Novel Kinematics for Cylindrical Grinding of Brittle Materials

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Abstract

Brittle materials are characterised by grinding direction related strength anisotropy attributed to the dual population of grinding induced microcracks. Surface grinding operations are therefore implemented such that the grinding lay is along the direction of maximum tensile stress in the component, which corresponds to minimal strength degradation. The kinematic configuration of conventional machine tools inherently precludes such an approach in cylindrical traverse grinding. To this end, the paper presents aspects of an innovative material-adapted kinematic variant, which corresponds to an enhancement in characteristic flexural strength of about 30% as compared to conventionally ground quartz samples.

Keywords:
Grinding; Anisotropy; Strength

1 INTRODUCTION

The widespread use of advanced engineering ceramics in high performance applications continues to be elusive despite their remarkable technological characteristics and concerted global research efforts in the past decade. One of the outstanding issues is the strength of these materials being susceptible to microscopic machining induced flaws that have an adverse impact on component performance and reliability.

Material removal rates currently employed in machining such brittle materials are highly conservative with a view to controlling surface integrity, which adds to the machining costs that are already prohibitive. Maximizing machining productivity with due consideration for constraints arising with reference to strength degrading surface damage is therefore the key to exploiting these materials. In this context, this paper details a novel, material-adapted machining process for cylindrical grinding of brittle materials, designed to facilitate enhanced material removal rates with the least detriment to strength.

2 BACKGROUND

A feature that is both academically intriguing and technologically significant in the grinding of brittle materials is the phenomenon of strength anisotropy in relation to the grinding direction. This serendipitous discovery is a consequence of the dual population of grinding induced microcracks in the material.

Malkin and Hwang present a comprehensive review [1] of the extensive literature on the mechanics of crack formation in brittle materials, as applied to grinding. The geometric characteristics of the crack system associated with scratching that simulates a single abrasive workpiece interaction event, is quite different from that of quasi-static normal indentation. Modelling the stress field in scratching using the Mitchell solution reveals [2] that the effect of the tangential load component associated with the relative motion of the abrasive is to increase tensile stresses normal to the direction of motion ahead of the point of contact. This favours the formation of median cracks along the direction of grinding, and as a result, they are usually deeper and somewhat elongated in shape, in comparison to radial cracks that are created across. The larger size and elongation of the median cracks cause the corresponding fracture strength σ_T in the transverse direction to be usually lower than σ_P measured parallel to the grinding direction (Figure 1). This is on account of a tensile stress in the transverse direction activating the median rather than the radial cracks.

In peripheral surface grinding of brittle components, care is hence taken to accomplish grinding along the direction of application of maximum tensile stress, such that failure would originate from the radial cracks, which relates to minimal strength degradation. For instance, a standard [3] for testing the flexural strength of advanced ceramics specifically stipulates surface grinding along the longitudinal axis of the test specimen. Similarly, the strength of silicon nitride bars that are surface ground longitudinally has been found [4] to be independent of the material removal rate, even when it was varied by a factor of 30, whereas the strength of samples ground transversely was considerably lower, and of a decreasing function of the removal rate. The ratio of the direction dependent strengths could be as high as 2, depending on the material, grain size and porosity [5].

In contrast to surface grinding, the strategy of orienting the grinding direction so as to exploit the phenomenon of strength anisotropy is not practicable in cylindrical grinding.

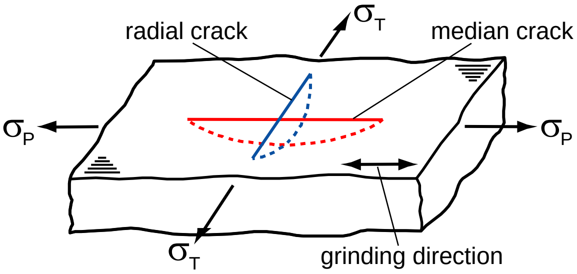

Figure 1: Grinding induced cracks in brittle materials.

This is due to the intrinsic kinematics of conventional machine tools rendering the grinding lay to be perpendicular to the longitudinal axis of the component (see Figure 2), which refers to transverse grinding. Appropriate as they are for grinding metals, the unfavourable implication for brittle materials ground on such machine tools is that the median cracks would indeed actuate failure in flexure, resulting in severe strength degradation. It is hence desirable to develop a kinematic scheme especially suited to cylindrical grinding of brittle materials, which takes advantage of the strength degradation anisotropy.

