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The ball on three balls test—Strength and failure analysis of different materials

Robert Danzer[a,b,*], Walter Harrer[a], Peter Supancic[a,b], Tanja Lube[a], Zhonghua Wang[a], Andreas Börger[a]

[a] *Institut für Struktur- und Funktionskeramik, Montanuniversität Leoben, A-8700 Leoben, Austria*
[b] *Materials Center Leoben, A-8700 Leoben, Austria*

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Abstract

The ball on three balls (B3B) test is a new method for biaxial strength testing of brittle materials. A detailed analysis of the stress field in the specimens and of possible measuring errors has been made recently. The B3B-testing method has several advantages compared to common three- or four-point bending tests: for example, the edges of the specimen have no influence on the testing results, small geometrical inaccuracies of the specimens or of the test jig have only a little effect on the maximum tensile stress and friction is of minor significance. Therefore the B3B-test seems to be suitable for miniaturisation.

In this paper the practical applicability of the B3B-test is investigated by measuring the strength of three ceramic materials having a low (electro ceramics), an intermediate (alumina) and a high (silicon nitride) strength. Specimens of different size (the smallest specimens had a volume of less than 1 mm^3) with polished or with as-sintered surface were tested. The results are compared with bending test results. In total more than 600 strength tests were performed. A pronounced size effect on strength could be observed, which is discussed in the framework of fracture statistics (Weibull theory).

In summary the B3B-test has been proven to be a cheap and easy new testing method, which can be used to determine the biaxial strength of brittle materials and which is particularly well suited for the testing of very small specimen.

Keywords: Strength; Defects; Failure analysis

1. Introduction

Strength testing of ceramics is—in most cases—performed in bending, where an uniaxial stress state occurs. Main advantages of the bending test procedure are an easy testing procedure combined with a relatively simple specimen preparation. During the last 20 years, the testing and evaluation procedure for bending tests have been broadly accepted and standardised.[1,2] The size of the standard test bar is 3 mm × 4 mm × 45 mm.

In service ceramic components are often biaxially loaded (e.g. during thermal shocks). This stress state is more searching for defects than an uniaxial state.[3] Many proposals for biaxial strength testing have been made in the past. A good overview on the methods, their strengths and their drawbacks, is given in the paper of Godfrey and John[4] or in the paper of Morell et al.[3] Several advantages are claimed for biaxial flexural testing of discs compared to uniaxial testing (in tension or in bending) including ease of test piece preparation, use for thin sheet materials and testing of a large surface area free of edge finishing defects.[5]

Specimens for biaxial strength testing have in general a circular disc shape. Many ceramic components, e.g. ceramic resistors, have the shape of a disc or of a rod and, for these parts, disc shaped specimens offer the opportunity to prepare specimens with a very limited machining effort (or even without any machining). The testing methods differ in the way of the load transfer to the specimen. Most common are the punch on ring and the ring on ring test,[6] which both produces a radial symmetric stress field in the specimen. This symmetry facilitates the determination of the stresses in the disc. A disadvantage is the not exactly defined contact situation, which occurs due to (small) geometric inaccuracies of specimen and jig and which cannot be completely avoided in practice. A poorly defined contact situation may cause significant errors in the strength determination.

* Corresponding author. Tel.: +43 3842 402 4100; fax: +43 3842 402 4102.
E-mail address: isfk@unileoben.ac.at (R. Danzer).

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An alternative testing method is the ball on three balls test (B3B-test), where the specimen is supported on three balls and loaded symmetrically by a fourth ball. In this loading situation the three-point support guarantees well-defined three point contacts, but the three-fold axis of symmetry makes the stress analysis very difficult. At the midpoint of the surface plane of the disc opposite to the loading ball a biaxial tensile stress state exists, which is used for the biaxial strength testing of the material. For linear elastic discs this situation has been numerically analysed in a wide range of parameters (geometry of disc and support, elastic constants of disc and support materials, etc.) by Börger et al.[7] The results will be discussed in the next chapter.

In a subsequent paper Börger et al.[8] analysed the measurement uncertainties of the B3B-test. This test has been recognised to be very tolerant for some out of flatness of the disc and also for other small geometries or some misalignment. Furthermore friction is recognised to be much smaller than in the commonly used bending tests. For these reasons the B3B-test can also be used to test as-sintered specimens and very small specimens.

