Specific grinding energy as an in-process control variable for ductile-regime grinding

Thomas G. Bifano* and Steven C. Fawcett†‡
* Aerospace and Mechanical Engineering, Boston University, Boston, MA, USA, and † Precision Engineering Center, North Carolina State University, Raleigh, NC, USA

This article addresses the problem of monitoring the material removal regime (ductile versus brittle) that occurs during the grinding of brittle materials. Often a ductile grinding regime is desired, but currently there is no way to measure the grinding ductility "in process." A model is developed to describe the dependence of the specific grinding energy on the material removal regime. It is found that the specific grinding energy will remain relatively constant for ductile-regime grinding but will decrease in a power-law relationship with an increasing material removal rate for brittle-regime grinding. Experimental confirmation of the proposed model is presented. The potential for using measurements of specific grinding energy to control the grinding ductility is established, and the benefits of such a closed-loop feedback system in ductile-regime grinding are explained.

Introduction

For many hard materials a transition from the brittle to the ductile grinding regime can be accomplished by precisely controlling the grinding in-feed rate.[1,2] *Ductile-regime grinding* is rapidly becoming an important machining process for the production of high-precision components from brittle materials.[2–4] Ductile material removal is a plastic deformation process, producing a smooth surface with no grinding-induced surface or subsurface fracture. Components produced using this process need little or no postpolishing. Alternatively, brittle-regime grinding is characterized by the removal of material through the formation and propagation of deep, irregular cracks in the workpiece surface. In general, components ground in the brittle regime require iterative polishing processes subsequent to grinding to remove this fracture damage. Therefore, the promise of ductile-regime grinding is that glasses, ceramics, and crystalline materials can be machined to precise tolerances using a deterministic process, without the need for extensive nondeterministic polishing.

Background

An analytic derivation has been developed for the transition from brittle-regime grinding to ductile-regime grinding. This model can predict the transition as a function of the material properties of the workpiece and the depth of cut made by an individual diamond abrasive grain of the grinding wheel.[2–5] It was found that there was a critical grain depth of cut, d_c, for the brittle-to-ductile transition. For grain depths of cut below the threshold value, the material removal process was largely ductile. For grain depths of cut above the threshold value, the material removal process was mostly brittle. In a series of plunge-grinding experiments, the model was shown to be reasonably accurate for most brittle materials.[1,2]

There are several difficulties in using this model to obtain ductile-regime grinding in an actual grinding operation. First, the model requires measurement of the abrasive grain depth of cut. If there is a single high diamond on the wheel, the grain depth of cut is equal to the plunge-grinding in-feed rate. Though unlikely to be physically accurate, the single-grain grinding wheel model has proved useful as a first-order approximation of actual grinding processes. If many diamonds protrude from the wheel at a given height, then the grain depth of cut is equal to the in-feed rate

divided by the number of active diamonds along a given cutting path of the wheel. This approximation is also inadequate to describe the geometry of the grinding wheel. It is more reasonable to assume that the trued grinding wheel consists of diamond grains protruding random distances beyond the grinding wheel bond, in which case the grain depth of cut can vary considerably in a single wheel revolution. On a well-controlled, stiff plunge-grinding system, the largest grain depth of cut made by diamonds randomly protruding from the bond is fixed by the in-feed rate per wheel revolution (i.e., it is some unknown but constant fraction of the in-feed rate). For all three diamond distribution geometries described previously, the maximum grain depth of cut is proportional to the in-feed rate per grinding wheel revolution. For contour grinding, the relationship between machine parameters and grain depth of cut is considerably more complicated, though recent research has successfully provided a mapping between machine parameters and grain depth of cut for some geometries of grinding by assuming a single "high spot" on the grinding wheel.[6] Also absent in the ductile-regime grinding model are the influences of other *machining variables* (grinding wheel bond, grinding wheel grit size, coolant chemistry, number of active grinding grains, grain height distribution) and *material properties* (work-hardening, temperature dependence, microstructural features), many of which have been shown to influence the critical depth of cut significantly.[1] Finally, there is a problem in that the model relates the critical depth of cut to the workpiece material properties K_{IC}, H, and E. These properties are difficult to measure at the material surface. They can be evaluated for the near-surface ($\sim 1 \mu m$) region using microindentation techniques,[7] but property values can vary considerably with the depth at which they are measured. Since the grinding processes described in this article often extend only several nanometers below the material surface, property values measured using micrometer-scale indentation are of questionable value.

