ADVANCES IN SHOT PEENING OF SILICON NITRIDE CERAMICS

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ABSTRACT

Shot peening is a common procedure to improve the static and cyclic strength of metal components. It is based on a multiple localized plastic deformation of near-surface regions. Ceramics show at room temperature the typical brittle material behavior of failure before deformation. Thus, strengthening of ceramics due to deformation induced compressive residual stresses has been thought to be not possible. Recent investigations showed, however, that also in brittle materials like ceramics high compressive stresses can be introduced near the surface.

This presentation compiles the status of the novel shot peening technique applied to silicon nitride ceramics. The results show that high compressive residual stresses in the GPa-range can be introduced in silicon nitride which may boost the static and cyclic load capacity of the near surface layer by a factor of up to 5. In addition, the fracture toughness of the near-surface region is dramatically improved.

SUBJECT INDEX

Ceramic, residual stress, strengthening, plastic deformation, fracture toughness.

INTRODUCTION

Non-transformation toughened ceramics show at room temperature the typical brittle material behavior of failure before deformation. Thus, strengthening of ceramics due to deformation induced compressive residual stresses – the main mechanism of shot peening - has been thought to be not possible.

Recent investigations (Pfeiffer, 2002; Pfeiffer, 2004) show however that, under specific shot peening conditions, also in brittle materials like ceramics high compressive stresses up to more than 1 GPa can be introduced near the surface. By exposing these strengthened surfaces to loading situations which are characterized by a steep near-surface stress gradient, a boost of load capacity could be obtained. Such loading situations exist in e.g. ball and sliding bearings or forming tools.

The aim of this paper is to compile the present status of the ceramic shot peening process and the latest results for silicon nitride which is one of the most important ceramic materials used in mechanical engineering applications.

EXPERIMENTAL DETAILS

Material investigated

The material investigated was a commercially available silicon nitride ceramic, N3208 (H.C. Starck Ceramics). The most important material characteristics are a bending strength of 877 MPa and a fracture toughness of 4.2 MPa $m^{1/2}$ (Rombach, 1995). Flat samples were prepared for the static and cyclic tests by polishing using 1-3 µm diamond abrasives.

Shot peening

The shot peening tests were carried out with a modified injection system. The pressurized air and the shot are applied to the jet nozzle in two different tubes. The shot is accelerated in the nozzle to a high velocity and hits the specimen's surface. The shot used was tungsten carbide beads with a diameter of 610 – 690 µm. The peening pressure ranged from 0.2 MPa up to 0.4 MPa. Typical peening times were 280 up to 840 seconds. The resulting Almen-intensity was in the range of 0.22 up to 0.28 mmA. The most important shot peening parameters are indicated in the figures.

Determination of residual stresses and dislocation density

The residual stresses and dislocation densities were determined by X-ray diffraction using CrKα-radiation and the {411} - diffraction lines of β-silicon nitride. The full width at half maximum (FWHM) of the diffraction line was calculated to characterize the dislocation density. The macroscopic residual stresses were derived from the peak shift determined for 11 ψ-angles between +45° and -45° using an X-ray elastic constant $1/2s_2$ of 3.89 GPa^{-1} and the well known $\sin^2\psi$-method (Müller, 1961). The penetration depth from which 67% of the diffracted X-rays arise was 8 µm. For depth probing of residual stresses, it was necessary to remove stepwise thin surface layers by polishing using 3 µm diamond abrasives. This mechanical material removal resulted in additional, but small compressive residual stresses.

Determination of load capacity

The static and cyclic load capacity was determined using the ball-on-plate test. The advantage of this test is the high surface sensitivity due to the in loading direction rapidly decreasing tensile stresses (Rombach, 1995). Fig. 1 shows the loading situation. The load on a silicon nitride ball is increased stepwise until a typical cone-crack could be detected by optical microscopy (see Fig. 2). Because of the statistical behavior of ceramics, the load which causes fracture varies from test to test within a certain scatter-band. Typically, 5 up to 10 samples with equal surface conditions were tested.

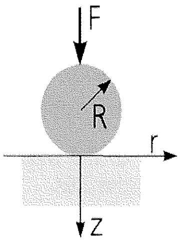


Fig. 1:Loading situation in the ceramic ball-on-plate test.

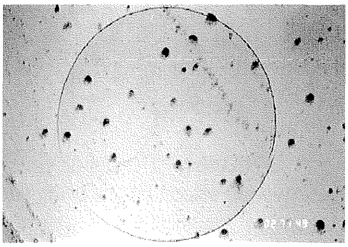


Fig. 2: Cone crack (∅ 400 µm) at the surface of a plate after loading in the ball-on-plate test.

