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Engineering Fracture Mechanics

Research Project

by

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1. Introduction

1.1 Brief introduction ceramics

Material such as silicon carbide (SiC) and Quartz are two of the advanced engineered ceramic materials designed to operate in extreme environments. One of the main reasons for the choice of these materials is due to their excellent electrical, mechanical or optical properties that benefit the semiconductor, MEMS and optoelectronic industry respectively. Most of these advance ceramics are used for as optic mirrors and windows requiring the surface to have a mirror like finish. This makes the manufacturing process extra complicated as researchers now have to understand these materials from an atomic level.

1.2 The challenges of working with brittle materials

Manufacturing these materials are extremely challenging due to their high hardness, brittle characteristics and poor machinability. Severe fracture can result when trying to machine SiC and quartz due to their low fracture toughness. However, from past and current research efforts, it has been proven that ductile regime machining of nominally brittle materials is possible. In order to machine these ceramics with a damage/subsurface damage free condition, it is important to only conduct ductile mode machining. Every material has its plastic/elastic zone, the challenge in ceramics is that the range of this zone is small and being able to identify it can be challenging. Advance ceramics have high hardness and are very abrasive making it difficult to machine from a fracture mechanics and tribological point of view.

1.3 The concept of ductile mode machining

Materials that are hard and brittle, such as semiconductors, ceramics and glasses, are amongst the most challenging to machine. When attempting to machine ceramics, such as silicon carbide (SiC), especially to improve the surface finish, it is important to carry out a ‘damage free’ machining operation. This often can be achieved by ductile mode machining (DMM) or in other words machining a particular hard and brittle material in the ductile regime. This means that the quantity of ceramic material to be removed by the finishing process must be very small, so that microcracks do not remain on the finished surface.[i] The insight into the origins of the ductile regime during single point diamond turning (SPDT) of semiconductors and ceramics was provided in the research done by Morris, et al.[ii] A detailed study of machining chips (debris) and the resultant surface was analyzed using TEM to evaluate evidence of plastic material deformation. This seminal research concluded that the machining chips were plastically formed and are amorphous due to the back transformation of a pressure induced phase transformation (not due to oxidation), and contains small amounts of micro-crystalline (brittle) fragments.

1.4 Precision machining ceramics with a crack-free surface

Material removal processes can be considered in terms of fracture dominated mechanisms or localized plastic deformation. A fracture dominant mechanism for ceramics, i.e., brittle fracture, can result in poor surface finish (surface damage) and also compromises on material properties and performance. A plastic deformation process can result in smooth and damage free surfaces, suitable for optical applications.

2. Engineering Fracture Mechanics

2.1 Material Removal and Fracture Mechanics

There are in general two types of fracture – ductile fracture and brittle fracture. Ductile fracture occurs after appreciable plastic strain and the criterion usually employed is the same as for yield (Tresca or von Mises). Brittle fracture occurs at a strain that is below the yield stress (perfectly brittle material) or relative close to the yield point (quasi-brittle material) and the criterion usually employed in such a case is the maximum tensile stress criterion. This states that fracture occurs on a plane perpendicular to the direction of maximum tensile stress (σ_1) when the maximum tensile stress reaches a critical value (σ_1 = constant). The fracture surface is usually in the direction of maximum shear stress in the case of ductile fracture. Brittle or quasi-brittle materials exhibit a greater ‘pressure coefficient of ductility’ than do ductile materials.

In some cases both types of fracture are involved. For example, in the tensile test of a ductile metal, initial fracture occurs in the center of the neck where the hydrostatic tensile stress is a maximum. As load is further increased, this initially tensile crack grows radially outward until the remaining area is insufficient to support the shear stress pertaining at which the final fracture occurs along a conical surface inclined approximately 45^o to the axis of the specimen. This is called a cup-cone fracture due to the appearance of the fracture surfaces. Figure 1 (refer to appendix) shows the types of fracture obtained in tension. In this particular report, we look at fracture for perfectly brittle materials.