Because of these problems, it is unrealistic to depend on open-loop control of the grinding ductility using the critical depth of cut model. If ductile-regime grinding is to be ensured while maintaining high productivity (e.g., as large a material removal rate as possible), some indicator of grinding ductility must actually be measured in real time for use in an active closed-loop control of the machining parameters.

A promising idea for real-time control of grinding ductility is the measurement of specific grinding energy (μ). The specific grinding energy is a direct measurement of the work required to remove material, and it will be demonstrated in this article that this quantity can theoretically be expected to provide a sensitive measure of the material removal regime. Actual measurements of μ

during the grinding process corroborate this theoretical model, offering some hope for the development of feedback control systems that could be used to maintain a ductile material-removal regime. The specific grinding energy model and the experimentally obtained results are presented.

The specific grinding energy

In ultraprecision grinding of brittle materials, the transition from ductile-regime grinding to brittle-regime grinding that results from an increasing grinding grain depth of cut is accompanied by a reduction in the specific grinding energy. Furthermore, as the grain depth of cut is increased beyond the transition point into purely brittle grinding, the specific grinding energy continues to decrease. The following analysis of the physical process of material removal provides a foundation for the relationship between specific grinding energy and grinding grain depth of cut.

Development of a specific grinding energy model

Figure 1 is a schematic of an abrasive grain-removing material in a ductile regime from a brittle workpiece. If the grinding load is small, then the grain plows a trough via plastic deformation of the workpiece, leaving a ductile-ground groove and a subsurface region of plastically deformed material. This is the ductile material-removal regime. Just beneath the plastic deformation zone is a region of residual tensile elastic stress resulting from the plastic deformation. If the grinding load is increased, the groove depth, plastic deformation zone, and elastic tensile stresses are also increased. At some critical grinding load, a median crack forms beneath the abrasive grain, propagating to a depth c_m. If the
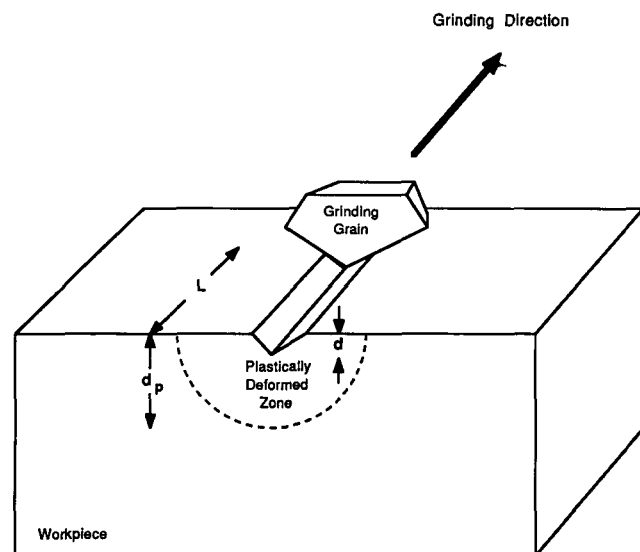

Figure 1 Schematic of an abrasive grain removing material from a brittle workpiece via ductile-regime grinding

load is increased above the threshold for median crack formation, the residual stresses left in the workpiece at the base of the plastic deformation zone will propagate cracks after the grinding grain has passed. These are called lateral cracks, and their formation and propagation to the workpiece surface leads to brittle material removal. The volume of material removed is determined by the lateral crack boundaries. A schematic of brittle-regime material removal is illustrated in *Figure 2*.

While there is a continuous increase in grinding energy (E) necessary to progress from ductile cutting to the onset of median cracking and finally to brittle lateral cracking, the volume of material removed increases discontinuously when the material removal mechanism changes. Furthermore, the volume of material removal is not linearly related to the grain depth of cut in brittle grinding, as it is in ductile grinding. Rather, it is related to the lateral crack dimensions. Since the specific grinding energy (μ) is a function of both the grinding energy and the volume of material removed, it is expected that a change in the specific grinding energy will accompany a transition from ductile-regime grinding to brittle-regime grinding. An attempt to quantify the relationship between the specific grinding energy and the grain depth of cut follows.

