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Shot Peening of Ceramics: Damage or Benefit?

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1 Abstract

Non-transformation toughened ceramics show the typical brittle material behavior of failure before deformation at room temperature. Thus, strengthening of ceramics due to deformation induced compressive residual stresses has been thought to be not possible. Nevertheless, preliminary investigations had shown that, using ceramic-specific parameters, shot peening can introduce high compressive residual stresses into the near-surface of silicon nitride and improve the load capacity. The aim of the presented investigation was to improve the shot peening conditions in order to extend the increase of load capacity while maintaining the surface integrity. The materials investigated where alumina and silicon nitride, the properties determined where residual stresses, load capacity and topography. For the assessment of the surface strengthening the X-Ray diffraction analysis (XRD) and the ball-on-plate strength test were used. Due to the low penetration depth of X-rays XRD allows to evaluate the peening-induced residual stresses. In the ball-on-plate test, the sample is loaded with a spherical silicon nitride indenter up to failure of the sample which is detected by a high frequency ultrasonic detector. The results show that high compressive residual stresses in the GPa-range can be introduced in silicon nitride and alumina which may boost the load capacity of the near surface layers by a factor of up to 9. Only little effect on the surface integrity could be obtained.

2 Experimental Details

2.1 Materials Investigated

The materials investigated were a commercially available silicon nitride and a commercially available fine-grained alumina. The most important material characteristics are given in Table 1.

Table 1: Materials investigated.

Material	Specification	Company	Young's modulus	Characteristic strength	Fracture toughness	Ref.
Silicon Nitride	SN-N3208	Ceramics For Industry, CFI	300 GPa	877 MPa	4.2 MPa $m^{1/2}$	[1]
Alumina	A61	Kennametal Hertel AG	390 GPa	400 MPa	4.0 MPa $m^{1/2}$	[2]

2.2 Shot Peening

Shot peening was performed with an injection system. Cemented carbide beads with a diameter of (650 ± 40) μm were shot on the surface of the ceramics using different pressures between 2 bar and 4 bar and treatment times between 280 and 840 seconds. The distance between the sample and the nozzle were 20 cm. All samples were polished using a 1 μm diamond abrasive prior to the shot peening. Because of the lower hardness of the Almen strip in relationship to the ceramics samples the treatment time were chosen 8.5 and 25.5 times longer than reaching the 98 % coverage of the Almen Strip.

2.3 Determination of Residual Stresses and Load Capacity

The load capacity of the shot peened and the polished reference samples was determined using the ball-on-plate test. The load on a 10 mm silicon nitride ball is increased stepwise until a typical cone-crack appears which follows exactly the maximum tensile stresses. Because of the statistical behavior of ceramics, the load which causes fracture varies from test to test within a certain scatter-band. Typically 17 samples with equal surface conditions were tested and the average fracture loads and the corresponding standard deviations were calculated. The stress field of this static ball-on-plate contact is typical for stress fields occurring in contact situation e.g. in roller-bearings. The contact induced stress fields show strong gradients and the tensile stresses, which lead to cracks in brittle materials, are restricted to a very thin surface layer.

The residual stress states of the near-surface layers of the samples were measured by X-ray diffraction. The mean stress values within the penetration depth in the range of 10 μm were evaluated using the so-called $\sin^2\psi$-method [3]. The most important measurement parameters are given in Table 2.

Table 2: Parameters of residual stress evaluations

Material	Lattice plane	Radiation	ψ-range	X-ray elastic constant $\frac{1}{2} s_2$
Silicon Nitride	{411}	CrKα	$-64° \le \psi \le 64°$	3.89 GPa^{-1}
Alumina	{220}	CrKα	$-64° \le \psi \le 64°$	3.15 GPa^{-1}

3 Results

3.1 Residual Stresses and Load Capacities

Fig. 1 correlates the near-surface stress states and the load capacities of polished and differently shot peened silicon nitride and alumina samples. The polished silicon nitride reference samples – representing the near-surface condition prior to shot peening – show small compressive residual stresses in the range of 100 MPa and a fracture load of about 3 kN in the ball-on-plate test.

