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Advantages of using the ball-on-flat device in rolling-contact testing of ceramics

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Abstract

In this paper we present a new rolling-contact device that uses the ball-on-flat testing principle, and discuss some potential advantages of this device compared to commonly used rolling-contact machines. The loading arm of the new device moves linearly in a reciprocating motion and rolls the ball over a flat specimen. Instead of discs, rods or similar, circular-shaped, specimens, we can use simple, small blocks or even standard flat flexure test bars as convenient and inexpensive specimens. For comparison and evaluation reasons some results of non-lubricated rolling-contact experiments on silicon nitride ceramics are also presented and compared with data from the literature.

Keywords: Rolling; Silicon nitride; Testing device; Wear resistance

1. Introduction

Engineering ceramics have the potential to play a greater role in many types of modern machinery. For rolling applications, silicon nitride is already widely accepted as the best ceramic material, due to its relatively high toughness and non-catastrophic failure mode,[1,2] and it has been successfully applied in all-ceramic and hybrid rolling bearings.[3,4] One of the important factors that still limit the use of silicon nitride and other ceramics is the cost of the final surface-finishing method.[5] This is, however, an essential procedure for applications in which structural ceramics show the best comparative performance. Furthermore, it is known that final-grinding and surface-finishing methods significantly affect the properties of ceramic materials,[6–10] nevertheless, a complete understanding of the critical parameters will require more investigations.

One of the reasons for the lack of data on rolling-contact performance is the cost of manufacturing and preparing samples and the complexity of the testing procedures. Most of the testers in current use for rolling-contact fatigue and wear, for example, disc-on-disc, ball-on-rod and the modified four-ball machine use relatively large and expensive samples, especially in the case when ceramic materials are used. In addition, these conventional machines are designed in such a way that the specimen or counter material revolves on an axis, typically at high speed, to reduce the testing time. The complex geometry of both the machine and the specimens is therefore unavoidable and very fine tolerances are demanded. Consequently, careful and time-consuming mounting and dismounting procedures are necessary. This makes rolling-contact experiments involving ceramics relatively expensive and time-consuming. In addition, research in rolling-contact wear, and particularly rolling-contact fatigue, require a lot of data for any statistical evaluation because of the characteristically high levels of scatter. This makes the cost of specimens and the convenience of the testing procedure even more important.

In this paper we present a rolling-contact device[11,12] that uses the ball-on-flat testing principle. Instead of conventional circular-shaped specimens, made specifically for the rolling-contact testing, flat samples and even standard flexural bars[13] can be used. For a comparison and an evaluation of the new device, a limited number of results from some non-lubricated rolling-contact experiments on silicon nitride ceramics are also presented and compared with data from the literature, which was obtained on conventional rolling-contact machines.

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2. Description of the device and samples

The new ball-on-flat rolling-contact device, schematically presented in Fig. 1, has three main parts: a loading unit (1), a ball (2) and a flat testing specimen (3). The loading unit has a screw rod, which connects it to the crank mechanism, which produces linear reciprocating motion. Depending on the drive unit of the crank mechanism, the velocity can be continuously varied over a wide range. On the upper side of the loading unit a normal force is applied through a stationary loading system, connected to a spring or a dead weight. The loading mechanism is a separate system and can provide a wide range of loads, depending on the conditions needed in the contact. When the load is applied with simultaneous movement of the loading unit, the ball is forced to roll between the lower flat specimen and the loading unit. With repeated rolling and the resulting stress cycles that accumulate in the specimen, rolling wear or rolling fatigue can occur. On its lower side the loading unit has a groove along the axis of movement, similar to the groove in ball bearings. The groove allows the ball to self-adjust in such a way that it is always rolling on its central part, this serves to lead the ball laterally over the same trace on the specimen during each rolling cycle.[12] Due to much higher contact area and consequently lower contact stress in the contact between the ball and the groove compared to testing contact between the ball and the flat sample, the damage of the groove is significantly lower than that of the testing surface. However, from time to time the wear of the groove unavoidably occurs and the lower part of the loading unit with the groove should be repaired or replaced.

