A NOVEL TEST METHOD TO MEASURE THE FRACTURE TOUGHNESS OF CERAMIC BALLS USED IN BEARINGS

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ABSTRACT
A novel mechanical test has been developed to measure the fracture toughness of the silicon-nitride balls used in modern hybrid bearings important for many defense, space and industrial applications. The ball is compressed diametrically between two hemispherical conforming dies, which causes the ball’s equator to bulge, generating a tensile hoop stress. Under applied load, a precrack placed at the equator grows. To calculate the ball’s fracture toughness at crack instability, finite element calculations of the applied stress field and an analytical solution for the stress intensity factor are used in the “two point plus semiellipse” method. The new technique appears more accurate than the indentation technique used to measure the toughness of ceramics.

KEYWORDS: fracture toughness ceramic balls hybrid bearings

INTRODUCTION
Over the last decade, silicon-nitride (Si₃N₄) balls have become an important component of “hybrid” bearings that combine these ceramic balls with steel races. Compared to the steel balls they replace, the ceramic balls are harder and less dense and offer higher compressive strength, better corrosion resistance, elevated operating temperature and reduced lubrication needs. These benefits make the hybrid bearings ideal for severe high-speed applications such as machine tool spindles, dental drills, vacuum turbomolecular pumps, and the liquid-oxygen main engine pumps used in the Space Shuttle.

Many of the standard tests of fracture toughness for ceramics are not possible for the fabricated silicon nitride ball because it is too small to provide enough material for the test specimen. While it is possible to make substitute specimens from a larger blank of silicon nitride, it is unlikely that the blank would have the same fracture toughness as the ball because they would not share the same history of grinding and processing. Therefore, it is much more satisfying (and potentially less costly) to measure the fracture toughness of the actual silicon nitride ball itself.

This paper presents a novel technique to measure the fracture toughness of the ceramic balls used in hybrid bearings. In this technique, the ball is compressed to cause the equator of the ball to bulge and generate a tensile hoop stress, which propagates a starter crack placed at the equator. The experimental technique is first presented in detail below, and experimental results are presented. The finite element technique is then used to calculate the tensile hoop stress under the applied load at which crack growth was observed. An analysis of the stress intensity factor for the test is next given and combined with the calculated tensile stress to provide the theoretical basis for the test’s fracture toughness calculation. The theory is finally used to extract fracture toughness values from the experimental results.

EXPERIMENTAL PROCEDURE
Silicon-nitride balls with 12.7 mm (0.500 inch) diameter and AFBMA grade 3 tolerance were tested. A precrack was placed in each ball by indenting it with a Vickers diamond. The silicon-nitride balls were indented at 250, 300, 350 and 400 N, with four balls indented at each load for a total of 16 balls.

The precrack was grown by loading the ball between a pair of platens. The platens were manufactured from tool steel quenched and tempered to a hardness of HRC 67. A hemispherical section with a radius of 6.35 mm and a depth of 3.56 mm was machined and lapped into one end of each platen. Figure 1 shows the experimental fixture.

The ball was placed between the opposing platens. Using the analogy of a globe, the ball was compressed by the hemispherical platens at its “North” and “South” poles, which produced a tensile hoop stress at the midplane (or “equator”). The Vickers indentation was centered on the equator with one halfpenny crack pointing “North and South” (normal to the equator) and the other pointing “East and West” (parallel to the equator). The halfpenny crack pointing “North and South” was
perpendicular to the applied equatorial tensile hoop stress and grew when the tensile stress was sufficiently intense. The other crack was parallel to the tensile stress and did not grow.

As the load was applied, the crack was imaged with a microscope. Figure 2 shows the initial crack before load was applied, the crack after significant subcritical crack growth but before unstable propagation, and the crack after instability.

ANALYSIS OF TEST METHOD

The analytical approach proceeds in five steps. First, finite element analysis is used to calculate the tensile hoop stress as a function of position in the ball under the applied load. Second, the calculated stress fields at the tips of the crack are inserted into an analytical solution [1] for the crack’s stress intensity factor, which is used to infer the equilibrium aspect ratio to which the growing crack settles before unstable crack growth commences through the “two point plus semiellipse” method [1]. A correction factor that accounts for a linear gradient in stress is incorporated [2]. Third, the calculated aspect ratio is used to complete the analytical solution for the critical stress intensity factor due to the applied tensile stress, which is one of two components of the crack’s fracture toughness. Fourth, a well-established analytical solution is used to calculate the critical stress intensity factor due to the residual tensile stress of the Vickers indentation [3], which is the second component of the crack’s fracture toughness. Fifth and finally, the two components of fracture toughness are summed to give the crack’s fracture toughness.

Contact between the ball and mating platens corresponds to contact between conforming bodies of revolution over a very large arc. However, the Hertzian solution requires that the radius of the circle of contact be small. Because an analytical solution for this case of contact is lacking, the present case was analyzed instead by the finite element method to calculate the crack’s stress field.

RESULTS

Figure 3 shows the fracture toughness for the sixteen tested silicon-nitride balls as a function of the net crack extension from the starting to final crack length. Figure 3 shows that the ceramic does not display an R-curve behavior, which is sensible because the quoted grain diameter of 1 micron for the ceramic is too fine to cause an R-curve effect.

From Fig. 3, the 16 tested silicon-nitride balls had an average fracture toughness of 4.85 MPa m$^{1/2}$ with a standard deviation of 0.36 MPa m$^{1/2}$. As a comparison, the initial crack lengths of the indentations provided an independent calculation of the fracture toughness [3], which gave an average fracture toughness of 5.48 MPa m$^{1/2}$ with a standard deviation of 1.34 MPa m$^{1/2}$. The new technique appears more accurate than the traditional indentation technique.

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REFERENCES