Ceramic workpiece integrity and residual surface stresses generated by single pass diamond grinding were evaluated for three flaring cup wheels and four machine-loop stiffnesses. Stresses in silicon nitride bars ground on one face were characterized by X-ray diffraction, strength by four-point bending, and grinding damage depth by scanning electron microscopy. A custom-built workpiece holder was used to tune the grinding machine-loop stiffness. Electrolytic in-process dressing was applied to one of the wheels to provide stable cutting conditions. The experimental results indicate machine stiffness does not have significant influence on flexural strength, but rather affects the depth of cut. All ground surfaces have some degree of damage and residual stress, and differences are revealed between wheel bonds and grit sizes. The competing phenomena of strength enhancement due to residual stress and strength degradation due to damage are discussed. © 2000 Kluwer Academic Publishers

1. Introduction

Fixed diamond abrasive grinding is widely studied and applied to produce ceramic components of high quality in terms of form and finish accuracy. While these features are often of primary concern, the processing conditions and final workpiece integrity may be equally important. To economically produce and improve the reliability of brittle materials, the machine dynamics and grinding conditions as well as the resulting workpiece state of stress, subsurface damage and strength should be considered. The fundamental objective of a grinding process is to achieve the maximum possible material removal rate while maintaining sufficient material integrity and dimensional accuracy.

The material removal mechanism in grinding brittle materials involves localized contacts that cause irreversible inhomogeneous deformation and fracture. This process leads to machined components that often contain a deformed layer, surface and subsurface microcracks, material pulverization, smeared areas, phase transformation regions, and other types of surface and subsurface damage [1–8]. This damage is the origin of both compressive and tensile residual stresses. It is well postulated that isolated elastic-plastic contact gives rise to a radially compressive residual stress field, with a corresponding locally tangent tensile residual stress field outside the plastic zone which surrounds the contact site. Strength-degrading cracks form on median planes within the local tensile stress field. Overlapping residual stress fields from adjacent damage sites in the ground surface form a layer of residual compressive stress. This compression tends to reduce, but does not eliminate, the residual tensile stress acting on the strength-controlling flaw [8].

Residual stresses in ceramic materials have long been recognized as having a significant influence on mechanical behavior and surface integrity [8–12]. Compressive residual stresses can enhance the strength of a specimen, in contrast to tensile residual stresses. Additionally, studies have shown that grinding-induced damage can be detrimental to the strength and thus the performance of ceramic parts [13–16]. The extent and nature of machining-induced damage resulting in workpiece strength reduction can strongly depend on the process parameters, for example the machine dynamics, grit depth of cut, or abrasive grit size [13, 17–24]. Furthermore, the extent of strength reduction is also related to the material properties, e.g. microstructure, grain size or fracture toughness [3, 12, 25–27].

Accounting for the process conditions and material properties, the strength of a ground ceramic workpiece depends on the baseline material strength and the competing phenomena of strength enhancement due to residual stress and strength degradation due to damage. Therefore, the strength $\sigma$ may be expressed as $\sigma = \sigma_b + \Delta \sigma_c - \Delta \sigma_d$, where $\sigma_b$ is the baseline workpiece strength; $\Delta \sigma_c$ is the strength gain through the introduction of compressive residual stresses; $\Delta \sigma_d$ is the strength loss due to grinding damage. Under normal grinding conditions, the superposition of strength gain due to $\Delta \sigma_c$ and strength loss due to $\Delta \sigma_d$ occurs simultaneously, which makes predicting ground workpiece
strength is difficult. This suggests that both residual stress and damage measurements are required to predict workpiece strength.

Several researchers have shown that surface grinding transverse to the tensile stress direction in bars subjected to four-point bending results in a lower strength compared to grinding in the longitudinal direction [13, 15, 19, 27]. Rice [27] reported that strength anisotropy, with reference to grinding direction, was higher for finer-grain materials. Strakna et al. [15] showed grinding conditions did not affect the strength in longitudinal direction; however, strength was reduced when grinding was performed in the transverse direction as the volumetric material removal rate was increased by a factor of 30.

Nondestructive and destructive approaches have been explored to assess damage in ceramics induced by a machining process. Ahn et al. [28] used an ultrasonic technique to detect subsurface lateral cracks in silicon nitride subjected to diamond indentation. A thermal wave measurement technique was also investigated. Both of these methods were successful in detecting cracks, but were less successful in detecting damage depth.

In order to directly observe subsurface damage, destructive techniques are likely required. Yoshikawa et al. [5], and Zhang and Howes [6, 7] used four methods to characterize damage induced by a single-point diamond for several ceramics. The slicing, etching, fracture and taper polishing methods were claimed to be equally effective for multiple-point diamond grinding. A different technique was used by Xu and Jahnmir [29], where an adhesive was used to mate the polished faces of two specimens prior to grinding, leaving approximately 1 μm between each specimen. After machining, the specimens were separated and optically viewed to identify subsurface damage.

Perhaps the most common method for evaluating machining effects on the strength of brittle materials is a bending test, where the surface of interest is subjected to tensile stress in bending. Using this technique, many investigators have assessed the effects of various grinding parameters and conditions on the bending strength of ceramics [12, 13, 15, 19, 20, 30].

The objective of this experimental study was to characterize the competing phenomena of strength enhancement due to residual stress and strength degradation due to damage for high pressure sintered silicon nitride (HPSSN) ground using flaring cup diamond wheels under several conditions. Three wheels were used, enabling two mean grit sizes and two bond types to be evaluated. Grinding was done in the transverse direction (using longitudinal feed) relative to the stress direction used in four-point bending tests. Results for four machine stiffnesses and two set depths of cut are reported. Residual surface stresses are characterized by X-ray diffraction. Surface finish measurements were done with a profilometer, and a standard four-point bending test was used to measure the workpiece transverse bending strength. After the strength tests, the largest remaining workpiece sections were taper lapped to ascertain the mean subsurface grinding damage using scanning electron microscopy (SEM). In addition, several samples were etched in hydrofluoric acid to observe the grinding damage.

2. Experimental procedure

All grinding tests were conducted on a precision grinding machine (Dover Instrument Corporation, Model 956-S) capable of achieving sub-micron tolerances. The vertical-spindle machine had a granite base and column to support the X-Y-Z aerostatic table and aerostatic spindle respectively. A closed-loop laser interferometer system provided a 75 nm slewing positioning resolution in the X, Y and Z-directions. The spindle axial run-out was 0.05 μm and the slide straightness error was 0.01 μm over 25 mm.

Single pass grinding was used on the HPSSN (Applied Signal Inc., GS-44) workpieces. Additional properties for the single phase polycrystalline material are shown in Table I. Two set depths of cut (SDOC) and four machine stiffnesses were used for each wheel. The approach used in this study was to select an SDOC and vary only the machine stiffness. In this way the actual depth of cut (ADOC), and hence the stock removal rate, changed with machine stiffness. This approach was selected to observe the static and dynamic responses of the machine for a given input (SDOC). The post grinding measurements reported are surface finish, bending strength, surface residual stress and damage depth.

2.1. Grinding process configuration

A unique aspect of this research was the application of the compliant workpiece holder shown in Fig. 1.

![Figure 1 Adjustable-compliance workpiece holder.](image-url)