As a first-order approximation, it can be assumed that the tangential force generated by a single abrasive grain removing material through plastic flow is given by

$$F_T \approx 3\sigma_Y A_c \qquad (1)$$

where F_T is the tangential grinding force on the grain, σ_Y is the yield stress for the workpiece material, A_c is the cross-sectional area of the grinding groove in a plane normal to the direction of
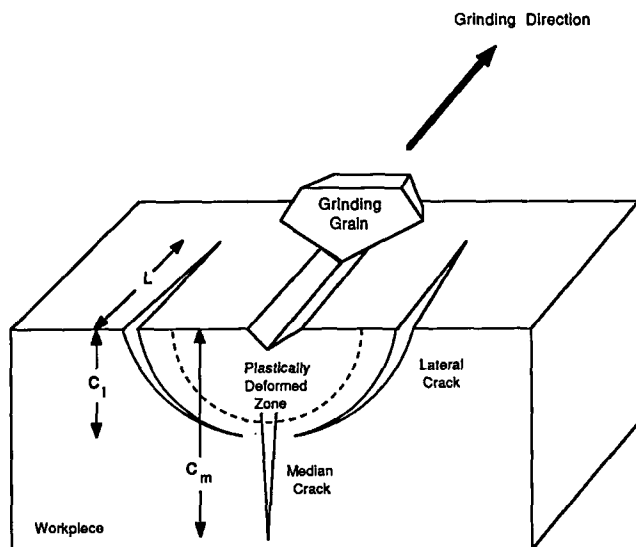
grinding, and H is the material hardness. The equation represents the assumption that all of the material in the path of the rigid grain is removed by plastic deformation. This approximation has been used with reasonable results in predicting the tangential cutting forces in ultraprecision diamond turning.[8] The energy, E_d, expended by the abrasive grain for this ductile cutting process is the product of the tangential force, F_T, and the cutting length, L:

$$E_d = F_T L \qquad (2)$$

For a grinding length of cut L, the volume of material removed by a ductile process is $V_d = A_c L$. From Equations (1) and (2) the specific grinding energy can be estimated:

$$\mu_d = \frac{E_d}{V_d} \approx 3\sigma_Y \approx H \qquad (3)$$

where the subscript d denotes a ductile process.

The equation is presented to identify the critical parameters associated with ductile material removal. It is not intended to be a completely accurate measure of the specific grinding energy since the energies associated with the creation of new surface area and the subsurface plastic and elastic deformations are neglected. To the extent that the material hardness H is independent of the grain depth of cut, this analysis indicates that the specific grinding energy remains *constant* with respect to changes in the grinding grain depth of cut, d. That is

$$\mu_d = K_d \qquad (4)$$

The applicability of this model to ductile cutting has been described in previous analytic and experimental research on energy dissipation in ultraprecision diamond turning of ductile materials. In a recent study of ultraprecision machining of copper, for example, it was found that the specific machining energy remained constant when μ reflects only chip formation energy (i.e., cutting) but was a decreasing function of depth of cut when rubbing and plowing energies became significant.[9] Similar behavior might be expected for brittle materials when they are machined in a ductile regime. To the extent that rubbing and plowing forces can be neglected, the constant μ model of Equation (4) is an acceptable first-order model.

When the grinding load increases to a value large enough to propagate lateral cracks, a different relationship between the specific grinding energy and the grain depth of cut emerges.

It will be assumed that to the first order, the material removed through lateral cracking is a half-cylinder of radius c_l and length L. Therefore, the volume of material removed is

$$V_b = \frac{\pi}{2} c_l^2 L \qquad (5)$$

where the subscript b refers to brittle-regime cutting.