2.2 Griffith's Fracture Theory

The first rational approach to fracture was due to Griffith (1924) for perfectly brittle materials. In his theory, Griffith reasoned that all real materials contain microcracks or equivalent regions of stress concentration that will grow with tensile strain until the elastic strain energy stored at the tip of the crack becomes sufficient to satisfy the surface energy associated with the generation of the new surface area accompanying crack growth, when the crack will spread spontaneously. The microcrack visualized by Griffith was elliptical in shape and as shown in Figure 2 (refer to Appendix). After Griffith, several other research such as Orowan (1950), Fisher (1953), Irwin (mid 50's), Paul and Mirandy (1975), Usui, Ihara and Shirakashi (1979) conducted fracture mechanics and developed theories to further help engineers understand this issue.

3. Physics of Ductile Mode Machining of Ceramics

3.1 Ductile Material Removal

According to the research carried out by Bifano et al.[iii], there are two types of material removal mechanisms associated with the machining process: ductile - plastic flow of material in the form of severely sheared machining chips, and brittle - material removal through crack propagation. This previous research discusses several physical parameters that influence the ductile to brittle transition in grinding of brittle materials. The researchers were successful in performing ductile mode grinding on brittle materials. However, these researchers did not propose or confirm a model or suitable explanation for the origin of this ductile regime. Bifano et al. also proposed a model defining the ductile to brittle transition of a brittle material based on the material's brittle fracture properties and characteristics. A critical depth of cut model was introduced based on the Griffith fracture propagation criteria. The critical depth of cut (d_c) formula is as follows:

$$d_c = (E.R) / H^2 \quad \text{...(3.1)}$$

where E is the elastic modulus, H is the hardness and R is the fracture energy.

The value of the fracture energy (R) can be evaluated using the relation:

$$R \sim K_c^2 / H \quad \text{... (3.2)}$$

where K_c is the fracture toughness of the material. The above two equations can be combined to represent the critical depth (d_c) as a measure of the brittle transition depth of cut:

$$d_c \sim (E / H) \cdot (K_c / H)^2 \quad \text{...(3.3)}$$

The researchers were successful in determining a correlation between the calculated critical depth of cut and the measured depth (grinding infeed rate). The constant of proportionality was estimated as to be 0.15 and this is now added into Equation (3.3) to generate a more accurate empirical equation:

$$d_c \sim 0.15 \cdot (E / H) \cdot (K_c / H)^2 \quad \text{...(3.4)}$$

In general, the modulus is constant, but the measured values of K_c and H are based upon the atmospheric (tensile stress) and high pressure (compressive stress) phases respectively. In reality, the expression should use the (higher) hardness of the atmospheric phase, rather that the more ductile high pressure phase, to determine the brittle fracture parameters (this also makes the analysis consistent). You can appreciate this more fully if you realize that the likely value of the hardness of the atmospheric phase, of Si or SiC, is much higher than the measured hardness (as a result of the HPPT); this higher hardness then reduces the critical depth proportionally.

3.2 Chip Formation (Blake and Scattergood Model)

A critical depth, d_c is experimentally determined before any ductile mode machining operation is carried out. Any depth beyond or exceeding the critical depth, which is also known as the Ductile to Brittle Transition (DBT) depth, will result in a brittle cut. In this model it is assumed that the undesirable fracture damage (which extends below the final cut surface) will originate at the critical chip thickness (t_c), and will propagate to a depth, y_c. This assumption is consistent with the energy balance theory between the strain energy and surface energy.

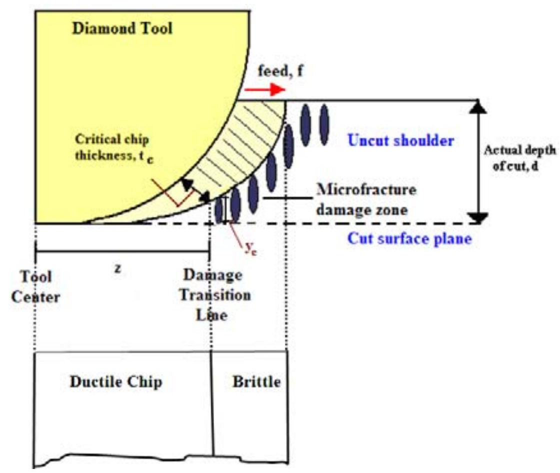

Figure 3: Model for ductile regime machining.

In general, the ductile-to-brittle transition (DBT) is a function of variables such as tool geometry (rake and clearance angle, nose and cutting edge radius), feed rate, cutting speed and depth of cut.

