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Simple mechanics model and Hertzian ring crack initiation strength characteristics of silicon nitride ceramic ball subjected to thermal shock

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ABSTRACT

This study investigated the ring crack initiation strength characteristics of silicon nitride ceramic balls subjected to thermal shock. Sphere indentation tests were conducted on ceramic balls following water quenching and furnace cooling operations performed in air and vacuum. The ring crack radius was significantly smaller because of the very thin silicon oxide (SiO_2) layer formed owing to heat treatment in air at high temperatures. In addition, the ring crack initiation load and Weibull shape parameter of water-quenched ceramic balls decreased with increasing temperature difference and remained relatively unaffected by the high-temperature oxidation. This phenomenon was mainly due to microscopic damage, which occurs near the surface of ceramic balls, caused by transient thermal stress developed during water quenching. A simple mechanics model based on the constant energy release rate criterion has been proposed for comparing experimental results obtained in this study against theoretical predictions, and results of the said comparison adequately verify strength characteristics of the aforementioned ceramic balls subjected to thermal shock.

1. Introduction

Bearings using ceramic balls made of silicon nitride (Si_3N_4) have been adopted in numerous industries including machine tools and turbomachinery. This is because ceramic balls have excellent mechanical properties, such as better heat/wear resistance, higher rigidity, and higher specific strength, compared to steel balls. In recent years, these bearings have been employed in the manufacture of turbine spindles in turbochargers [1] and jet engines [2], which operate in harsh environments with high loads, high temperatures, rapid temperature changes, and high rotational speeds [3]. Consequently, with increase in the number of such applications, high-end engineering components using these types of bearings require assurance in terms their operational reliability. There, therefore, exists a need to examine fracture characteristics of brittle ceramic balls, especially with regards to the damage and fracture caused by contact loads under harsh real-world operating environments.

It is well known that ring, cone, radial, and lateral cracks occur when Hertz load due to contact acts on ceramics structures [4]. In particular, initiation of ring cracks in ceramic balls during the operation of the bearings may leads to fatal damage. Consequently, ring crack initiation characteristics have been investigated in the past via sphere indentation tests performed on ceramic plates at room temperature. Ohgushi et al. [5] and Okabe et al. [6] discussed the theoretical basis of ring crack initiation strength as well as its

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Nomenclature

Symbols

a_{th}	contact circle radius obtained from Hertzian theory
c	length of micro-surface cracks
c'	specific heat
C_C	value for critical crack length involved in ring crack initiation in the virgin ball
C_R	value for critical crack length of the WQ balls
d_o	grain size calculated based on contact strength analysis of ceramic ball
D_L	diameter of ceramic ball
D_U	diameter of spherical indenter
E	young's modulus
F	ring crack initiation probability
G_{RC}	energy release rate for ring crack initiation in the virgin ball
G_{th}	energy release rate for microscopic damage due to transient thermal stress
$G_{RC\text{-}R}$	energy release rate for ring crack initiation after thermal shock
h	heat transfer coefficient
i	modified order of P_f for n data points
K_I	stress intensity factor of mode I
K_{IC}	fracture toughness of mode I
$K_{I\text{-}RC}$	stress intensity factor for ring crack initiation after thermal shock
K_{th}	stress intensity factor for microscopic damage
m	shape parameter of P_f
$\overline{m}$	shape parameter of ΔT_i
n	number of data points
P_f	ring crack initiation load
P_{ci}	thermal shock fracture probability
P_o	scale parameter of P_f
$\overline{P}_f$	average value of ring crack initiation load
r_{RC}	ring crack radius
R_L	$D_L/2$
R_U	$D_U/2$
T_1	prescribed temperature
T_2	temperature of water used for quenching
ΔT_i	temperature difference (T_1-T_2)
ΔT_o	scale parameter of ΔT_i
Y_{RC}	constant depending on geometry of the critical crack of length C_C
$Y_{RC\text{-}R}$	constant depending on geometry of the critical crack of length C_R
σ_b	three-point bending strength
σ_{th}	tensile thermal stress
$\sigma_r(r_{RC},z)$	Hertzian contact stress along the z-direction at r_{RC}
σ_{RC}	ring crack initiation strength
$\sigma_{RC\text{-}R}$	ring crack initiation residual strength after thermal shock
ν	poisson's ratio
α	thermal expansion coefficient
β	biot's modulus
ρ	density
λ	thermal conductivity

Abbreviations

WQ ball	ceramic ball quenched in water
FQ-A ball	ceramic ball cooled within furnace in air
FQ-V ball	ceramic ball heated and cooled within furnace in vacuum
FEM	finite element method
SEM	scanning electron microscope
SCG	slow crack growth

scatter and initiation position from the viewpoint of fracture mechanics. On the other hand, Licht et al. [7,8] discussed ring crack initiation position by means of modified Weibull distribution and contact damage behavior. Wereszczak et al. [9,10] investigated the effects of target materials and elastic modulus as well as the size dependence of an indenter on ring crack initiation. Ichikawa et al. [11] discussed the theoretical relationship between the four-point bending and the ring crack initiation strength in Si_3N_4 using the concept of effective area based on Weibull theory. They reported that the relation could not be explained based on the effective area concept.

Concomitant with these studies, fracture characteristics of ceramic balls subjected to static and dynamic loads have also been investigated. Regarding static strength characteristics, Ichikawa et al. investigated the ring crack initiation load [12], its scatter [13], and crush strength properties [14]. Kida et al. [15] and Supancic et al. [16] investigated strength characteristics of ceramic balls with notch and pre-crack. In terms of dynamic strength characteristics, rolling fatigue properties [17,18], fatigue damage mechanism [19,20], fatigue damage modeling based on fracture mechanics [21], and methods of fatigue life prediction [22,23] have been investigated in various extant researches. Assuming operational scenarios with damaged ceramic balls, Hadfield et al. investigated failure modes of ceramic balls with ring crack defect [24], pre-crack [25], and delamination [26]. However, studies assuming harsh real-world environments have been limited to investigations concerning rolling fatigue characteristics of ceramic ball bearings under constant high temperatures [27–29] and high-speed rotations [30]. To the best of the authors' knowledge, contact failure characteristics of ceramic balls subjected to thermal shock caused by rapid temperature changes have yet been neither experimentally nor theoretically investigated under real-world operating environments [31,32].

The proposed study was performed to clarify the basic strength characteristics of ring crack initiation in ceramic balls subjected to rapid temperature changes. First, sphere indentation test was performed on ceramic balls following water quenching and furnace cooling in air and vacuum. Next, the ring crack initiation load and its statistical characteristics were discussed based on experimental data and concepts of fracture mechanics. Finally, the validity of discussions presented in this paper was verified via experimental results and their comparison against predictions obtained using the proposed simple mechanics model.