Figure 2 Schematic of an abrasive grain removing material from a brittle workpiece via brittle-regime grinding

For Vicker's indentation of brittle materials, it has been shown that the median crack length c_m is related to the normal indentation load F_n by a power law[7]

$$c_m \propto F_n^{2/3} \tag{6}$$

Previous studies on abrasive machining of glass in the brittle regime permit the conclusion that in such processes the *depth of subsurface damage* is approximately seven times the *peak-to-valley roughness*.[10,11] Referring to the schematic of brittle grinding depicted in *Figure 2*, it is reasonable to estimate the depth of subsurface damage as c_m. Also, since the surface left after brittle grinding is predominantly formed by lateral cracks intersecting the material surface, it is reasonable to estimate the peak-to-valley roughness as c_l, the radius of the lateral crack. For this analysis, then, it will be assumed that the median crack length is seven times the lateral crack radius, independent of the grinding grain depth of cut. This permits a scaling relation

$$c_m \propto c_l \tag{7}$$

The Vicker's hardness relation ($F_n = \beta H d^2$) is strictly valid only for indentations without fracture. Nonetheless, it has been verified experimentally that the existence of median cracks up to 100 μm in glass does not alter the hardness relation.[12] Therefore, even in brittle indentation it is a reasonable assumption that

$$F_n \propto d^2 \tag{8}$$

where d is the depth of indentation. If these indentation results can be extended to grinding, then one can combine Equations (6), (7), and (8) to obtain

$$c_l \propto d^{4/3} \tag{9}$$

The energy, E_b, necessary for brittle fracture of workpiece along the lateral crack is given by

$$E_b = A_s \gamma_s \tag{10}$$

where A_s is the area of new surface generated by fracture and γ_s is the surface energy of the material (usually a constant). The area of fracture surface generated by median and lateral cracks can be estimated as two half-cylindrical surfaces of radius c_l and length L (the lateral crack) combined with two planar surfaces of dimensions $c_m \times L$ (the median crack). The energy for brittle fracture can now be found:

$$E_f = (2\pi c_l + 2c_m) L \gamma_s \tag{11}$$

where the subscript f denotes the energy corresponding to material removal processes involving fracture.

The energy required to generate the plastic deformation zone depicted in *Figure 2* might also be significant in brittle cutting. It has been established that lateral cracks nucleate at the bottom of the plastic deformation zone. This result is derived from Hill's classic plasticity solution for a point load on a semi-infinite elastic/plastic half-plane, which concludes that the maximum residual tensile stresses after indentation and unloading occur at the elastic/plastic boundary some distance beneath the point of indentation. Both theoretical plasticity models[13] and observation[14] have confirmed this result for diamond indentation and scratching of glass. Therefore, if the diameter of the plastic deformation zone (d_p) is approximately equal to the radius of the lateral cracks (c_l), one can conclude from Equation (9) that $d_p \propto d^{4/3}$. The energy required to generate the plastic deformation zone scales with the material's yield stress and the volume of material deformed. That is

$$E_p = \alpha \sigma_Y V_p \tag{12}$$

where α is a constant and V_p is the volume of the plastic deformation zone. If the plastic deformation zone diameter d_p is approximately equal to c_l, then $V_p \approx \frac{\pi}{4} c_l^2 L$, and the total energy for brittle-regime grinding is

$$E_b = E_f + E_p = \left(2\pi c_l \gamma_s + 2c_m \gamma_s + \frac{\pi}{4} \alpha \sigma_Y c_l^2 \right) L \tag{13}$$

The specific grinding energy for brittle grinding, μ_b, can be found by combining Equations (5), (7), and (13):

$$\mu_b = \frac{E_b}{V_b} = K_1 + \frac{K_2}{c_l} \tag{14}$$

where K_1 and K_2 are geometric and material constants.

The resulting relationship between the specific grinding energy and the grain depth of cut for brittle-regime grinding is found by combining Equations (9) and (14):

$$\mu_b = K_b d^{-4/3} + K_p \tag{15}$$

where K_b is a combination of geometric constants and the material properties K_{IC}, E, H, and γ_s, and K_p is a constant proportional to H representing the relative energy expended to create the plastic deformation zone. Physically, Equation (15) predicts that the specific grinding energy will decrease with an increasing grain depth of cut, asymptotically approaching a constant value K_p for large values of d. While this analysis represents considerable simplification of the grinding process, it is a fairly accurate model of the relative dependence of specific grinding energy on the material removal regime, as shown in the following section.

