Sādhanā, Vol. 22, Part 3, June 1997, pp. 473–481. © Printed in India.

Machining and surface finishing of brittle solids

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Abstract. Ceramic materials are finished primarily by abrasive machining processes such as grinding, lapping, and polishing. In grinding, the abrasives typically are bonded in a grinding wheel and brought into contact with the ceramic surface at relatively high sliding speeds. In lapping and polishing, the ceramic is pressed against a polishing block with the abrasives suspended in between them in the form of a slurry. The material removal process here resembles three-body wear. In all these processes, the mechanical action of the abrasive can be thought of as the repeated application of relatively sharp sliding indenters to the ceramic surface. Under these conditions, a small number of mechanisms dominate the material removal process. These are brittle fracture due to crack systems oriented both parallel (lateral) and perpendicular (radial/median) to the free surface, ductile cutting with the formation of thin ribbon-like chips, and chemically assisted wear in the presence of a reactant that is enhanced by the mechanical action (tribochemical reaction). The relative role of each of these mechanisms in a particular finishing process can be related to the load applied to an abrasive particle, the sliding speed of the particle, and the presence of a chemical reactant. These wear mechanisms also cause damage to the near ceramic surface in the form of microcracking, residual stress, plastic deformation, and surface roughness which together determine the strength and performance of the finished component. A complete understanding of the wear mechanisms leading to material removal would allow for the design of efficient machining processes for producing ceramic surfaces of high quality.

Keywords. Ceramic surfaces; abrasive machining processes; surface finishing; wear mechanisms.

1. Introduction

The thrust towards improved efficiency in gas turbines and internal combustion engines, the improved performance of wear resistant components, and the unique electrical and magnetic property requirements in electronic devices and sensors have focused attention on the development of reliable components made of advanced ceramic materials. The use of these materials reached about $14 billion per year in sales in 1990 and continues to grow at a rate of 4% per year (Jahanmir *et al* 1992). The advantages of advanced ceramics over other materials include high hardness and strength at elevated temperatures, chemical stability, low friction, and high wear resistance. However, those properties that give ceramics superior wear resistance also make them difficult to machine. In addition, the limited ductility of these ceramics makes forming methods that rely on extensive plastic deformation useful only for ceramics in the green state. Thus, extensive machining is required for manufacture of complex shapes with high quality surfaces. Machining costs can constitute up to 80% of the cost of the manufactured component. A detailed understanding of the wear mechanisms underlying the machining of ceramics and the damage that they leave behind should allow for more economical manufacture of reliable advanced ceramic components.

Recent authors have reviewed several aspects of wear of ceramics including Braza *et al* (1989) who overviewed its relationship to contact fatigue, Larsen-Basse (1994) who compared and contrasted wear of ceramics with much that is already known about cemented carbides and cermets, and Jahanmir & Dong (1994) who give examples of maps of wear regimes for relevant contact pressure and temperature. The following reviews mechanical aspects of wear associated with machining.

2. Material removal processes

While turning and milling are used extensively in machining of metals, they are not efficient for fully densified ceramics due to rapid tool wear and large amounts of surface damage. Diamond turning can be used for machining ceramics in the green state but finish machining is still required on the densified ceramic. Thus, surface finishing of ceramics is primarily accomplished by abrasive finishing processes such as diamond grinding, lapping, and polishing. These processes are required to meet the stringent tolerance and surface finish requirements in structural and electronic ceramics (e.g. $< 0.05\ \mu\text{m}$ rms in magnetic recording heads, silicon wafers, face seals, and bearings). The abrasive processes remove material mechanically and introduce damage on the surface of ceramics (Marshall *et al* 1983). This damage is usually in the form of residual stresses and cracks which have a major influence on the mechanical properties and integrity of the machined ceramic surface. Moreover, plastic deformation and subsequent residual stresses induced by surface finishing alter electro-magnetic properties such as permeability, resistivity, and refractive index of the surface in electronic ceramics (Stokes 1972) causing deterioration of their performance in electronic devices.