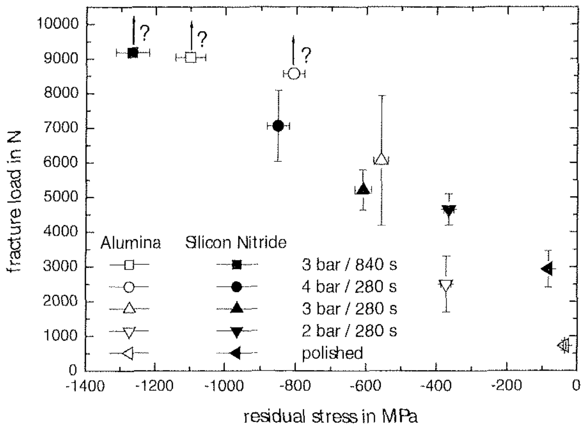

Figure 1: Fracture load versus residual stress of silicon nitride and alumina samples in polished and different shot peened conditions

Shot peening allowed introducing up to 1.25 GPa compressive residual stresses. These compressive stresses shifted the load needed to fracture the surface layers from 3 kN to more than 9 kN. In the case of the samples with the highest compressive residual stresses the increase of near-surface strength was so high, that the load limit (9.2 kN) of the ball-on-plate testing device was reached in some cases and the samples passed the test without any crack. Thus, for the most effective shot peening process no error bar could be calculated for the fracture load. The results for similar experiments on alumina are also shown in Fig. 1. As obtained for silicon nitride high compressive residual stresses up to 1.1 GPa were created to the shot peening. These compressive stresses boost the fracture load from 0.7 kN up to more than 9 kN. Again, the load range of the ball-on-plate testing device was not high enough to introduce Hertzian cone cracks in all samples treated with the two most effective shot peening conditions.

3.2 Surface Roughness

Shot peening may influence the surface integrity in two ways. First, each hit by a bead will produce a localized macroscopic deformation accompanied by the creation of dislocations in the near surface crystallites. These effects are needed to create the strength increasing compressive residual stresses. The superposition of many localized deformations will result in an overall roughness of the surface. The surface topography resulting from a shot peening condition which comprises a more or less complete overlay of dips is shown in Fig. 2. In the optical micrograph nearly no difference between the polished reference surface and the shot peened area can be obtained. In addition no significant transfer of debris to the surface is obtained which can be concluded from the natural voids of the material still being visible at the peened surface.

Fig. 3 shows the average roughness of the surface for the polished reference sample and after different peening treatments respectively. The shot peening of the surface leads to a small increase of the roughness up to 0.09 μm for the highest peening pressure of silicon nitride sam-

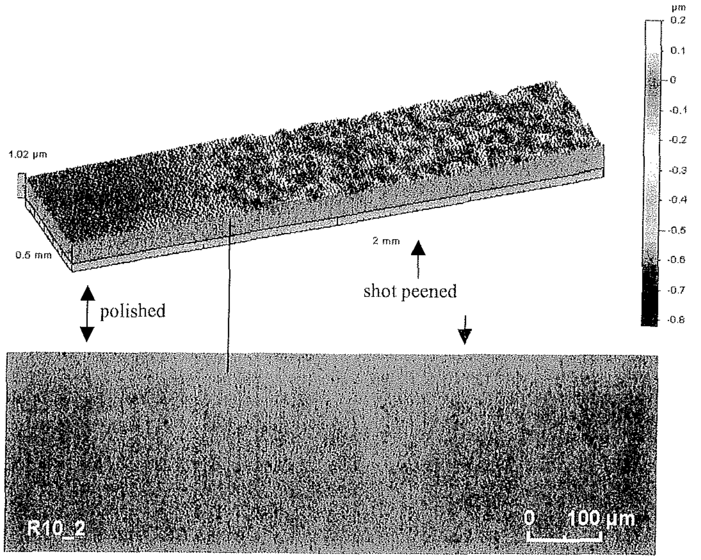

Figure 2: Topographical map (top) and optical micrograph near the boarder between a polished and a shot peened (2 bar) area of a silicon nitride sample

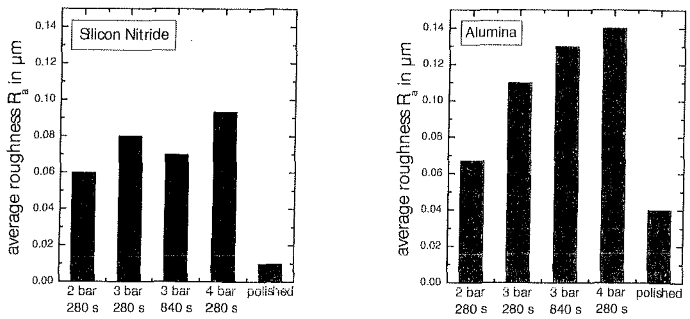

Figure 3: Average roughness R_a of the polished and shot peened silicon nitride and alumina samples

ple and 0.14 µm for the alumina sample. One reason for the higher roughness of the alumina samples could be the lower hardness compared to the silicon nitride ceramic.