Several instances of process performance enhancement through adoption of an appropriate kinematic configuration can be found in the literature. Sakaida and Tanaka [6] report lower strength degradation in face grinding of silicon nitride workpieces owing to the process kinematics being such that flaws are induced in the stock that is subsequently removed, in comparison to peripheral surface grinding wherein the flaws are left beneath the generated surface. Likewise, Denkena et al. [7] obtained a surface finish in face grinding of silicon that was 7 times as good as in peripheral surface grinding, due to grinding performance in face grinding being independent of the topography, profile and wear of the grinding wheel. Tönshoff et al. [8] review an innovative kinematic scheme wherein the wheel axis is tilted relative to the axis of the workpiece in an external traverse cylindrical grinding process so as to reduce the wheel-work contact length. This has been found to reduce thermal and mechanical loads, and result in an enhanced surface integrity attributed to effective cooling linked to the reduced contact area.

3 PROPOSED NOVEL PROCESS

The process kinematics proposed in this paper is a variant of conventional cylindrical grinding (Figure 2), and is realized by the relative rotation of the wheel through 90° in the horizontal (XY) plane such that the grinding lay is along the longitudinal axis of the component, with a view to enhancing its flexural strength.

Unlike conventional traverse cylindrical grinding, wherein wheel wear is localized at the leading edge of the wheel, wear in the novel process would tend to occur along a thin circumferential band. Wear can however be distributed uniformly over the wheel width by inclining the workpiece in the XY plane in relation to the feed direction, so as to engage different sections of the wheel as the workpiece traverses past it in the X-direction. Alternatively, an appropriate cross feed could be implemented in the Y-direction.

In the novel configuration, the wheel-work contact area is independent of the wheel width, unlike conventional cylindrical grinding. For typical grinding parameters, the contact area would therefore be comparatively lower in the novel process. The reduced contact area should be beneficial in terms of lower grinding forces that translate into better geometric form and dimensional tolerances when grinding slender components between centres, and in promoting effective cooling due to facilitated access of grinding fluid into the grinding zone. The difference in kinematics however brings about a disparity in the overlap ratio vis-à-vis conventional cylindrical grinding, as explained below with reference to Figure 3.

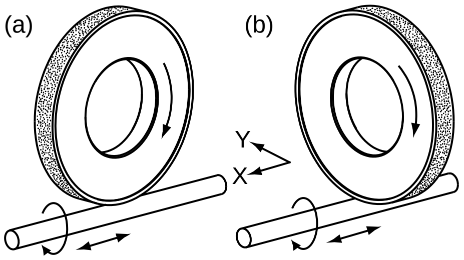

Figure 2: (a) Novel, and (b) conventional cylindrical traverse grinding.

In conventional cylindrical grinding, the overlap ratio is given by (b_s/f_a) where b_s is the wheel width and f_a is the feed per revolution of the work. In the novel process, the overlap ratio can be written as (l_c/f_a), where $l_c=\sqrt{(d_s a_p)}$ is the geometric wheel-work contact length projected along the feed direction, d_s is the wheel diameter and a_p is the radial depth of cut. The machining time per pass in both cases is determined only by the traverse feed rate v_{ft}. For a constant radial depth of cut, if both the machining time and overlap ratio need be the same between the two configurations, the work speed v_w in the novel process would have to be increased by a factor of (b_s/l_c).

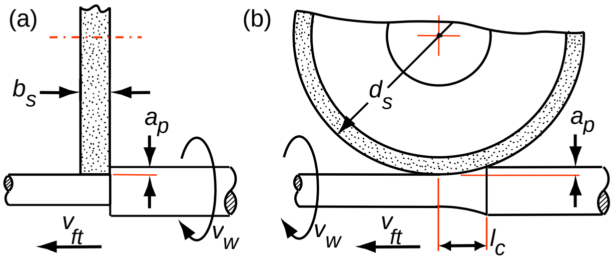

Figure 3: Comparison of overlap in: (a) conventional, and (b) novel processes.

4 EXPERIMENTAL

To validate and quantify the efficacy of the novel concept, fused silica (General Electric Type 214 quartz) rods of 7 mm diameter were ground to a diameter of 6.5 mm, using conventional and novel processes. The taper was less than 5 μm over the specimen length of 100 mm.

Quartz was chosen as the work material to facilitate quantitative fractographic analysis of the ground samples, considering that microstructural features could possibly obscure fracture origins in ceramic materials like alumina. The processes were compared in terms of flexural strength and surface finish, with the machining time and material removal rate maintained identical between the two configurations to establish parity.

Grinding was accomplished centerless and wet, in the down grinding mode with no spark-out passes. Experiments involved a 203 mm diameter, 12.7 mm wide, 1A1 resin-bonded diamond wheel with 140/170 mesh size abrasives of 75 concentration. The wheel speed, work speed, axial feed rate and radial depth of cut per pass were 30 m/s, 441 rpm, 2.54 mm/s and 10 μm, respectively, for both configurations. Since the time taken to machine a sample was the same in both cases, for the grinding conditions listed above, the overlap ratio for the novel configuration was ~9 times as small as the conventional process.