In general, the material removal rates (MRR) in grinding are higher than the MRR in lapping and polishing. The higher MRR in the initial rough grinding operation leads to surface damage in the form of microcracks which may extend as deep as $100\ \mu\text{m}$ into the surface. Rough grinding is followed in turn by fine grinding, lapping and polishing in which this damage is removed to varying degrees. Furthermore, the lapping and polishing operations may also leave damage behind on the surface in the form of residual stresses and severely plastically deformed layers.

Grinding of ceramics is accomplished primarily with grinding wheels containing diamond abrasive grits (Subramanian 1988). The diamonds are fixed to the wheel through relatively compliant resin bonds or stiff vitrified bonds. The grits are statistically distributed over a range of sizes with an average size of ~ 100 μm in wheels designated as coarse and ~ 5 μm in wheels designated as fine. Typical process parameters used in grinding include wheel surface speeds of 25 to 50 m/s, depths of cut of 0.5 to 30 μm, and table traversal speeds of ~ 20 mm/s. These parameters lead to an MRR per unit wheel width of the order of 0.1 to 1 $\mathrm{mm}^3/\mathrm{mm/s}$ and normal grinding forces per unit wheel width of 5 to 100 N/mm. For a given depth of cut, the grinding force typically increases as the abrasive particle size in the wheel decreases. Here the depth of cut refers to the depth of material removed in a single traversal of the wheel across the ceramic surface. However, the depth removed by a single particle is much smaller than this and varies over the length of contact between wheel and workpiece. The length of contact is $l = \sqrt{2Rd}$ (neglecting wheel deflection) where R is the radius of the wheel and d is the depth of cut; typical contact lengths are in the range of 1 to 2 mm.

The force applied to the grinding wheel produces wheel and machine deflections so that the actual length of contact varies from that calculated using geometry (Hucker *et al* 1994). The wheel deflection is due to the localized contacts between the stiff diamond abrasive particles (embedded in a compliant bond) and the workpiece as well as a global deflection due to the stress distribution associated with transmission of the total contact force through the wheel. A definitive calculation of the number of active abrasive particles, i.e. the number of particles actually engaged in the cutting action, and the distribution of forces on these particles is as yet unavailable. However, the statistical distribution of particles on the wheel surface suggests that many of the particles have depths of cuts much less than but of the order of the grinding depth of cut. Furthermore, the contact pressure between a single particle and the ceramic surface is very high and approximately equal to the ceramic hardness. This is to be contrasted with the average pressure across the wheel-ceramic interface estimated from force measurements, which is well within the elastic range.

The large relative sliding velocity produces high temperatures at the abrasive-workpiece interface. For typical grinding conditions, infrared radiometric measurements of the peak temperatures have shown them to be as high as 1300°C (Hebbar *et al* 1992). These values are consistent with measurement and analysis of temperatures in single point grinding under similar grinding conditions. Further substantiation of high grinding temperatures is provided by the presence of spherical particles in grinding swarf while grinding hardened steels (Lu *et al* 1992). The grinding temperatures are localized near the surface and the resulting thermal gradients generate thermal stresses which are also important in understanding the grinding process.

The localized nature (i.e. local to the single abrasive particle-ceramic contact) of the contact stresses and temperatures during grinding, and a variety of observations pertaining to deformation and stresses on machined surfaces, strongly suggest that to understand the material removal mechanism during ceramic grinding, it would be useful to analyse the sliding indentation of a ceramic surface by a hard particle under depths of cut and sliding velocities occurring in grinding. Indeed, this view underlies much of the following discussion.

Lapping and polishing of ceramics are carried out by placing a slurry of abrasive particles in a liquid vehicle between the specimen and a hard block (lapping) or a soft pad (polishing).

The block is loaded against the workpiece by hydraulic or mechanically applied pressure and rotated at slow speed. The particles roll and slide across the ceramic surface so that the wear resembles three-body wear as opposed to the two-body wear in grinding. Polishing is usually performed after initial grinding has been used to generate the workpiece shape; its primary purpose being the generation of smooth surfaces. A hard lapping block is used when stringent tolerances on the flatness of the workpiece are required, while polishing generates a much smoother surface since many of the abrasive particles are embedded in the soft lapping block. Diamond particles are used extensively but softer abrasives such as Al_2O_3, SiC, and cerium oxide are also widely used. As in grinding, the particles are statistically distributed over a range of sizes with the average particle size ranging from 0.05–70 μm.