3.3 High Pressure Phase Transformation (HPPT)

Although ceramics are naturally very brittle, micromachining these materials are possible if sufficient compressive stress is generated to cause a ductile mode behavior, in which the material is removed by plastic deformation instead of brittle fracture. This micro-scale phenomenon is also related to the High Pressure Phase Transformation (HPPT) or direct amorphization of the material. [iv] *Figure 4* shows a graphical representation of the highly stressed (hydrostatic and shear) zone that results in ductile regime machining.

Patten and Gao[v] state that ceramics in general undergo a phase transformation to an amorphous phase after a machining process. This back transformation is a result of the HPPT that occurs when the high pressure (compression or hydrostatic pressure) and shear caused by the tool is suddenly released after a machining process. The HPPT is usually characterized by the amorphous remnant that is present on the workpiece surface and within the chip. This amorphous remnant is a result of this back transformation from the high pressure phase to the atmospheric pressure phase due rapid release of pressure in the wake of the tool. There are two types of material removal mechanisms: ductile mechanism and the brittle mechanism. For experiments conducted in this research, ductile mode machining was carried out making use of the HPPT phenomenon. In the ductile mechanism, plastic flow of material in the form of severely sheared machining chips occur, while material removal is achieved by the intersection and propagation of cracks in the brittle fracture mechanism. Due to the presence of these two competing mechanisms, it is important to know the DBT depths (or critical size) associated with these materials before attempting a machining operation.

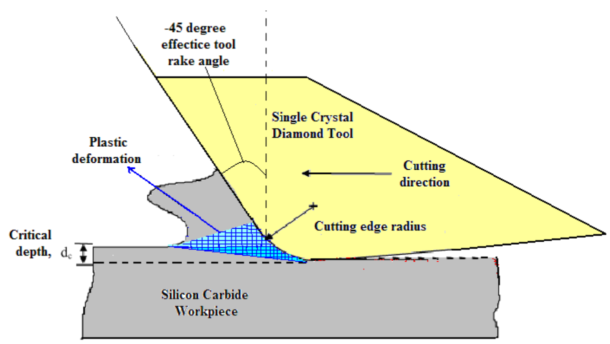

Figure 4: A ductile machining model of brittle materials

Figure 4 shows a ductile cutting model indicating the zone of high compressive and shear stress, i.e. the zone of plastically deformed material in brittle materials. A -45^{o} rake angle tool is demonstrated in the above schematic, which is very helpful to creating the conditions, pressure and shear, necessary to generate the high pressure ductile phases of semiconductors and ceramics.

3.4 Surface Characteristics/Finish

The surface characteristics and surface finish (roughness) are of major concern for all of the work in this thesis. Most often, the main goal for machining on are to improve the surface roughness. Surface characteristics are extremely important in this research as all materials require a mirror finish in order to have good optical qualities for high power laser devices (optical mirrors and windows). It is essential to understand the surface behavior, properties, pattern, characteristics and topography before carrying out any machining. In general, a surface roughness measurement is done to understand the surface topography.

In general, the surface is seen to be improving as long as the material is removed in the ductile regime (plastic deformation). There are several factors that could affect the surface quality of the workpiece while machining. These factors include tool geometry, tool wear, external vibration (from tool or spindle), cutting speed, feed, depth of cut and friction forces. Fritz Locke et al., in Jahanmir's book about machining of ceramics[vi], describe the correlation between the machining parameters and the resultant surface finish. It is stated that the surface quality of the work piece tends to worsen at higher feeds and this finding is consistent with the results obtained from this research. The tool nose radius plays an important role in the surface finish of the workpiece. In general, a larger tool nose radius and a smaller feed yields in a better surface. This relationship is given by the equation:

$$Hmax = f^2 / 8R, \text{ for } f << R \quad \text{……………………………………………}(3.5)$$

Where Hmax is the predicted theoretical surface roughness, f is the feed and R is the tool nose radius. It is also important to realize that surface roughness degrades with machining time due to tool wear development.[vii] Every parameter that is involved in the manufacturing process play a vital role in the fracture mechanics aspect of these ceramics.

4. Manufacturing Processes – Related to My Current Research

A good manufacturing technique should provide both high product quality and cost effectiveness. . There are several manufacturing techniques such as turning, milling, polishing, finishing, lapping and honing that are used to. Traditionally, turning and milling are considered roughing/semi-finishing operations. Polishing is used to obtain the final surface finish; this operation is carried out to remove micro-cracks, scratches and voids (these damages are usually caused by previous manufacturing operations). Lapping and honing generally are carried out for obtaining form and shape accuracy such as flatness and sphericity.