Ground samples were strength tested using a semi-articulating four-point flexure fixture meant for cylindrical rods, with inner and outer spans of 40 and 80 mm respectively. 15 samples each for the novel and conventional configurations, and 15 as-drawn samples were tested in a single set-up, following a random order. The results were analysed using 2-parameter Weibull statistics, adopting the maximum likelihood method. Fractographic analysis of samples was performed with the aid of optical and scanning electron microscopy.

5 RESULTS AND DISUSSION

5.1 Flexural strength

Figure 4 presents a comparison of the strength distribution of samples ground in the novel and conventional processes in perspective to strength of as-drawn quartz, in the form of a Weibull plot. Inspection of the fracture surfaces indicated that failure in ground samples originated exclusively from grinding-induced surface flaws, unlike as-drawn samples that comprised a dual distribution of material flaws and handling damage. The single active flaw population in the ground samples is exemplified by the better fit of the corresponding data to a linear trend in the Weibull plot, in comparison to as-drawn samples.

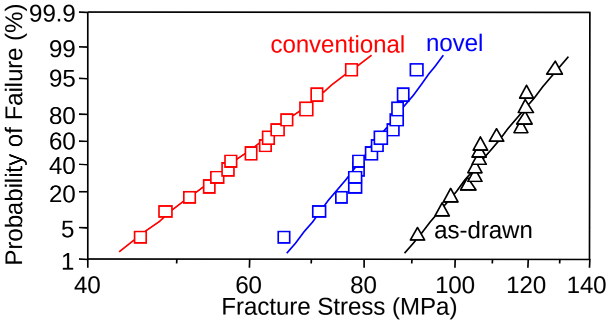

Figure 4: Weibull plot of strength data.

The morphology of the ground surfaces was indicative of a material removal mechanism dominated by fracture rather than plastic deformation, as observed by Huerta and Malkin [9] during diamond grinding of glass, which explains the lower strength of the ground samples. The Weibull parameters corresponding to flexural strength of the ground samples (Table 1) however denote that the characteristic strength obtained in the novel process is 30% higher than that in the conventional process. Furthermore, the Weibull modulus realized in the novel process is about twice as high, which signifies a lower variability in strength. These indices represent a truly substantial quality enhancement in the novel configuration, which entails just a simple adaptation of process kinematics.

Subsequent to strength testing, samples were examined fractographically with the objective of comprehending the difference in strength obtained in the two processes. Typical fractographs are shown in Figure 5 with the fracture origins indicated by arrows. In all cases, fracture mirrors were incomplete and elongated in the radial direction, characteristic of failure in bending that entails a stress gradient. The fracture surfaces also displayed minimal mist and hackle, more so in the conventionally ground samples, due to their lower strength.

Figure 6 depicts representative fracture origins with the fracture surface tilted somewhat to expose part of the ground surface. The origins comprised distinctive 'V' features characteristic of grinding flaws that are not quite perpendicular to the tensile stress (specimen) axis, which relate to the spiral lay pattern associated with the wheel cross feed in cylindrical grinding [10].

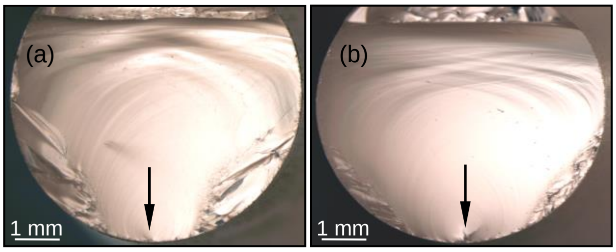

Figure 5: Representative fracture surfaces relating to: (a) novel, and (b) conventional processes.

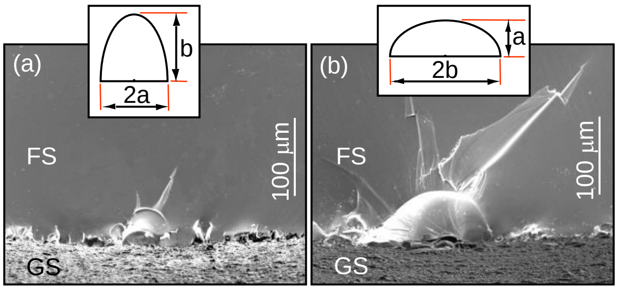

Figure 6: Typical fracture origins corresponding to:
(a) novel, and (b) conventional processes.
(FS: fracture surface; GS: ground surface)

The geometric characteristics of grinding flaws are in good agreement with the data reported by Mecholsky et al. [11] who investigated surface grinding of soda-lime glass with a wheel of a grit size similar to the one used in the present work. The flaws induced in conventional cylindrical grinding were significantly larger in respect of corresponding flaws in the novel process. Furthermore, approximating the flaws to be semi-elliptical in shape, the major axis of the ellipse was found to be oriented along the circumferential direction in conventionally ground samples, in contrast to along the radial direction in samples ground in the novel process (see insets in Figure 6). The former relates to a higher stress intensity.