Experimental results

The specific grinding energy for a plunge grinding operation is given by

$$\mu = \frac{F_T v_w}{L d w} \tag{16}$$

Table 1 Grinding conditions for plunge grinding experiments

Configuration	10-cm diameter, 6.3-mm wide cup wheel, plunge grind
Grinding wheels	4-8 μm diamond
In-feed rate	Controlled. Adjustable range: 1–1,000 nm/rev
Workpiece	5 mm × 5 mm × 20 mm parallelepipeds
Fixed conditions	$v_w = 0.314$ m/rev, $w = 6.3$ mm, $L = 5$ mm

where μ is the specific grinding energy, F_T is the tangential grinding force, v_w is the normalized wheel speed (wheel peripheral speed divided by wheel rotational speed), L is the workpiece length in the cutting direction, d is the normalized workpiece in-feed rate (in-feed rate divided by wheel rotational speed), and w is the grinding wheel rim width.

For plunge grinding, d is proportional to the grinding grain depth of cut for an individual abrasive grain.

Soda-lime glass, BK-7 glass, fused silica glass, HIP silicon carbide, and CVD silicon carbide were ground at various controlled grinding in-feed rates under the conditions described in *Table 1*. For each of these experiments, the tangential grinding force was measured during grinding either by monitoring the grinding-spindle motor torque or by measuring the overall tangential grinding force directly using a piezoelectric force gauge mounted on the workpiece holding mechanism. All measurements included only forces between the wheel and the workpiece, excluding spindle resistance but including hydrodynamic and frictional forces between the workpiece and the grinding wheel. In relating measured specific grinding energy to the model, it was assumed that the measured grinding energy was dominated by cutting energy. The grinding wheel was re-trued before each cutting test. The average tangential grinding force was measured for the last 10 μm of a 40-μm overall grinding depth. After grinding, each workpiece was analyzed using scanning electron microscopy or optical interference microscopy to determine the area percent of surface fracture that resulted from the grinding operation. Soda-lime glass, BK-7 glass, fused silica glass, and HIP SiC all exhibited significant ($\geqslant 5\%$) surface fracture when plunge ground under the conditions described. In *Figure 3* are graphs of the measured μ versus the grain depth of cut to the $-\frac{4}{3}$ power for soda-lime glass and BK-7 glass. In *Figure 4* are graphs of the measured μ versus the grain depth of cut to the $-\frac{4}{3}$ power for fused silica glass and HIP silicon carbide. If the proposed relation in Equation (15) is correct, then the data for each brittle-ground material should fall along a straight line on these