SPDT was a chosen as the material removal method as it offers better accuracy, quicker fabrication time and lower cost when compared to grinding and polishing.[viii] Grinding is often the most expensive process in common use as it's the most expensive per unit volume of stock removal. In the manufacture of ceramic components, grinding can comprise up to 80% of the total cost.[ix] The high demand in the optical and electronic industry has been consistently pushing and breaking the barriers in various nanotechnology areas such as SPDT. Such advances are essential in order to economically produce high quality semiconductor, ceramic and glass parts. SPDT is well known for providing advantages due to the level of precision of the equipment. SPDT was an ideal material removal process for my research projects as it is capable of:

- machining in the ductile regime: able to control several parameters precisely such as depth of cut, cutting speed and feed, allowing ductile mode machining,
- very controlled material removal process: in the nanometer range,
- cost efficient; tools can be reused after relapping,
- time efficient: the limit of ductile regime machining can be pushed (vary the material removal rate by adjusting the depth of cut and feed rate) to minimize the number of passes, unlike polishing where only very little material can be removed at once, and
- it provides good surface finish: best surface roughness, Ra, achieved in this research is about 38nm.

5. Conclusion

It is important to understand the fracture toughness and corresponding material limits (fracture tolerance) in ceramics when attempting to machine them. Ceramics (i.e., SiC and quartz) are extremely brittle materials but can be successfully machined at the nano/micro scales. The results of this research confirmed that brittle materials (i.e. SiC and quartz) can be machined in the "ductile regime".

It is also vital to establish ductile regime machining conditions for finishing and smoothing ceramics, as brittle mode behavior results in pitting, micro-cracks and uncontrolled subsurface damage. One of the first steps in attempting ductile mode machining is to establish/determine a critical depth of cut or the Ductile to Brittle Transition (DBT) of the material. The DBT of a material can be determined by performing cuts at the nano to micro scale on the material surface, which has been previously smoothed (generally by polishing) so as to be able to more readily determine the onset of fracture.

6. Appendix

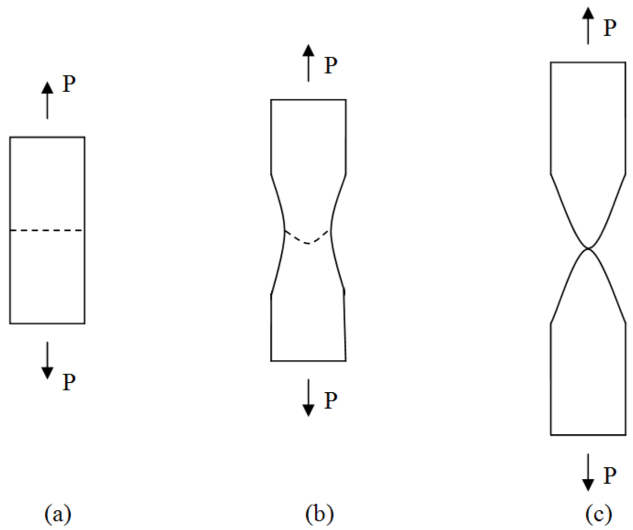

Figure 1: Types of fracture (a) Perfectly brittle material. (b) Partially ductile material (cup-cone pattern) (c) Perfectly ductile material.

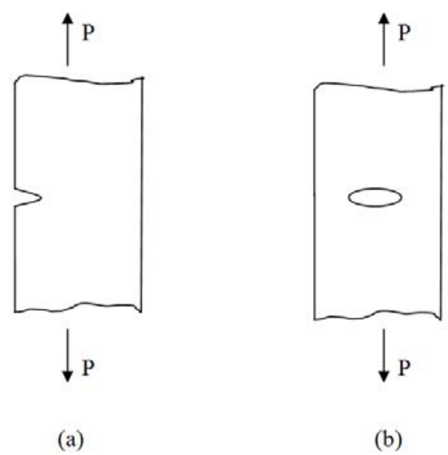

Figure 2: Elliptical crack in plane stress tensile specimen. (a) Crack at surface. (b) Internal crack.

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