Testing specimens can be simple blocks, with the only restriction being that they have flat and parallel upper (a) and lower (b) surfaces (Fig. 2). Furthermore, standard flexural bars that are used for testing the flexural strength of advanced ceramics[13] can be used in this device. Instead of large, circular-shaped specimens like discs, rods or cups, which also require close tolerances, the specimens can be standard, widely available and commonly used in ceramics research. This makes them more convenient and easier to obtain at a relatively low cost. Another potential advantage is the ease with which surfaces produced by different surface-finishing techniques and grinding orientations[9,10] can be prepared. This is not always possible with geometrically more complicated samples and testing principles.

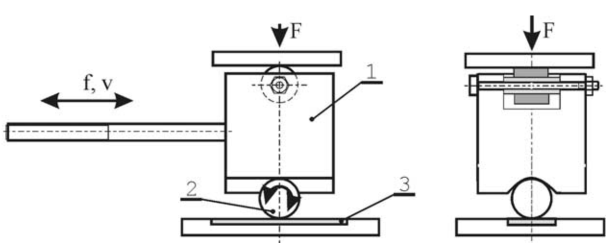

Fig. 1. Schematic of the rolling-contact device using ball-on-flat testing principle. Loading unit (1), ball (2), flat testing specimen (3).

3. Experimental

The material used in this investigation was hot-isostatically-pressed silicon nitride (HIPSN) with β-silicon nitride as the major phase, this is a material which is often used for ball-bearing applications (Elektroschmelzwerk Kempten GmbH, Kempten, Germany). The material properties, as received from the manufacturer, are presented in Table 1. The 4.763-mm balls used for testing were of grade 5 with a R_a roughness better than 0.03 μm, while the flat specimens were cut from standard flexural bars[13] to dimensions of 3×4×20 mm and polished to a roughness of about $R_a = 0.01$ μm. Before and after the tests all the samples were ultrasonically cleaned in ethanol for several minutes. Each experiment was performed with a new ball, while 2–4 experiments were performed with the same flat sample. The surfaces were investigated with topographical (T8000, HommelWerke GmbH, Schwinningen, Germany) and SEM (JEOL T330A, JEOL Ltd., Tokyo, Japan) analyses.

The tests were run in a reciprocating testing machine with a crank mechanism producing a stroke length of 12.2 mm at a frequency of 5 Hz. The normal force applied to the contact was 250 N, which resulted in an initial Hertzian pressure of 4.2 GPa. All the experiments

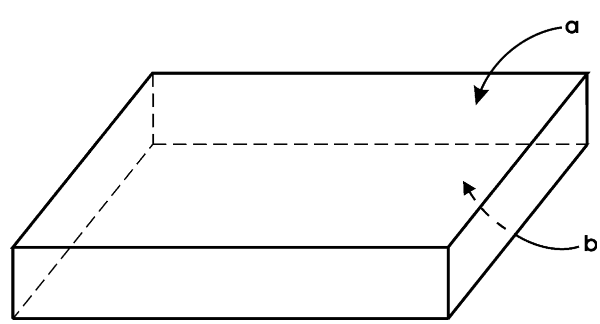

Fig. 2. Schematic of the flat testing sample.

Table 1
Properties of hot-isostatically-pressed silicon nitride measured at 20°C

Property	Value
Density (g/cm^3)	>3.16
Hardness (HV 05/HV 10)	1750/1500
Flexural strength (MPa)	>750
Young's modulus (MPa)	320 000
Toughness K_{IC} (MPa$\sqrt{m}$)	6.0
Poisson's ratio	0.27
Compressive strength (MPa)	>2500
Grain size, max (μm)	10

were performed under non-lubricated conditions in a laboratory environment (RT≈20 °C, RH≈50–60%). Two types of tests were performed. In the first type, tests were stopped after 10^4, 5×10^4, 10^5, 5×10^5, 10^6 and 1.5×10^6 cycles and subsequent wear and surface analyses were made. Each experiment was performed on a fresh, clean and un-damaged surface. For each testing condition at least two experiments were performed. The second type of experiment was a continuously running test with intermediate stops at a selected number of cycles, the same as those mentioned above. The purpose of this kind of experiment was to check the repeatability of the experiments in the two modes and thus the possibility of using the device in intermediate-stopping experiments.[12] This can save a lot of time when testing the necessary large number of loading cycles, characteristic for rolling-contact applications. After every intermediate stop the topographical analyses were made and the test was re-started on the same worn, rolling surface. In all the experiments, the coefficient of friction was recorded throughout the test.

