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Materials Science and Engineering A 404 (2005) 221–226

MATERIALS SCIENCE & ENGINEERING A

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Ceramic rolling elements with ring crack defects—A residual stress approach

Zulfiqar Ahmad Khan [a,*], Mark Hadfield [a], Shogo Tobe [b], Ying Wang [a]

[a] *Sustainable Design Research Centre, School of Design, Engineering and Computing, Bournemouth University, Talbot Campus, Fern Barrow, Dorset BH12 5BB, UK*

[b] *Department of Mechanical Engineering, Ashikaga Institute of Technology, 268-1 Omae-cho, Ashikaga City, Tochigi-Prefecture 326, Japan*

Received in revised form 19 May 2005; accepted 27 May 2005

Abstract

Experimental results of rolling contact fatigue on ceramic bearing elements with refrigerant lubrication are presented. Residual stress measurements located on the contact path and other locations on the surface are described. An X-ray method was employed. Residual stress measurements are helpful in predicting rolling contact fatigue life. In addition, analysing the relationship of residual stress with rolling contact fatigue is an important study, which will provide guidelines on the design, process and manufacturing of these elements. During this research, ring crack defects were induced in ceramic rolling contact bearing elements. A compressive residual stress value of −73 MPa near the ring crack and a comparatively lower value of −12 MPa on the contact indicate sub-surface crack initiation and propagation. The average fatigue spall ranges from 100 to 148 μm in depth.

Within the spall area residual stress measurements suggest that compressive residual stress is relieved much faster in the region of sub-surface damage.

Keywords: Silicon nitride; Bearing elements; Rolling contact; Refrigerant lubrication; Residual stress

1. Introduction

Ceramic/silicon nitride bearing elements are an attractive design solution for high speed turbine, precision machine tools and various automotive applications. High demand of employing these elements in severe conditions of high contact stress, high temperature, high speed and restricted lubrication have put tremendous pressure on design engineers to evaluate the material and advise applicable design strategies. The introduction of the new generation of hydrocarbon refrigerants in various systems, where these rolling contact ceramic bearing elements are employed raises further demands to evaluate the fatigue performance with refrigerant lubrication.

Silicon nitride bearing elements were studied in this research. This material meets all the essential requirements of a bearing-grade element and is widely used. Silicon nitride bearing elements are hot isostatically pressed (HIPed), glass encapsulation which assures 100% density, high beta phase content, micrometer-sized grains and magnesia doped material. Due to hot isostatically pressing (HIPing), they have zero porosity, fine grain microstructure (∼2 μm), minimal level of dopant. A dopant or sintering aid is the controlling factor concerning corrosion resistance. Magnesia-based silicon nitrides are highly inert in most liquids and gases. Table 1 shows some properties of silicon nitride bearing elements. Fig. 1 shows a micrograph of an etched out silicon nitride bearing element. The microstructure of bearing-grade silicon nitride is discussed in References [1,2]. Silicon nitride bearing elements have shown practical advantages over traditional steel elements due to their mechanical and physical properties [3–5]. Research into the rolling contact fatigue life performance of

* Corresponding author. Tel.: +44 1202 965079; fax: +44 1202 965314.
E-mail address: zkhan@bournemouth.ac.uk (Z.A. Khan).

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doi:10.1016/j.msea.2005.05.087

Table 1
Properties of silicon nitride, Si_3N_4

Grain size	~2 μm
Compressive strength (room temperature)	3.5 GPa
Density (% theoretical)	3.16 g/cm^3 [>99.9%]
Weibull modulus	>15
Elastic modulus	320 GPa
Poisson's ratio	0.26
Vicker's hardness HV10	1550

