitrides for rolling elements. With respect to crack propagation, typical experimental analyses using models of crack growth derived from an artificially induced crack will be summarized. Those results are compared with observations of propagation from a pre-existing natural flaw to assess the validity of the models. Major modelling methods of initial cracks via a numerical analysis will be also listed. Finally, to improve the reliability of ceramic bearings, areas where information needs to be enriched will be discussed.

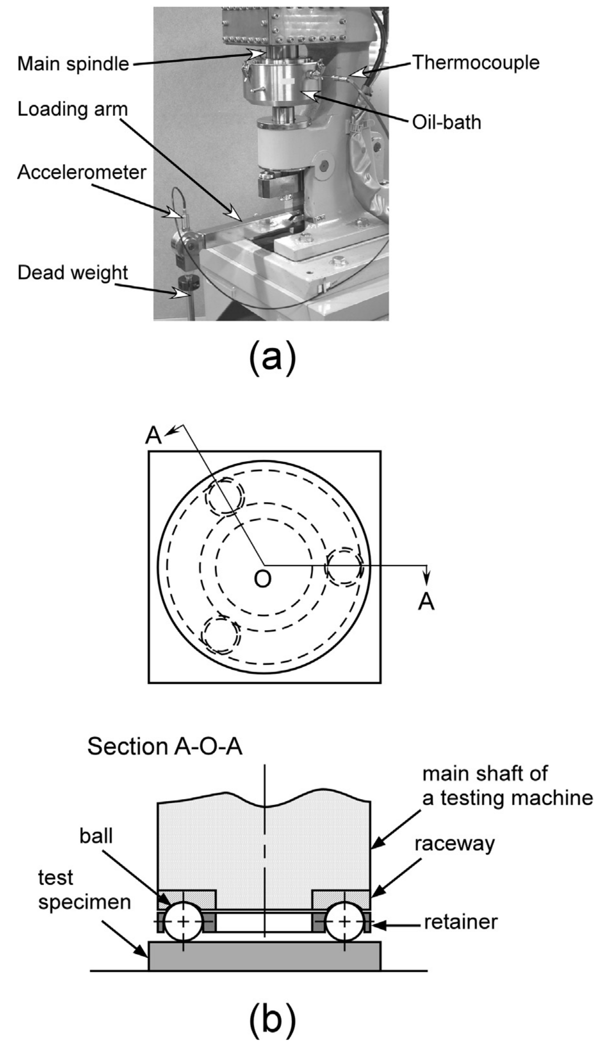

Fig. 1. Testing setup of the balls-on-flat configuration: (a) appearance of testing machine, and (b) schematic.

2. Experimental analysis of RCF

2.1. Methods of RCF testing

Four major RCF test methods, balls-on-flat (BOF), balls-on-rod (BOR), two-roller, four-ball configurations, have been used for various ceramics in the last few decades. The schematic of the BOF configuration is shown in Fig. 1[1] [34]. This method was designed to simulate the loading configuration of a thrust bearing. The test load is applied to the

[1] Fig. 1 through 3, 5 through 8, and Tables 1 and 2 are reproduced by courtesy of ASTM International, West Conshohocken, PA, USA.