The tests were performed using a servo-hydraulic testing machine. In case of the cyclic experiments 10^6 cycles with a frequency of 60 Hz were used before inspection of the surface. Silicon nitride balls with a diameter of 10 mm and 4.78 mm were used. For determination of the depth distribution of the static load capacity a stepwise material removal using 3 µm diamond abrasives was performed.

Determination of fracture toughness

The depth distribution of the fracture toughness within the near-surface region affected by shot peening was determined using the Vickers indentation technique (Warren, 1995) and a stepwise material removal using 3 µm diamond abrasives. Five up to 7 indentations were used to calculate average fracture toughness values.

RESULTS

Residual stress and dislocation density.

The depth distribution of residual stresses and width of the diffraction lines (FWHM, as a measure for the dislocation density) determined for two typical peening conditions are shown in **Fig. 3**.

The different peening conditions result in different residual stress distributions. In case of the lower peening pressure (0.2 MPa), the maximum compressive stress of 1.2 GPa occurs at the immediate surface and decreases continuously to approximately -150 MPa within the first 60 µm. The higher peening pressure (0.3 MPa) results in maximum compressive residual stresses of 2.0 GPa 25 – 30 µm below the surface. They decline to approximately -130 MPa within the first 80 µm.

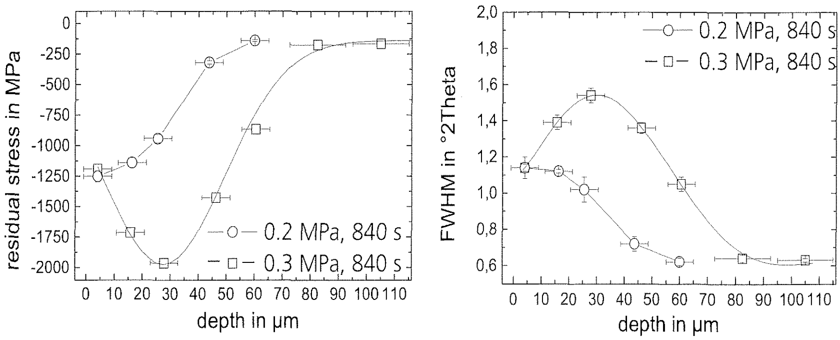
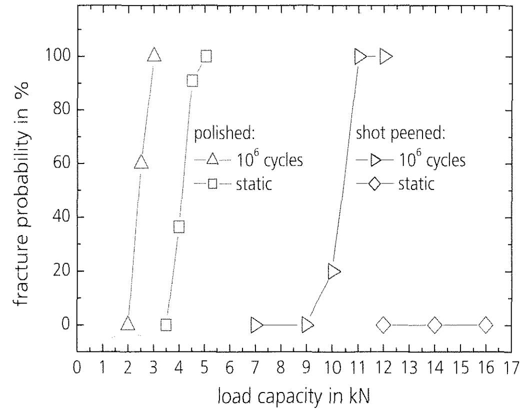


Fig. 3: Depth distribution of residual stresses (left) and width of the diffraction lines (right) of shot peened silicon nitride using two different peening pressures.

Static and cyclic load capacity

The results of the static and cyclic ball-on-plate tests are shown in Fig. 4. The fracture probability as a function of the load is plotted for the shot peened (0.3 MPa / 840s) and the polished reference surfaces, respectively.

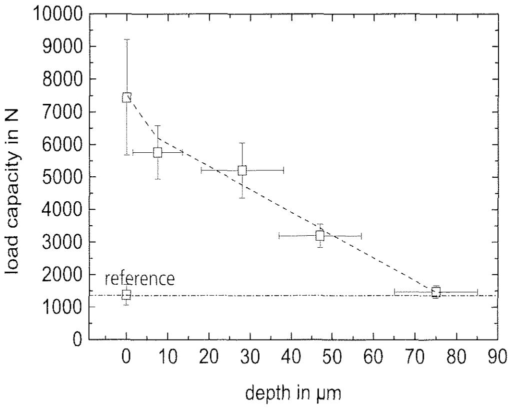
Fig. 4: Fracture probability of polished and shot peened samples, respectively, determined in static and cyclic ball-on-plate tests. Note that in case of the static tests of the shot peened samples the capacity of the test equipment was exhausted.



For a fracture probability of 50 %, the polished reference achieved a static load capacity of about 4 kN and a cyclic load capacity of 2.5 kN. The cyclic load capacity of the shot peened samples reached 10.5 kN which is a gain of a factor 4. The shot peening treatment increased the static load capacity to more than 16 kN. The capacity of the testing device was not high enough to introduce any cracks into the shot peened surface. From the result of no failure up to 16 kN, a gain of the static load capacity of a factor of at least 5 can be concluded.