In the following, B3B-tests on a silicon nitride, an alumina and a zinc oxide (varistor) ceramic are reported. Specimens of different size are used to demonstrate the size effect on strength for these materials. The test results are also compared with bending test results.

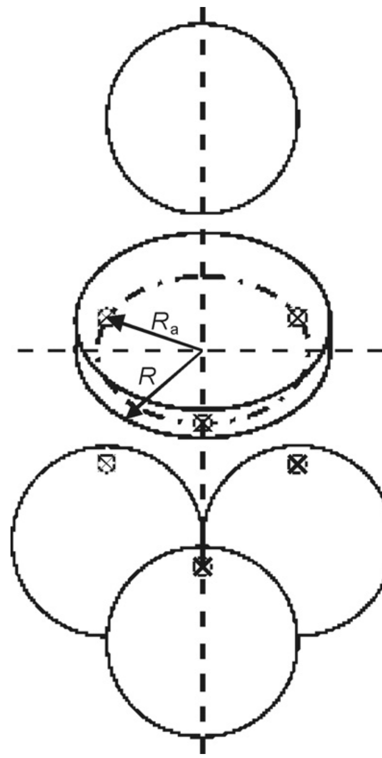

Fig. 1. Schematic sketch of the loading situation in the ball on three balls test.

2. Stresses in the specimens

In the B3B-test one surface of a disc shape specimen is supported on three balls equidistant from its centre. The opposite face is centrally loaded with a fourth ball normal to the orientation of the plane and the fracture force is measured. The maximum principal tensile stress (σ_{max}) in the disc, which occurs on the disc surface opposite the centred loading ball, is used to define the strength. To reduce the parameters having influence on this stress all balls have the same size and the three supporting balls touch each other. Their contact points with the disc forms an equilateral triangle; its circumradius is called support radius of the disc, R_a. The stress field in the disc depends on the applied force, the geometric set-up of the test (disc thickness and diameter, size and the position of the balls) and also on the elastic properties of ball and disc materials. Fig. 1 shows a schematic sketch of the test assembly. It should be noted that the three-fold symmetry of the support causes a three-leaf clover shape of the stress field.

In an extensive FE-analysis the stress σ_{max} has been analysed in a wide range of parameters.[7] Within negligible errors and within the linear elastic approximation the loading by balls can be replaced by a point loading (this is true for σ_{max} although cannot be true for the stress field as a whole) and the elastic properties of the fixture can be neglected. It could also be shown, that the Young's modulus of the specimen has no influence on σ_{max} (but the Poisson ratio υ has). Then the stress σ_{max} is given by:

$$\sigma_{max} = f(\alpha, \beta, \upsilon)\frac{F}{t^2}, \qquad (1)$$

where F is the applied force, t is the thickness of the disc and f is a dimensionless factor—namely the dimensionless maximum tensile stress—which only depends on the ratio of thickness to the radius of the disc, $t/R = \alpha$, the ratio of the support radius to the disc radius, $R_a/R = \beta$, and on the Poisson's ratio of the investigated material, υ. For the parameter range $0.05 \leq \alpha \leq 0.60$, $0.55 \leq \beta \leq 0.90$ and $0.20 \leq \upsilon \leq 0.30$ an analytical approximation (to the numerical results) can be found in reference 7. In this range of parameters the function f is between ~1 and 3.

For specimens outside of this specification a special FE calculation has to be made to determine the maximum tensile stress in the specimen. Since a point loading model within the linear elastic approach is sufficient for this purpose[7] this calculation can be done within reasonable time.

The determination of the complete stress field needs much more effort than that of the maximum principle stress, e.g. a proper analysis of the contact problem. Its path strongly depends on the ratio α and to a lesser extent also on the parameters β, and υ. In thick ($\alpha > 0.5$) disks the tensile loaded area is much wider as in thin ($\alpha \leq 0.1$) discs,[7] where the membrane solution gets relevant.