ceramic (silicon nitride) rolling bearing elements has intensified in the past decade. Recent experimental programmes both on full scale and bench testing of the silicon nitride rolling elements have enabled researchers to identify modes of rolling contact failure and durability. The use of advanced non-destructive tests (NDT) for physical examination of these rolling contact elements have helped understanding the tribological characteristics of the silicon nitride rolling elements. Since these rolling contact bearing elements are subjected to high cyclic contact stresses the surface and sub-surface residual stresses are important in establishing a relationship to fatigue life performance. An understanding of residual stress within complex materials is needed to evaluate the effect of the manufacturing process, characterise failure modes and evaluate the in-service loading conditions of the concentrated rolling contacts [6]. The finishing process parameters have influence on the residual stress [7]. The residual stress value within the silicon nitride will vary due to primary processing (hot isostatically pressing) and surface finishing methods [6]. In respect to surface finishing methods there is significant pressure to accelerate material removal rates to reduce product financial costs. In addition to traditional grinding and lapping methods new processes such as magnetic force [8] and tribochemically assisted [9] have been considered for silicon nitride materials. It is therefore necessary to monitor manufacturing residual stresses within the finished silicon nitride bearing elements to advise on the design parameters related to residual stress. Measurements of surface residual stresses in Si_3N_4 laminates by Raman spectroscopy methods and residual stresses in particle-reinforced ceramic composites are provided [10,11].

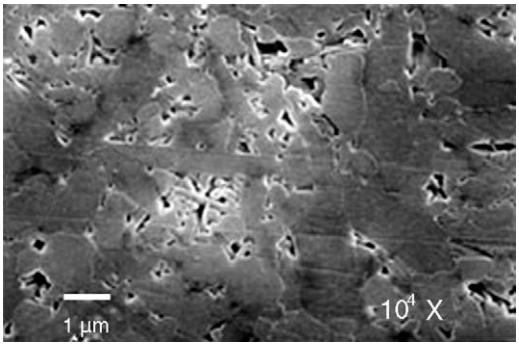

Fig. 1. Micrograph of glass-phase etched silicon nitride, Si_3N_4.

2. Rolling contact fatigue testing with refrigerant as a lubricant

Due to environmental impact legislation, refrigerants have evolved to include hydro-fluorocarbons (HFC) such as R134a and hydrocarbons (HC) such as R600a. The saturation pressures of these refrigerants are relatively high. It is therefore difficult to obtain material wear test properties of these refrigerants used in mechanical applications. This research responds to the need for bench testing of rolling contacts using the new generation refrigerants as lubricants. A pressurised chamber was designed and manufactured to achieve liquid state of the refrigerant as lubrication for the rolling contact fatigue experiments. A modified four ball TE92 High Speed Rotary Tribometer was used for rolling contact fatigue tests [12].

3. Residual stress measurement testing methodology

3.1. Background

The standard diffractometer method is usually called two exposure method [13], because two plane-spacing measurements are made, one of dn at $\psi = 0^\circ$ and one of di at $\psi = 45^\circ$.

The strain can be determined, either by a calculation involving the mechanically measured elastic constants of the material, or by a calibration method involving measurement of the strains produced by known stresses. The strain is calculated from Eq. (1).

$$\varepsilon = \frac{\Delta d}{d} = \cot\theta_0 \, \Delta\theta \tag{1}$$

where ε is the strain, d the atomic spacing, θ_0 the angle of diffraction in a stress-free condition and θ is the incident angle between the X-ray and the plane of the multilayer.

Stress can be calculated from the following relationship as follows. Partial derivatives are taken because all but the variable of interest are held fixed during the differentiation.

$$\sigma = \left(\frac{E}{1+\nu}\frac{\partial(\varepsilon)}{\partial(\sin^2\psi)}\right) = -\left(\frac{E\,\cot\theta_0}{2(1+\nu)}\frac{\partial(\theta)}{\partial(\sin^2\psi)}\right) \tag{2}$$

where σ is the calculated stress, E the Young's modulus, ν the Poisson's ratio and ψ is the angle between sample normal and diffraction plane normal.

Here

$$K = -\left(\frac{E\,\cot\theta_0}{2(1+\nu)}\right) \tag{3}$$

where K is the stress or elastic constant and

$$M = \frac{\partial(\theta)}{\partial(\sin^2\psi)} \tag{4}$$

where M is the slope $(2\psi - 2\theta)$ and express strain, then Eq. (2) may be re-written as

$$\sigma = KM \tag{5}$$