Engineering Fracture Mechanics 169 (2017) 292–308

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

journal homepage: www.elsevier.com/locate/engfracmech

Lifetime prediction of ceramic components – A case study on hybrid rolling contact

Iyas Khader [a,b,*], Stefan Rasche [c], Tanja Lube [c], Rahul Raga [b], Ulrich Degenhardt [d], Andreas Kailer [b]

[a] Department of Industrial Engineering, German-Jordanian University, P.O. Box 35247, Amman 11180, Jordan
[b] Fraunhofer-Institute for Mechanics of Materials IWM, Wöhlerstraße 11, 79108 Freiburg, Germany
[c] Instituts für Struktur- und Funktionskeramik der Montanuniversität Leoben, Peter-Tunner-Strasse 5, 8700 Leoben, Austria
[d] FCT Ingenieurkeramik GmbH, Gewerbepark 11, 96528 Frankenblick, Germany

ARTICLE INFO

Article history:
Received 4 March 2016
Received in revised form 18 September 2016
Accepted 24 October 2016
Available online 4 November 2016

Keywords:
Silicon nitride
Rolling-contact fatigue
Stress intensity factor
Weight function method
Lifetime prediction
Negative load ratio

ABSTRACT

In this study, fatigue life predictions were made for silicon nitride components undergoing hybrid ceramic-steel rolling contact. Three-dimensional stress fields were extracted using a bespoke finite element model and subsequently used to calculate stress intensity factors by means of the weight function method. Crack-growth rates were estimated by assuming crack growth to follow a Paris power-law expression whose material parameters were obtained from four-point bending fatigue experiments under fluctuating tensile load ($R = 0.1$) and fully-reversed alternating load ($R = -1$).

The crack-growth behavior obtained from the calculations was compared with experimental results obtained from twin-disk-type RCF experiments. The calculated lifetime predictions were in accordance with the experimental results. Crack formation and propagation was found more likely to occur in locations undergoing alternating load rather than those undergoing pure fluctuating tensile load.

1. Introduction

Ceramic rolling elements made of silicon nitride possess exceptional advantages over conventional steel bearings in terms of hardness, chemical stability, long life, and low density. Additionally, the low adhesion affinity between steel and silicon nitride [1,2] provides significant advantage for hybrid bearings in marginal lubrication conditions.

Rolling elements such as bearing balls undergo one of the most severe mechanical loading of all machine elements. The stresses engendered in application are extremely localized and bound to a very small volume of the loaded material – both on the surface and in the depth. A plethora of literature is available on the topic of rolling-contact fatigue (RCF) of silicon nitride [3–6]; for recent reviews cf. [5,7,8]. On the macroscopic scale, RCF is regarded as cyclic crack growth, which is governed by a complex three-dimensional time-dependent contact stress field.

There is a general agreement that fatigue cracks in ceramics, except for phase-transforming ceramics, are associated with pre-existing flaws [9,10]. Therefore, fatigue life predictions of ceramic components can be contemplated by assuming that macroscopic cracks develop from pre-existing flaws. Moreover, there are no known differences to exist between static and cyclic loading conditions as far as the mechanisms of microscopic deformation or microcrack nucleation are concerned [11]. It has been shown that the mechanism of crack advancement in ceramics is identical under cyclic and static loading,

* Corresponding author at: Department of Industrial Engineering, German-Jordanian University, P.O. Box 35247, Amman 11180, Jordan.
E-mail addresses: iyas.khader@gju.edu.jo, iyas.khader@iwm-extern.fraunhofer.de (I. Khader).

http://dx.doi.org/10.1016/j.engfracmech.2016.10.014
0013-7944/

Nomenclature

a	crack length
A^*	material parameter in Paris law
C^*	constant in the modified Paris law, a function of A^*, n, and R
da/dN	crack-growth rate
e	position variable along the axial direction (Z); $e = 0.0$ at the plane of symmetry (i.e., center of the contact ellipse)
f	load frequency; set in experiment
F_N	applied normal load; set in experiment
i	linear segment in the piecewise integration procedure
$K_{I,max}$	maximum stress intensity factor in *mode I*
$K_{I,min}$	minimum stress intensity factor in *mode I*
K_{IC}	fracture toughness
$K_{IC,air}$	measured fracture toughness of SN-GP black in air
$K_{IC,water}$	measured fracture toughness of SN-GP black in water
K_{Ii}	SIF contribution in each segment (i) of the piecewise integration procedure
L	depth variable along the radial direction (ρ); $L = 0.0$ at the surface of the roller
$m(x, a)$	weight function
M_1, M_2 and M_3	coefficients in the weight function
n	material exponent in Paris law
N	number of load cycles
p_o	maximum contact pressure
$\overrightarrow{P_0Q_0}$	reference crack path at $\varphi = 0$
$\overrightarrow{PQ}$	crack path
r_1	major radius of the contact ellipse
r_2	minor radius of the contact ellipse
R	load ratio
S_{max}	maximum principal stress; obtained from FEM
x	position along crack path, $0 \leqslant x \leqslant a$
Z	axial direction; Fig. 3
ΔK	applied stress intensity range
ϵ	eccentricity of the contact ellipse
Φ	circumferential direction; Fig. 3
φ	angular position variable in the circumferential direction (Φ)
υ	Poisson's ratio
ρ	radical direction; Fig. 3
$\sigma_i(x)$	stress magnitude in each segment i of the piecewise integration procedure
$\sigma_I(x)$	local stress field; $\sigma_1 = S_{max}$
σ_{r1}	maximum tensile stress at the major radius of the contact ellipse
σ_{r2}	maximum tensile stress at the minor radius of the contact ellipse

whereas, in the former crack shielding in the crack wake is constantly weakened by cyclic loading, particularly during unloading [9]. For instance, by considering frictional grain bridging to be the predominant shielding mechanism in silicon nitride, Dauskardt [12] developed a conceptual model, based on cyclic sliding wear, to explain its degradation. It was argued that repetitive sliding wear eventually leads to a decrease in the toughening capacity of the bridging zone by reducing the frictional pullout stress, hence, reduces grain bridging stress and exposes the crack tip to an increased portion of the applied stress intensity. A recent review of fatigue degradation in ceramics, which summarizes the described mechanisms, can be found in Ritchie and Launey [13].

Studies have shown that crack-growth rate in engineering ceramics under cyclic load is primarily dependent on the maximum stress intensity K_{max} rather than the stress intensity range ΔK [14–17]. The strong K_{max} dependence is often explained in the light of the primary crack-advancing mechanism, which is identical in cyclic loading to that under static loading; whereas, the weak ΔK dependence is attributed to a mere effect of shield degradation primarily occurring during unloading; a treatment of this topic pertaining to silicon nitride ceramics can be found in [18,19].

The work of Lube et al. [20] enabled the identification of distinct differences on the microscopic level in the failure mechanism of silicon nitride subjected to fluctuating tensile load (R = 0.1) and alternating "fully-reversed" load (R = −1); the latter is similar to the loading scenario prevailing in rolling contact.

Prediction of crack growth and lifetime in ceramic components can be foreseen by calculating stress intensity factor (SIF) cycles for cracks at various locations. Fatigue life estimation is expressed as the number of load cycles a crack experiences until a certain crack length has been reached or until critical crack growth is predicted; hence, a Paris power-law [21] can