3. Experimental procedure

Specimens were machined out of three different ceramics having a high, a medium and a low strength. Different specimen sizes (radius, thickness, etc.) and loading conditions (loading radius) were used to study the size effect on strength, which is predicted by Weibull theory.[9,10] When the tensile loaded surfaces of the B3B specimens were machined special care was

Table 1
Mechanical properties of investigated materials

	Silicon nitride	Alumina	Varistor ceramic
Young's modulus (GPa)	305[a]	380[b]	107[a]
Poisson ratio (–)	0.28[a]	0.24[b]	0.35[b]
Mean strength[c] (MPa)	869[a,c]	>400[b]	101[a,c]
Fracture toughness[a,d] (MPa m$^{1/2}$)	4.9 ± 0.9[a]	3.2 ± 0.1[a]	1.3 ± 0.1[a]

[a] Own measurements.
[b] Data from the supplier.
[c] Four-point bending with a 40/20 mm span length according to EN843-1.
[d] Single edge V-notch beam method (SEVNB; [14,15]).

taken to avoid machining damage. The surface finish was made according to ENV 843-1. In the case of one material (the alumina) the tensile loaded surface has been kept in the as-sintered condition.

3.1. Investigated materials and specimens

3.1.1. Silicon nitride ceramics

The investigated material is a typical commercial gas pressure sintered silicon nitride ceramics with Al_2O_3–Y_2O_3 additions. It has a needle like grain structure, a high strength and a reasonable fracture toughness. It has been produced by CeramTec, Plochingen, BRD (trade name SL200). The material was provided in form of plates with dimensions of 102 mm × 47 mm × 11 mm. This material (the same production lot) is used as a reference material in the ESIS reference material testing program. For more details see reference 11 and also the paper of Lube and Dusza.[12] Some mechanical properties are listed in Table 1.

The smallest B3B specimens had a volume of less than 2 mm^3 and the largest B3B specimens had a volume of more than 5000 mm^3. In total 157 strength tests were made using eight different types of specimens (including bending specimens).

3.1.2. Alumina ceramics

The investigated material (AL23) is a typical commercial 99.7% pure Al_2O_3 ceramics produced by FRIATEC GmbH, Germany. It was delivered in form of discs (radius 10 mm, thickness 3 mm). It has a bimodal grain structure. Large grains having a diameter around 20–30 μm are surrounded by smaller grains with a diameter of a few micrometers. Some mechanical properties are listed in Table 1.

For that material the as-sintered surface was used as tensile loaded surface of the specimens. Therefore the delivered discs could be used as B3B specimens without any further machining. In the case of the other specimens special care was given to keep the as-sintered surface in its original condition. The smallest B3B specimens had a volume of less than 1 mm^3. In total 315 strength tests were made using 14 different types of specimens.

3.1.3. Zinc oxide varistor ceramics

Commercial varistors delivered by EPCOS (cylinders: radius 21.5 mm, height 43 mm) were used for this investigation. The microstructure consists of ZnO grains, which are surrounded by Bi_2O_3 and spinel phases. The porosity is around 10 vol.%. The microstructure of varistors is described in more detail in 13. Some mechanical properties are listed in Table 1. The bending test specimens were cut out of the cylindrical components normal to the axis of the cylinder. In total 166 strength tests were made using six different types of specimens.

3.2. Strength measurements and data analysis

The strength measurements were performed in analogy to EN 843-1. The experimental procedure is described in references.[16,17] For each type of B3B-test (defined by the specimen geometry and the loading radius) the effective volume and the effective surface have been determined by full stress analysis of the specimens (FE calculations) in the framework of the conventional Weibull theory.[9,10]

Due to the statistical nature of the strength of brittle materials the sample has—in general—different properties as the parent population.[18] This causes an uncertainty in the determination of the Weibull parameters, which is accounted for in the standards by confidence intervals (in general the 90% confidence interval is reported in the data). Of course, the interval becomes wider as the sample size becomes smaller. For each set of tests the Weibull parameters (characteristic strength and Weibull modulus) and their confidence intervals have been determined.

It should be noted that the Weibull theory predicts a dependence of the effective volume and surface on the Weibull modulus: as wider the strength is distributed (as lower is the Weibull modulus) as larger are the effective volumes and the effective surfaces, respectively. Therefore confidence intervals for the Weibull modulus also determine confidence intervals for effective volume and surface.