Soda Lime Glass
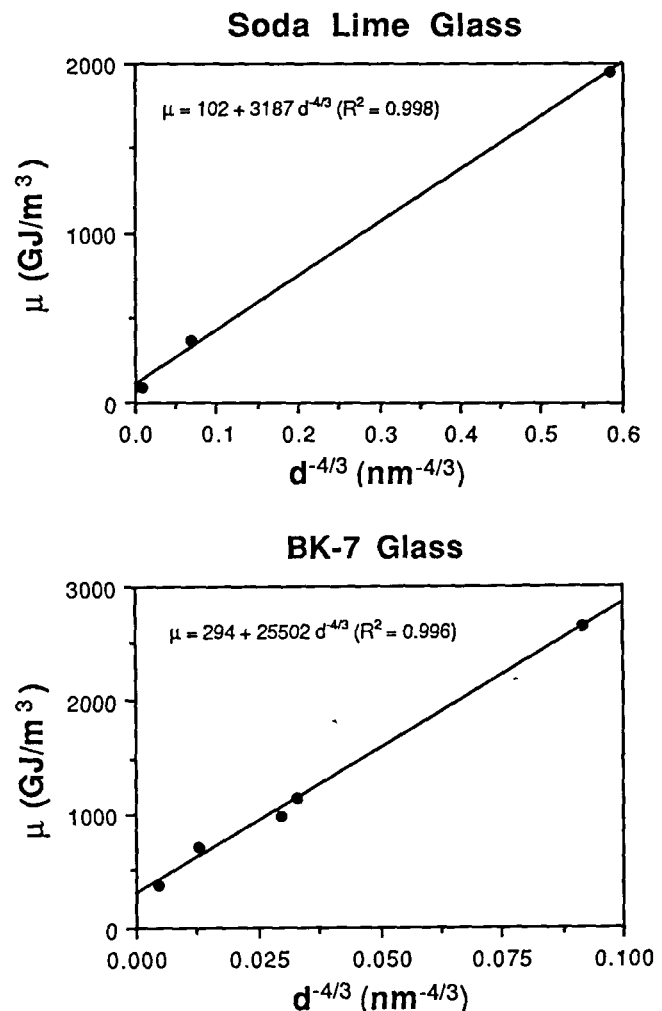
BK-7 Glass

Figure 3 Specific grinding energy versus $d^{-4/3}$ for soda-lime glass (top) and BK-7 glass (bottom)

axes. The slope and intercept of the line represent constants absorbed by K_b and K_p of Equation (15). The superimposed solid lines in *Figures 3* and *4* are the best fits of the data to Equation (15). The proposed model accurately represents the experimentally measured relationship between μ_b and d for all four materials. Each of these materials exhibits a nominally linear relationship between μ and $d^{-4/3}$. The average correlation coefficient for the four data sets is 0.99. An alternative way to interpret the data is to subtract the projected intercept (K_p in Equation [15]) from the measured specific grinding energy. The relationship between the new term, $\mu - K_p$, and d should follow a power-law relationship: i.e., on logarithmic axes, $\mu - K_p$ should vary with the $-\frac{4}{3}$ power of d. *Figure 5* is a composite graph of all of the data for brittle-regime grinding (including those data points available for brittle-regime grinding of CVD silicon carbide). The open data points represent samples ground using a bronze bond grinding wheel with concentration 50, while the filled data points represent samples
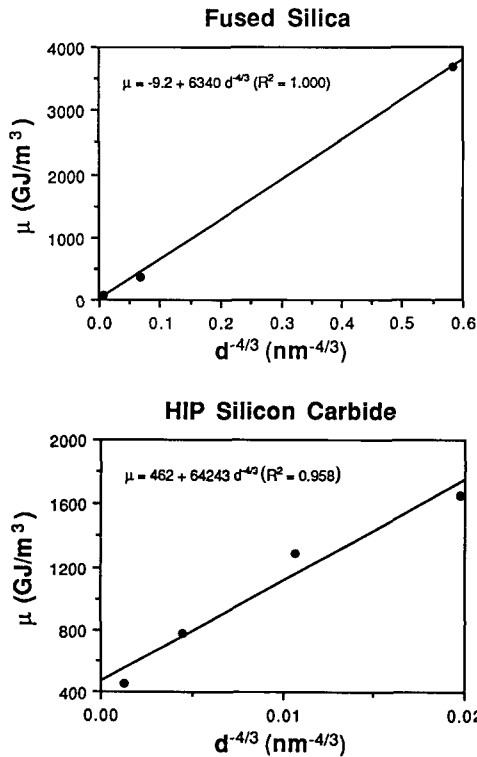
Fused Silica

$\mu = -9.2 + 6340\ d^{-4/3}\ (R^2 = 1.000)$

HIP Silicon Carbide

$\mu = 462 + 64243\ d^{-4/3}\ (R^2 = 0.958)$

Figure 4 Specific grinding energy versus $d^{-4/3}$ for fused silica glass (top) and HIP silicon carbide (bottom)

Brittle Grinding Behavior

- ● CVD SiC
- ■ BK-7 Glass
- ▲ HIP SiC
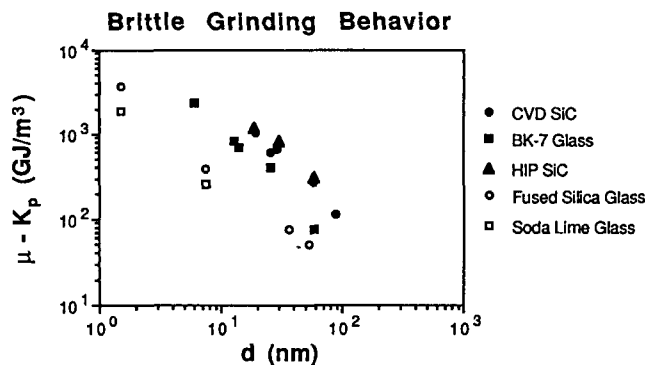- ○ Fused Silica Glass
- ◻ Soda Lime Glass

Figure 5 Modified specific grinding energy, $\mu - K_p$, versus grain depth of cut, d, for various materials ground in the brittle regime

ground using a resin bond grinding wheel with concentration 75. The data from each of the five materials fit the model, with an average slope of −1.30 compared with the theoretically predicted slope of −1.33.