The stress intensity factor is quite insensitive to the curvature of the free surface [12]. It is hence expedient to apply an approximate solution available for surface flaws in a flat plate to cylindrical rods, which would otherwise necessitate advanced three-dimensional numerical techniques. Accordingly, the ratio of the average strengths σ_n and σ_c can be expressed [13] as:

$$\sigma_n / \sigma_c = \left(\sqrt{a_c / a_n}\right)\left(\Phi_n / \Phi_c\right) \tag{1}$$

where the subscripts n and c refer to the novel and conventional processes, respectively; a is the flaw size that refers to the semi-minor axis of the ellipse, and Φ is the stress intensity shape factor given by the complete elliptical integral of the second kind, evaluated as:

$$\Phi(a/b) = \int_0^{\pi/2} \sqrt{\cos^2\theta + (a/b)^2 \sin^2\theta}\, d\theta \tag{2}$$

b being the semi-major axis of the flaw. Substitution of appropriate variables in equation 1 with values from Table 1 yields a ratio of 1.56 that represents an error of

Table 1: Comparison of novel and conventional processes (Intervals indicated denote 95% confidence limits).

Process	Characteristic strength (MPa)	Weibull modulus	Average strength (MPa)	Average flaw size a (μm)	Average flaw aspect ratio (a/b)	$\Phi(a/b)$
Novel	83.5 (80.6, 86.5)	15.2 (10.2, 22.6)	80.6 ± 3.4	32 ± 3	0.61	1.286
Conventional	64.1 (60.0, 68.4)	8.2 (5.7, 11.9)	60.7 ± 4.0	72 ± 4	0.54	1.239

~15% with reference to the measured ratio of average strengths of 1.33, a discrepancy typical of approximate fracture mechanics analyses. The analysis above further indicates that the difference in strength between the two processes is accounted for in large part by the two-fold difference in flaw size, with the shape factor relegated to a relatively minor influence.

Depending on the application, the proposed novel process would not be warranted if grinding entails a wheel with a grit finer than 600 mesh size, since in such cases, strength is largely controlled by intrinsic material flaws rather than grinding damage [10]. Similarly, in addition to the evident limitation of grinding certain geometries such as square shoulders, the process would also be not essential for grinding coarse-grained or porous materials that do not exhibit significant strength anisotropy [5].

5.2 Surface finish

On account of the material removal mechanism being predominantly fracture related, the roughness along and across the grinding direction was found to be not significantly different, for samples ground in both configurations.

Figure 7 details the distribution of the surface roughness parameter R_a obtained in the conventional and novel processes, measured along and perpendicular to the specimen length, respectively, based on a sample size of 48 measurements each. It can be seen that the mean roughness (1.31±0.04) obtained in the novel process is fairly higher than the samples ground conventionally (1.00±0.04), although the variability is similar. This is to be expected considering that the overlap ratio in the novel process was about an order of magnitude lower, and therefore pertains to a relatively insignificant spark-out effect.

The extent of spark-out can however be enhanced in the novel process by increasing the work speed, without incurring any increase in the grinding cycle time. Though this would lead to an increase in the grit depth of cut, it can be expected to not have an adverse influence on component strength, considering that flexural strength has been found [14] to be independent of grit depth of cut, provided grinding is performed longitudinally as in the novel process.

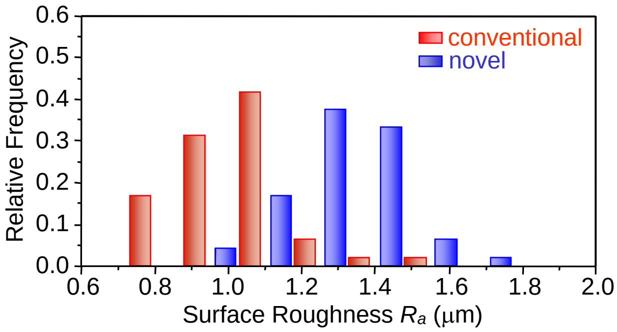

Figure 7. Comparison of surface finish obtained in novel and conventional processes.

6 CONCLUSIONS

The paper presents the scientific basis and proof of concept for the kinematic configuration of a new class of machine tools especially suited for cylindrical grinding of brittle materials. The proposed material-adapted innovative kinematic variant of the cylindrical traverse grinding process related to reduced variability and a 30% increase in characteristic strength, in the grinding of quartz samples. The commercial implications of this new technology cannot be overemphasized, given that a large proportion of components manufactured using brittle materials comprise cylindrical features that require grinding.

7 ACKNOWLEDGMENTS

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