The mean sliding velocity between the abrasive and the ceramic in lapping and polishing is of the order of 0.5 m/s or less which is two orders of magnitude less than that in grinding. In contrast to grinding, the sliding induced temperatures are thought to be insignificant in lapping and polishing. The forces on individual abrasive particles vary, with the total force applied to the block or pad being a process variable. In general, the surface roughness (R_a) of the finished surface increases with increasing lapping pressure. Typical removal rates in lapping and polishing range from $0.001 - 1\ \mathrm{mm}^3/\mathrm{s}$ which is less than that observed in grinding for a typical grinding wheel of 5 mm in width. The smaller MRR suggests that less damage is left behind on the surface from lapping and polishing than from grinding. As in grinding, the material removal can be viewed as due to sliding indentation for the particles that slide, and due to quasi-static indentation for particles that roll. This idealization is consistent with microscopic observations of lapped and polished surfaces, and wear particles formed by these processes (Chauhan *et al* 1993).

Recently, a model for the distribution of abrasive particle forces during lapping based on statistical size distribution of the particles has been developed (Chauhan *et al* 1993). In that paper, the required compliance of the particle workpiece contact is calculated by assuming that it is the same as that for an indentation with a conical indenter. An interesting result from the calculation is that approximately only 1 out of 10^5 particles is actively engaged in material removal at a given time. Further, by assuming that the surface roughness of the finished surface is related to the depth of the plastic zone produced by a particle, the surface roughness could be predicted from the properties of the abrasive particles and the workpiece, and the lapping pressure. The mean surface roughness, R_a, is found to be related to the average particle force while the peak-to-valley surface roughness, R_t, is related to the maximum force applied by a particle. The predictions of this model are, for most cases, in excellent agreement with experimental observations from lapping and polishing of Al_2O_3, soda-lime glass, and Ni-Zn ferrite using SiC abrasive slurries of different particle sizes. A similar calculation has not been carried out for grinding in part because of difficulties associated with measurement of the surface profile of the grinding wheel and lack of characterization of the statistical distribution of particle sizes on the wheel surface.

3. Material removal mechanisms

A glimpse into the wear processes that cause material removal during the abrasive machining of ceramics is provided by optical and electron microscopy of machined ceramic

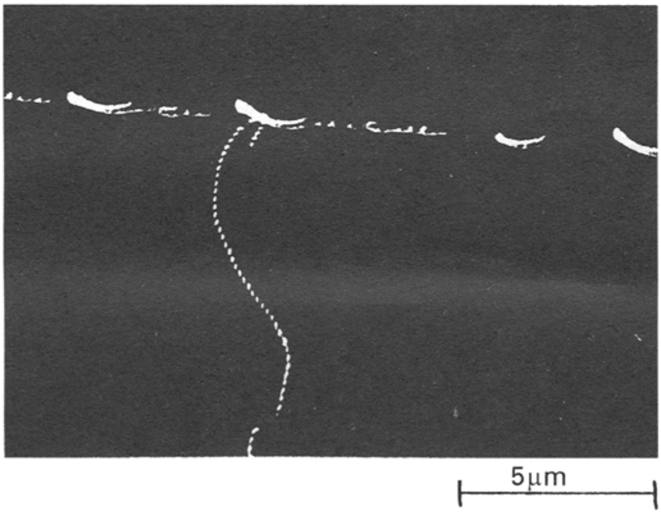

Figure 1. SEM micrograph of ribbon-shaped polishing chips from soda-lime glass.