B3B-tests produce a biaxial stress state. To compare data of B3B-tests with bending test data an equivalent stress has to be determined, which accounts for the more damaging loading in biaxial testing compared to uniaxial testing.[10] Although the proper definition of such a stress is still in discussion the principle of independent action (PIA)[19] is often used. The PIA equivalent stress is:

$$\sigma_{\mathrm{eq,PIA}} = (\sigma_{\mathrm{I}}^m + \sigma_{\mathrm{II}}^m + \sigma_{\mathrm{III}}^m)^{1/m}, \qquad (2)$$

where σ_{I}, σ_{II} and σ_{III} are the principle tensile stress components. For a biaxial stress principal it holds: $\sigma_{\mathrm{eq,PIA}} = \sigma_{\mathrm{I}}(2)^{1/m}$.

The strength test results are summarized in Figs. 2 and 3. Plotted are the equivalent characteristic strength values versus the effective volume or the effective surface, respectively. Scatter bars are only shown for some selected data to keep the plot clearly arranged. They refer to the 90% confidence intervals, which result—as discussed above—from the sampling procedure.[18] Not indicated is the scatter due to other measurement uncertainties. In a paper of Börger et al.[8] it has been shown that measurement uncertainties increase with decreasing specimen size (especially the specimen thickness has a large potential contribution). For the used specimens measuring uncertainties

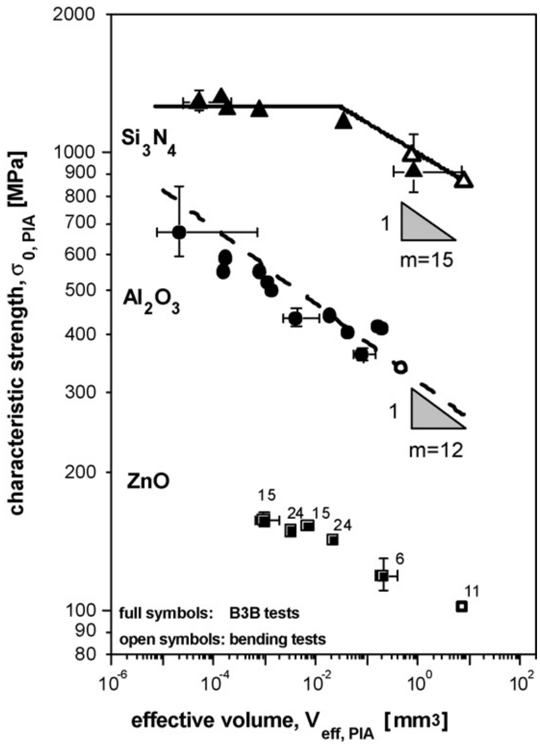

Fig. 2. Strength vs. effective volume measured in B3B and bending tests. Plotted is the equivalent characteristic strength (using the PIA criterion) of each data set. The scatter bars shown for some data refer to the 90% confidence intervals arising from the sampling procedure: silicon nitride, alumina and varistor ceramic.

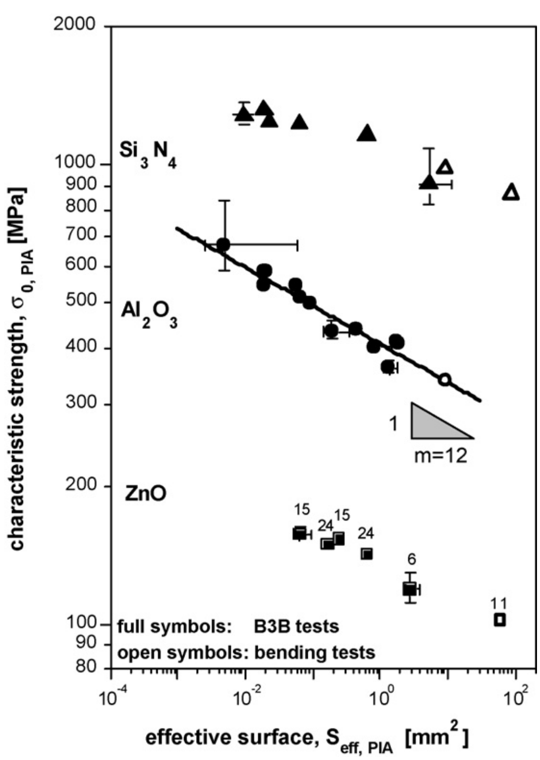

Fig. 3. Strength vs. effective surface measured in B3B and bending tests. Plotted is the equivalent characteristic strength (using the PIA criterion) of each data set. The scatter bars shown for some data refer to the 90% confidence intervals arising from the sampling procedure: silicon nitride, alumina and varistor ceramic.

should be smaller than 5% of the strength value in any and smaller than 1% in most cases.