Within the range of grain depths of cut available on the ultraprecision grinder, CVD silicon carbide undergoes a transition from purely ductile-regime grinding to moderately brittle-regime grinding (e.g., from 0% surface fracture to 11% surface fracture). From the theory described previously, it is expected that the μ will remain relatively constant for grain depths of cut

corresponding to ductile-regime grinding and will decrease according to Equation (15) for grain depths of cut corresponding to brittle-regime grinding. When plotted on the same axes as *Figure 3*, it is expected that the brittle-regime data will fall along a straight line, and the ductile-regime data ($\mu = K_d$) will fall along a horizontal line. *Figure 6* is a graph of the measured μ and areal percent surface fracture versus the grain depth of cut to the $-\frac{4}{3}$ power for CVD silicon carbide. For the smaller grain depths of cut (right side of graph), which correspond to negligible ($\sim 0\%$) surface fracture, μ remains relatively constant. For the largest grain depths of cut (left side of graph), which correspond to moderate ($\leqslant 11\%$) surface fracture, μ decreases along a straight line. The best-fit theoretical asymptotes corresponding to ductile-regime and brittle-regime grinding are superimposed as solid lines on the graph. The ductile-brittle transition is clearly discernible from the data and fits the theoretical model proposed. While there is
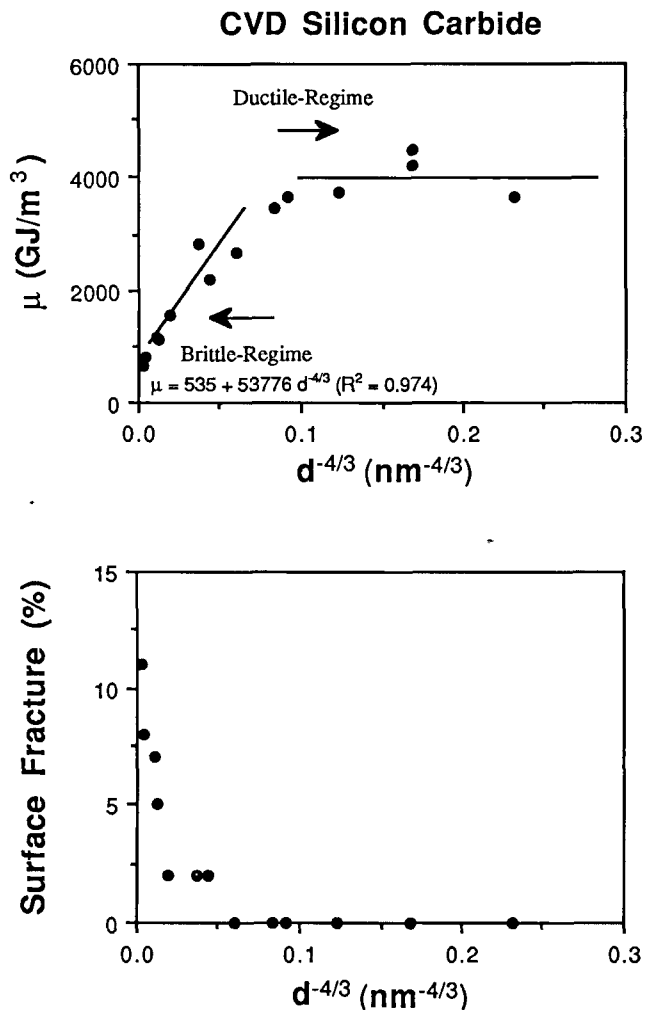
CVD Silicon Carbide

Ductile-Regime

Brittle-Regime

$\mu = 535 + 53776\ d^{-4/3}\ (R^2 = 0.974)$

Figure 6 Specific grinding energy (top) and areal percent grinding-induced surface fracture (bottom) versus the grain depth of cut to the $-\frac{4}{3}$ power for CVD silicon carbide

insufficient data to conclusively support the proposed model for ductile-regime specific grinding energy, the existing data conform reasonably to the predicted relationship.