surfaces and machining chips. Such microscopic observations have shown that material removal occurs as a consequence of one or more of the following: lateral cracks breaking open onto the surface; gross fracture due to grain pull-out; median/radial cracks intersecting with each other; and plastic micro-cutting through the formation of chips as in single-point turning of metals. These observations have also been confirmed through electron microscopic studies of chips and wear particles formed by machining. The dominance of a given mechanism is closely related to the loads applied by individual abrasives on the ceramic surface during machining. Typically, when the externally applied loads transmitted by the abrasives are small, plastic micro-cutting or indentation (with upward displacement of material around the indent) mechanisms are found to dominate. This is particularly so when polishing at low loads and/or with a flexible, soft polishing cloth (polishing block) or in the so-called "ductile regime" mode of grinding. The surfaces produced by these modes of material removal/displacement are characterized by their extreme degree of smoothness. Also, the plastic micro-cutting action of material removal leads to the formation of thin ribbon-like chips even when machining brittle solids such as glass, ferrites, or MgO. Figure 1 shows such a chip formed during the polishing of soda-lime glass. Machined surfaces of ceramics such as Ni-Zn ferrite, soda-lime glass, Si_3N_4, and zirconia created by this plastic mechanism of removal do contain residual stresses of the order of 20–50 MPa (Chandrasekar *et al* 1991). Furthermore, dislocation etch-pitting experiments on ground and polished blocks of single crystal MgO show the presence of an intensely deformed surface layer with high dislocation densities. Both these observations reinforce the hypothesis of a plastic micro-cutting mechanism of material removal as well as the formation of microindentations and plastic scratches on machined ceramic surfaces. The plastic material removal mechanism in nominally brittle solids is no doubt a consequence of the large hydrostatic stresses generated in a small volume underneath the ceramic surface by the abrasive particles.

When larger loads are transmitted through the abrasives, a transition is seen to occur in the material-removal action from the ductile regime cutting to wear particle formation by

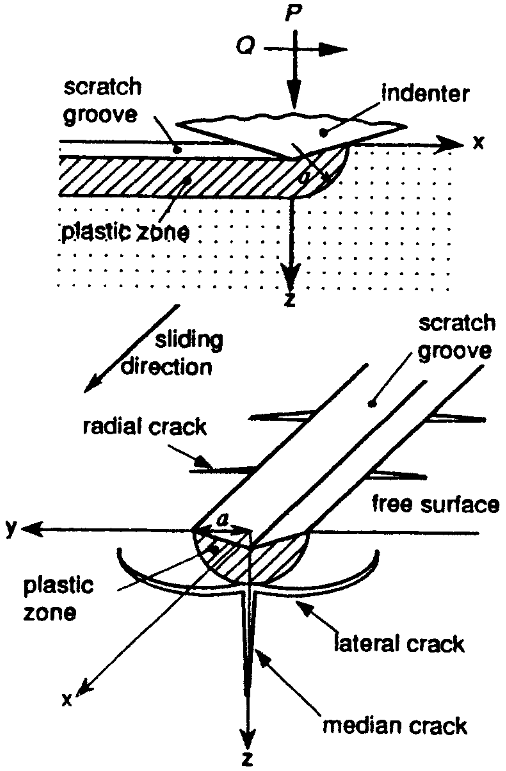

Figure 2. Schematic of sliding indentation and resulting fracture.

brittle fracture. The most common modes of material removal by brittle fracture are due to lateral cracks breaking open onto the surface, grain pull-out, or a crushing-type of material removal. Again, these conclusions have been reached from microscopic observations of machined surfaces and wear particles.

In order to understand better these mechanisms, and the driving forces behind them, it is worthwhile to analyse a reduced model for the machining of ceramics. This is provided by the sliding indentation process which entails a single abrasive particle sliding across the ceramic work-piece. This configuration has been examined extensively in the literature (Broese van Groenou *et al* 1979; Swain 1979; Evans and Marshall 1981; Cheng and Finnie 1990; Ahn *et al* 1993). A schematic of this experiment and the resulting crack pattern are shown in figure 2. As summarized by Ahn *et al* (1993), the experimental results delineate different force regimes in which the various crack patterns illustrated in figure 2 occur. For a Vickers indenter sliding on soda-lime glass, the results can be summarized as follows. At normal loads less than $\sim$ 0.05 N, no cracking is observed but a groove is formed indicating localized plastic deformation. The formation of such grooves in some cases is a consequence of material removal by a plastic-cutting mechanism, which produces chips similar to those shown in figure 1. In other cases, the groove is merely a sliding indent, i.e. the material within the groove is displaced mostly to the sides of the groove. In this latter instance there is no material removal but just a plastic indentation. In the force range of 0.05–0.8 N, a median crack is observed perpendicular to the surface. The depth of the median crack increases with normal force. In the range 0.8–3 N median cracking is accompanied by lateral cracking parallel to the surface. At loads in the higher portion of this range, lateral cracks break through to the surface causing material removal. At still higher loads, say 3–6 N there is considerable crushing of particles in the scratch groove, along with a median crack.