3.3 Evaluation of Single Hits

Silicon nitride and alumina samples showed similar results concerning the surface integrity. The area and depth of the localized deformation can be evaluated by inspecting single hits on the

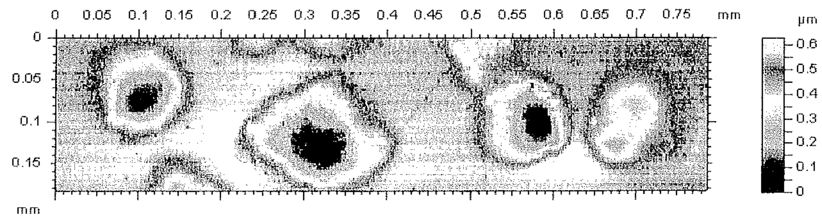

Figure 4: Topography of a polished silicon nitride surface with dips produced by single hits of cemented carbide beads at maximum peening pressure of 4 bar

surface. Fig. 4 shows the topography of the most intense shot peening condition with 4 bar peening pressure.

Fig. 5 shows the mean values of the diameter and depth of single dips as a function of the peening pressure. The mean values were calculated from the measurement of typically 25 dips per peening pressure. Higher pressures leads to a higher velocity of the beads and to a larger deformation. The plastic deformation is somewhat higher in alumina than in silicon nitride.

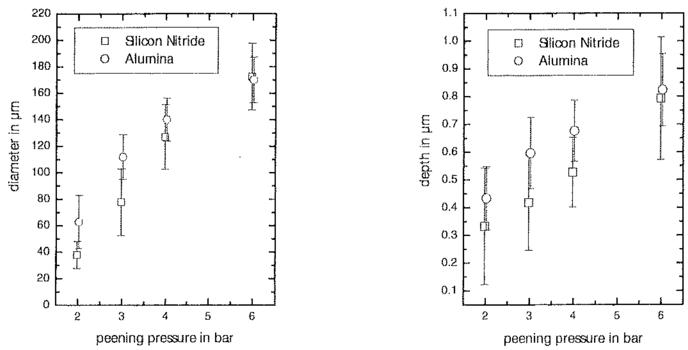

Figure 5: Diameter and depth of single hits by different peening pressures for silicon nitride and alumina

In order to detect a possibly introduced damage due to shot peening the alumina and silicon nitride samples where carefully inspected for cracks. In case of the peening pressures with 3 and 4 bar very few cone cracks could be obtained near some single hits. Fig. 6 shows one of the rarely detectable, partially developed cone cracks near a single hit of an alumina sample.

4 Conclusions

Shot peening is a common technique to improve the strength of metal components. Up to now, it has not been successfully applied to ceramics, as these brittle materials have been assumed to show no significant plastic deformation due to mechanical loading and hence would not de-

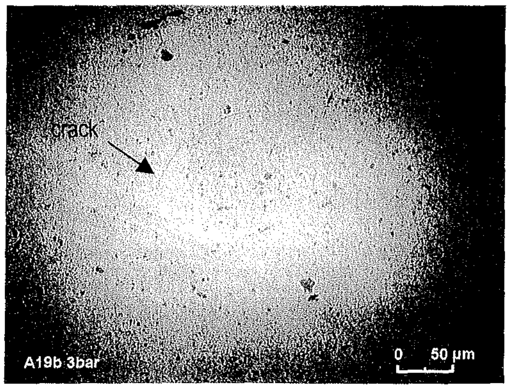

Figure 6: Partially developed cone crack in alumina due to a single hit

velop any residual stresses improving the strength. The presented results show however that under specific shot peening conditions also in brittle materials like silicon nitride and alumina high compressive stresses up to more than 1 GPa can be introduced near the surface. No significant damage is obtained. Exposing these strengthened surfaces to loading situations, which are characterized by a steep near-surface stress gradient, a boost of load capacity and strength can be evaluated. Such loading situation exists in, e.g., roller and sliding bearings or cutting tools. Further investigations will concentrate on increasing the depth of the compressive residual stress field, on the integrity of edges and on the possibility of restoring the strength of »roughly« machined ceramics. The patented shot peening procedure is now going into the first application which is the increase of the load capacity of full ceramic roller bearings.

5 Acknowledgement

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6 References

[1] Rombach, M.: Experimentelle Untersuchungen und bruchmechanische Modellierung zum Versagensverhalten einer Siliciumnitridkeramik unter Kontaktbeanspruchungen, Dissertation Universität Karlsruhe, 1995.

[2] Op de Hipt, M.: Randzonencharakterisierung hartbearbeiteter und tribologisch belasteter Al_2O_3 und SiC-Keramiken, Fortschritt-Berichte VDI Reihe 5 Nr. 521, VDI-Verlag, 1998.

[3] Müller, P., Macherauch, E.: Das $\sin^2\psi$-Verfahren der röntgenographischen Spannungsmessung, Z. ang. Phys. 13, 1961, 305-312.