4. Results and discussion

Fig. 3 shows the wear loss for the flat samples under the selected conditions. The wear results for each condition are presented as an average of all the tests, i.e. from both types of experiments. After 10^4 rolling cycles no wear could be measured with the techniques used and the surfaces looked shiny-polished, the same as before the experiment. With an increasing number of cycles the wear scar became larger, however, the wear factors were still low, i.e. of the order of 10^{-9} mm^3/Nm and the corresponding dimensionless wear coefficients were between 10^{-8} and 10^{-7}. Practically the same wear values were obtained in previously reported dry-rolling studies on silicon nitride.[14,15] The repeatability of the tests was satisfactory, including the intermediate stopping mode, as can be seen from the error bars (±1 standard deviation) in Fig. 3.

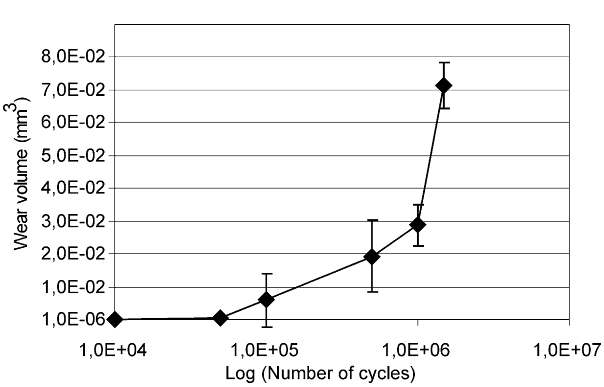

Fig. 3. Wear volume of flat samples at 10^4, 5×10^4, 10^5, 5×10^5, 10^6 and 1.5×10^6 cycles.

SEM analyses confirmed mild-wear contact conditions, as expected from the wear calculations. The wear was initiated as surface wear damage in the form of small and shallow micro-pits formed by brittle fracture [Fig. 4(a)]. The newly formed debris was crushed into smaller wear debris and due to the high contact stresses it agglomerated and formed a top surface multi-layer, which subsequently delaminated and spalled, [Fig. 4(b)]. In areas that were not damaged the layer was very smooth. As the number of cycles increased, the layer became thicker and delaminated more intensively, thus increasing the wear loss (Fig. 3). No subsurface-originating rolling-contact fatigue cracks or spalls, typical for lubricated contacts,[16–19] were observed on the silicon nitride surfaces. Therefore, the rolling-contact wear process occurred faster than the rolling-contact fatigue under these conditions and dominated the rolling-wear