A stress analysis that approximates the localized inelastic deformation using a sliding blister field has been completed by Ahn *et al* (1993). This was obtained by extending the blister field model for static indentation proposed by Yoffe (1982). In this model the strength of the blister field is evaluated as a function of the indentation load by measuring the volume of the scratch groove (figure 2). The value of the tensile stress in the uncracked solid at the location of the different systems is reported by Ahn *et al* (1993). The stress that would initiate a lateral crack is found to be small for low loads and equals the median crack driving stress near loads at which lateral cracks are typically observed to occur. That is, the sliding blister model accurately predicts the experimentally observed critical load for lateral crack formation in soda-lime glass. To date, a complete stress analysis of the sliding indentation of brittle materials does not exist.

It must be observed here that the sliding indentation forces in the results summarized above are in the range of forces applied to abrasives during lapping and polishing. The lapping force calculations described earlier yield average particle forces in the range 0.03–0.6 N for the lapping and polishing of glasses, ferrites, and Al_2O_3 under typical conditions. The smaller forces correspond to abrasive particle sizes of $\sim 1\ \mu m$ while the higher forces correspond to particle sizes of $\sim 63\ \mu m$. The smaller of the force values are in the range where plastic material removal by cutting has been observed both during polishing and sliding indentation. The higher particle forces are well in the range of conditions for which lateral cracking is a dominant mechanism of material removal in sliding indentation experiments.

The calculation of volumetric wear as a function of process variables in abrasive machining processes has not been carried out to any significant extent. Evans & Marshall (1981) used fracture mechanics to obtain a formula for wear volume as a function of applied force and ceramic material properties, based on a mechanism of lateral cracking to describe material removal. However, their formulae for predicting the onset of lateral cracking as well as volumetric removal rates have not been validated by experiment, e.g. Larsen-Basse (1994). The analytical estimation of such wear rates during the grinding, lapping, and polishing of ceramics, based on the different wear mechanisms that are operative, is a problem worthy of detailed study.

4. Discussion

This short review of recent work on abrasive machining of ceramics has highlighted the two main mechanisms of wear associated with material removal: (1) brittle fracture with lateral cracks intersecting the machined surface, when the load applied by an abrasive particle is high, and (2) ductile micro-cutting with chip formation taking place as in single point machining of metals. The evidence for these mechanisms has come from microscopic observations of machined surfaces, chips and wear particles; from a consideration of the forces and pressures applied by the individual abrasive particles in machining, and from the nature of deformation occurring in ceramic surfaces under sliding microindenters subjected to loads similar to those acting on abrasive particles. Other observations pertaining to residual stresses, magnetic property changes, microcracking and strength of machined ceramics provide further support for these mechanisms. For example, lapped and finely polished surfaces of crystalline ceramics typically have residual compressive stresses and high dislocation densities in shallow surface layers which support a mechanism of material removal by plastic cutting, and material displacement by indentation. Furthermore, such surfaces show little evidence of microcracking and there is very little strength degradation and strength anisotropy in lapped and finely polished ceramics. In contrast, coarsely polished or ground surfaces of ceramics show considerable microcracking in the surface layers as well as strength anisotropy and strength degradation. This is consistent with a mechanism of material removal and wear taking place by brittle fracture.

In conclusion, the cost effective machining of ceramics necessitates an understanding of the deformation processes and stress fields in ceramics produced by a sliding indenter under conditions of pressure and temperature prevalent in machining. By controlling and exploiting the transition between wear particle formation by ductile cutting and by brittle fracture, it should be possible to increase material removal rates and significantly improve the quality of the machined surface. The use of active chemical reagents to enhance or decrease material removal through tribochemical reactions at the interface between the abrasives and the ceramic workpiece should also be beneficial in this regard.

The research was supported in part by the National Science Foundation through grants MSS 9057082, Jorn Larsen-Basse, Program Director and DDM 9057916, Bruce Kramer, Program Director.

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