Conclusions

An analytic model has been developed to relate the grinding grain depth of cut to the specific grinding energy for ultraprecision machining of brittle materials. Experimental results corroborate the model, particularly in the brittle regime. From the model and experiments presented in this article, it is reasonable to conclude that the specific grinding energy is a useful process parameter for control of grinding ductility. Although specific grinding energy measurements reveal a quantitative measure of the ductile-brittle transition, there are difficulties with the measurement of μ in a realistic grinding process. Extension of this technique to grinding geometries more complicated than plunge grinding requires measurement of two quantities: the grinding energy and the material removal rate. For plunge grinding, these quantities were easily established by the measurable parameters of Equation (16). For more complicated grinding geometries, measuring the material removal rate as an in-process variable may be difficult. In spite of these problems, the potential for real-time control of the grinding regime using μ feedback in an actual grinding process has been established by the results presented in this article.

Acknowledgments

References

1   Bifano, T. G. "Ductile-regime grinding of brittle materials." Ph.D. diss., North Carolina State University, 1988
2   Bifano, T. G., Dow, T. A., Scattergood, R. O. "Ductile-regime grinding: A new technology for machining brittle materials." *Transactions of the ASME Journal of Engineering for Industry* 1991, **113**, 184–189
3   Yoshioka, J., Koizumi, K., Shimizu, M., Yoshikawa, H., Miyashita, M., Kanai, A. "Ultraprecision grinding technology for brittle materials: Application to surface and centerless grinding processes." Milton C. Shaw Grinding Symposium, Komanduri, R. and Maas, D. eds. ASME Production Engineering Division, vol. 16, 1985, pp. 209–227
4   Stowers, I. F., Komanduri, R. and Baird, E. D. "Review of precision surface generating processes and their potential application to the fabrication of large optical components." *Proc. SPIE* 1988, **966**, pp. 62–73
5   Bifano, T. G., Dow, T. A. and Scattergood, R. O. "Ductile-regime grinding of brittle materials: Experimental results and the development of a model." *Proc. SPIE* 1988, **966**, pp. 108–115
6   Fawcett, S. C. and Dow, T. A. "Extension of the 1-D critical depth of cut model for brittle materials to 3-D contour grinding." *Proc. 1990 Ann. Mtg. ASPE* 1990, pp. 135–138
7   Marshall, D. B. and Lawn, B. R. "Indentation of brittle materials." Microindentation Techniques in Materials Science and Engineering, ASTM Special Tech Pub 889, Blau, P. J. and Lawn, B. R. eds. 1985, pp. 26–45
8   Drescher, J. D. and Dow, T. A. "Tool force model development for diamond turning." *Precision Engineering* 1990, **12**, pp. 29–36
9   Lucca, D. A., Seo, Y. W., Komanduri, R. and Rhorer, R. L. "Energy dissipation in ultra-precision machining." *Proceeding of the 1991 Design & Manufacturing Systems Conference*, Austin, TX, January 1991, pp. 263–268
10 Hed, P. P. and Blaedel, K. L. "Advanced fabrication of optical materials," Lawrence Livermore National Laboratory, UCID-21041-86, 1986
11 Hed, P. P., Brown, N. J., Edwards, D. F. and Stolcis, R. S. "Fine grinding of optical glass with bound abrasives." Lawrence Livermore National Laboratory, UCID-19323-85-2, 1985
12 Lawn, B. R., Jensen, T. and Aurora, A. "Brittleness as an indentation size effect." *J. Mat. Sci. Lett.* 1986, **11**, pp. 573–575
13 Swain, M. V. "Microfracture about scratches in brittle solids." *Proc. R. Soc. Lond. A.* 1979, **366**, pp. 575–597
14 Chiang, S. S., Marshall, D. B. and Evans, A. G. "The response of solids to elastic/plastic indentation." *J. Appl. Phys.* 1982, **53**, pp. 298–306