4. Discussion

4.1. Silicon nitride ceramics

Weak regions (i.e. defects) in the microstructure are Fe-containing inclusions and agglomerations of the glassy grain boundary phase, which are often associated with porous regions. In the case of the bending tests and of the B3B-tests on specimens having an effective volume larger than 10^{-2} mm^3 all identified fracture origins were such defects. Therefore a volume dependence of strength ($\sigma_0 V_{eff}^m$ = constant; σ_0, characteristic strength of the data set; V_{eff}, effective volume of the specimen; m, Weibull modulus) follows from Weibull theory.[9,10] The straight line in Fig. 2 shows that behaviour. The slope of the line corresponds to the modulus ($m \cong 15$), which has been determined in the bending tests. The large B3B specimens follow the trend from the bending tests. For the specimens having a smaller effective volume a plateau value for the characteristic strength at around 1300 MPa can be observed. The scatter of strength for these data sets is very small, which results in very high values for the Weibull modulus ($m \cong 20$–30).

Such a plateau can be explained by the occurrence of machining flaws, which may become significant at very high stresses. It is theoretically predicted in several papers, e.g. in reference 18. Indeed for a material with a fracture toughness of $K_c \approx 5$ MPa m$^{1/2}$ and if $Y = 1, 12$ is used for the geometric factor of the crack (this would be typical for scratches) the Griffith/Irwin criterion predicts a critical crack length of around 4 μm at a stress of 1300 MPa. Machining cracks of that size are likely to occur but a fractographic confirmation is missing yet.

Another possible explanation for the observed behaviour is the occurrence of a very high defect density (for small defects), which have been recently mentioned to occur in very small specimens.[20] In this case an upper bound to strength and an increase of the Weibull modulus are expected to occur for tests on very small specimens.

In other papers[18,21] multimodal defect populations have been also claimed to be responsible for a strength–specimen size dependency as shown for silicon nitride in Figs. 2 and 3.

4.2. Alumina ceramics

In the case of that material the as-sintered surface has been tested and a surface dependence on strength (instead a volume dependence) is expected to occur. The mean Weibull modulus of all data sets is $m \approx 12$. In Figs. 2 and 3 the lines interpolating the alumina data points correspond to the Weibull predictions based on the bending data. It is obvious, that the trend predicted from flexural data better fits a surface than a volume flaw analysis of the biaxial B3B experiments. The size of the critical crack in the specimen having the highest strength is about 16 μm. Defects of that size can be recognised on the as sintered surface of the specimen.

4.3. Zinc oxide varistor ceramics

In the case of varistor ceramics volume flaws (pores) arising from spray dried and agglomerated powders have often been identified as fracture origins (e.g. see reference 20). The critical crack size is relatively large (∼50–100 μm) and the density of defects is relatively high. Unfortunately an in depth fractographic study of the investigated specimens is missing in the current state of investigation. The characteristic strength data shown in Figs. 2 and 3 suggest a pronounced size effect, which may be caused by volume as well as by surface flaws.

But the extreme variability of the Weibull modulus (the number near the symbol gives the value of the Weibull modulus) makes a fracture statistical interpretation of the results difficult.

5. Summary

More than 100 bending tests and around 500 B3B-tests were performed on specimens of very different size. This work clearly demonstrates, that:

- the preparation of B3B-test specimens is relatively cheap and easy;
- the B3B-test is relatively easy to perform; and
- an influence of contact stresses did not occur.

Specimens with a volume of less than 1 mm^3 could be successfully tested. Possible future applications are the testing of electronic parts or of parts of the micro system technique.

All investigated materials had a significant size effect on strength. For the alumina ceramics—which has been tested with the as-sintered surface—this size effect is caused by surface defects. In the case of silicon nitride glassy agglomerates were found to be fracture origins in the larger specimens. Although a fractographic analysis of the smaller specimens has not been done yet machining cracks are assumed to be responsible for an upper bound of strength in these specimens.

In summary the B3B-test appears to be a cheap and easy to use method to determine the biaxial strength of brittle materials.

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