The depth distribution of the static load capacity had to be determined using a smaller indentation ball (4.76 mm diameter) as the tests with the 10 mm indentation balls exceeded the load capacity of the testing equipment. Fig. 5 shows that the increase of the load capacity more or less follows the depth profile of the compressive residual stresses (see **Fig. 3**).

Fig. 5: Depth distribution of the static load capacity of shot peened silicon nitride (0.3 MPa / 840s). The load capacity of the not shot peened material is shown as reference.



At the immediate surface, the load capacity of the shot peened sample is about 5 times higher than the load capacity of the untreated (polished) reference sample. At a depth of 75 µm the load capacity has declined to the level of the reference sample.

Fracture toughness

Fig. 6 shows a composite of two micrographs of Vickers indentations in a polished and a shot peened silicon nitride surface, respectively. It becomes obvious, that the resistance against the initiation and growth of cracks is substantially improved through the shot peening. The crack initiation is nearly completely suppressed in the surrounding of the Vickers indentation into the shot peened surface, whereas the indentation into the polished surface shows the typical cracks at the corners of the indentation.

From the crack length, the fracture toughness KIc can be determined. It should be pointed out that, by definition, the fracture toughness is a material characteristic which should be independent from any post-sintering machining. Thus, the fracture toughness values determined in this study are a mixture of material characteristics and residual stresses generated by the shot peening.

The depth distribution of the fracture toughness within the shot peening affected surface layer, determined through Vickers indentations after a stepwise material removal is shown in Fig. 7 for the same shot peening condition as used for the depth probing of the load capacity (see Fig. 5). The residual stress state of that shot peening condition is shown in **Fig. 3** (peening pressure 0.3 MPa). The comparison of the depth distributions of residual stress, load capacity and fracture toughness prove that the driving forces for the dramatic improvement of the near-surface properties are the compressive residual stresses.

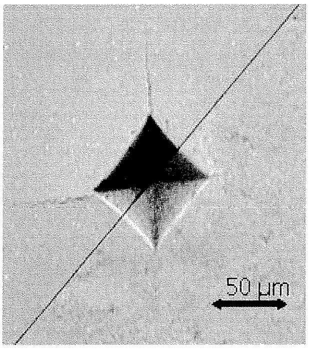


Fig. 6: Vickers indentation of a polished (left) and a shot peened surface of silicon nitride.

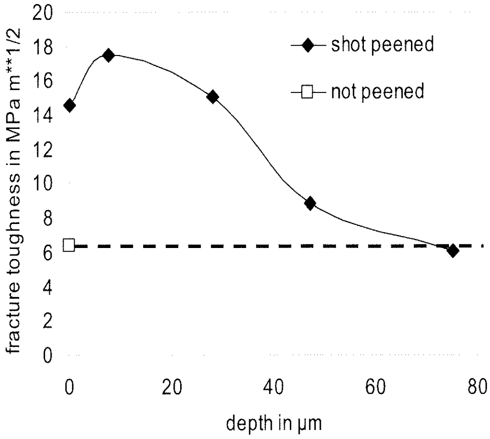


Fig. 7: Depth distribution of the fracture toughness of shot peened silicon nitride (0.3 MPa / 840s). The fracture toughness of the untreated material is shown as reference.

DISCUSSION AND CONCLUSION

The presented investigations show that, using a novel shot peening process for brittle materials, micro-plastic deformation and high compressive residual stresses up to 2 GPa can be introduced into the near-surface region of ceramics, which decline within the first 100 µm. The shot peening process can dramatically increase the strength properties of the near-surface region. The static and cyclic load capacity tests as well as the Vickers indentation tests show an increase of the near-surface load capacity and the fracture toughness by at least a factor 3. In addition, the depth profiles of the load capacity and fracture toughness exhibit no weak subsurface areas within the shot peening affected surface layer. Microscopic investigations, not shown here, revealed no significant damage of the shot peened near-surface layers. Contrary to these findings, fracture mechanical calculations based on the superposition of residual stresses and loading stresses during strength tests indicate the possibility of some subsurface damage (Pfeiffer 2005). However, the presented results state the overall benefit of the near-surface strength properties from peening induced compressive residual stresses. This is confirmed by investigations on machined and additionally shot peened roller bearing components, which showed the possibility to compensate machining induced damage by shot peening induced residual stresses (Pfeiffer, 2004).

Further investigations will concentrate on increasing the depth of the compressive residual stress field, on the effect of shot peening on the bending strength of ceramics and on the application of this promising technique to other types of ceramics.

ACKNOWLEDGMENTS

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