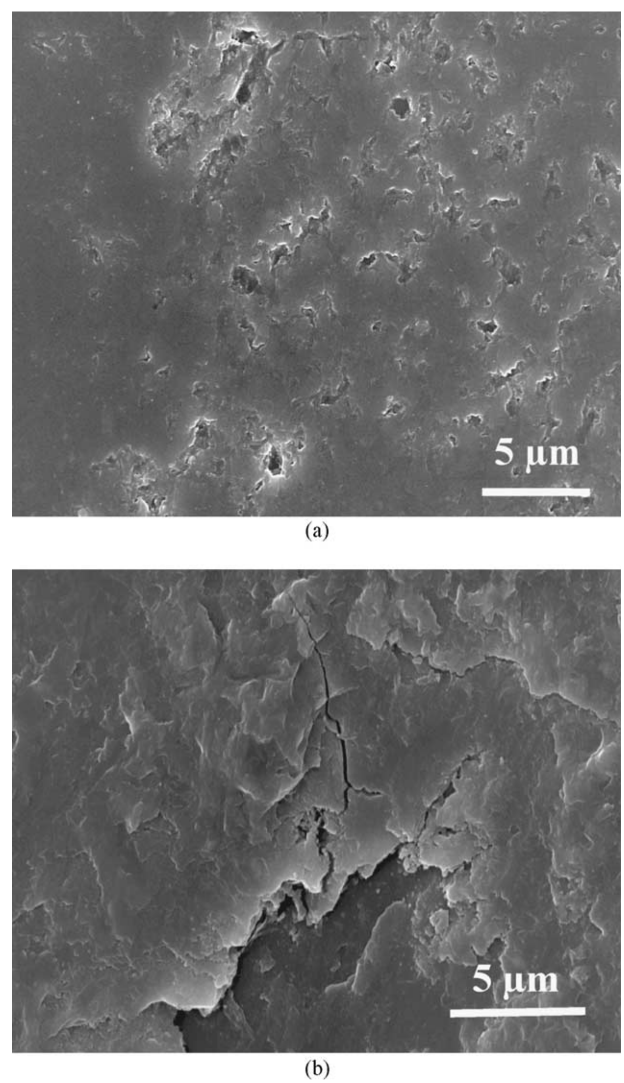

Fig. 4. SEM images of worn surfaces on the flat silicon nitride samples (a) after 5×10^4 rolling cycles showing surface-originating micro fracture and (b) after 10^6 rolling cycles showing fracture of the compacted wear debris layer.

process. These observations are in agreement with the literature data on the non-lubricated rolling wear of silicon nitride at low sliding ratios,[14] where at wear coefficients smaller than 10^{-6} cracks were not detected. Also, in another study,[15] just slightly higher wear coefficients (around 7×10^{-7}) that we observed were reported. The wear mechanism in that study was defined as surface brittle fracture, which was, however, not pronounced in a severe manner, and is thus consistent with our results.

According to the results obtained the presented rolling-contact device shows a lot of potential for rolling-contact testing, and in particular for rolling-wear applications. This is, in contrast to typical uni-directional rolling testers, due to characteristically lower, but continuously-variable velocity of the reciprocating mechanisms. The obtained wear mechanisms and wear factors confirm the adequate, repeatable and comparable testing procedure with conventional machines. In addition, the good repeatability of the tests in the intermediate stopping mode suggest a possibility of reducing the testing time for the rolling wear tests by employing this kind of testing.

In addition, the presented device uses simple and small block specimens, which are significantly less expensive than typical specimens used in existing rolling-contact devices. This could be of major importance in the rolling testing of ceramics due to the high machining cost[5] and the need for many experiments due to statistical evaluation of data. Furthermore, standardised flexural bars[13] can also be used, or, with minor adjustments, the leftover specimens from flexural strength tests. This is very convenient because these are commonly used specimens and are therefore widely available and can be easily prepared for rolling-contact tests almost without any additional costs. In addition, the flat specimens allow for the testing of a variety of different surface-finish conditions, like various grinding orientations, which is not possible for example with a modified four-ball machine, and is more difficult with other conventional rolling-contact machines, such as disk-on-disk or ball-on-rod due to the more complex geometry and testing principle. Also, for particular stages of on-going research, where a few series of ceramic materials with slightly different properties are prepared and their rolling performance is of interest, specimens with such a simple shape are easy and inexpensive to prepare.

One of the other important advantages of this device is that there are no revolving parts (except the standard, high-quality bearing balls) and therefore many of the difficulties with fine tolerances and dynamic effects like vibrations and shocks are avoided. Finally, but by no means less importantly, with only minor changes to the design the presented device can be attached to practically any crank mechanism, which is a simple and inexpensive piece of equipment, and already exists in many laboratories. In this way a large investment in a rolling-contact machine can be avoided.

5. Conclusions

- The presented ball-on-flat rolling-contact device is simple and can be attached to practically any crank mechanism with only minor design adjustments. There are no revolving parts in the new device, except the high-precision (and relatively inexpensive) bearing balls, this means difficulties with sharp tolerances and dynamic affects are avoided.
- Small blocks can be used as testing specimens, these are usually less expensive than larger and circular-shaped specimens. Furthermore, standard flexural testing bars can be used, which makes the rolling-contact experiments more convenient and cheaper.
- Our limited number of results obtained from the rolling-contact testing of silicon nitride ceramics are repeatable and show similar failure modes to those observed in other comparative studies. Rolling wear seems to be the predominant wear mechanism under the selected non-lubricated conditions.
- The good repeatability of the results suggests that it is possible to perform rolling-contact tests in intermediate-stopping mode, thus reducing the testing time.

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