Ductile Regime Nanomachining of Single-Crystal Silicon Carbide

We have demonstrated the ability to perform a ductile material removal operation, via single-point diamond turning, on single-crystal silicon carbide (6H). To our knowledge, this is the first reported work on the ductile machining of single-crystal silicon carbide (6H). SiC experiences a ductile-to-brittle transition similar to other nominally brittle materials such as silicon, germanium, and silicon nitride. It is believed that the ductility of SiC during machining is due to the formation of a high-pressure phase at the cutting edge, which encompasses the chip formation zone and its associated material volume. This high-pressure phase transformation mechanism is similar to that found with other semiconductors and ceramics, leading to a plastic response rather than brittle fracture at small size scales. [DOI: 10.1115/1.1949614]

Keywords: Ductile-to-Brittle Transition, Single-Point Diamond Turning, Nanomachining, Cutting Forces, Surface Finish, SEM/TEM Analysis, Crystal Orientation

1 Introduction

Nominally brittle materials, such as semiconductors and ceramics, can often be deformed plastically if the scale of the deformation is small enough to avoid brittle fracture. Typically, the size scale for the ductile-to-brittle transition occurs in the range associated with nanotechnology applications (10–100 nm). Below the transition, i.e., in the ductile regime, these materials behave much like metals, even to the extent that “chips” are formed similar to those produced during metal machining operations. These metal-like chips are a characteristic of the high-pressure phase transformation that occurs during the machining process [1]. It is generally accepted, at least for semiconductors such as silicon, that the ductility of these materials—at room temperature—is due to the formation of a ductile high-pressure metallic phase, which occurs during mechanical contact and deformation [2, 3]. A high-pressure metallic phase of SiC has been theoretically examined and experimentally demonstrated [4–10]. At room temperature, or more specifically below a transition temperature [11], these materials behave as nearly ideal brittle solids in the classical or Griffith sense, i.e., they fail due to fracture without evidence of plastic deformation, at least at the macroscopic scale (greater than a micrometer). However, at small scales (less than a micrometer) these materials can be plastically deformed (even at low temperatures), exhibiting a ductile response to mechanical deformation processes such as nanoindentation and nanomachining [12, 13]. Below the ductile-to-brittle transition temperature (less than ≈ 1/2 the melting temperature T_m), dislocations in these materials are nearly immobile. Therefore, traditional dislocation events leading to macroscopic plastic deformation are generally inoperative, i.e., below the transition temperature dislocation mobility is very low and mechanisms such as dislocation glide, twins, partials, and kinks do not facilitate macroscopic ductile behavior, especially at high strain rates such as occur during machining. However, at the pressures (more accurately compressive and shear stress) that occur in the region of tool-workpiece contact, high-pressure phase transformations occur in these nominally brittle materials and these high-pressure phases are generally metallic, which leads to the observed ductile response [14]. Evidence of the occurrence of the high-pressure “metallic” phases can be observed in the by-products of the deformation process. The surface of the ductile machined material, along with the debris removed, i.e., machining chips, is amorphous if the machining process was conducted in the ductile regime. By ductile regime we mean that the process was dominated by ductile material removal rather than brittle fracture events. In addition to the amorphous remnant generated from a crystalline material, ductile machining is characterized by smooth surfaces (similar to a polished surface) free of fracture damage, such as cracks. Ductile machining is also characterized by higher cutting forces, as it takes more energy to remove material in a ductile rather than a brittle mode. Therefore, cutting forces can also be used to assess the material removal mechanism. Of course, high cutting forces generally lead to higher tool wear, which is a necessary trade-off and must be considered in order to evaluate economical production conditions.

At high temperatures, i.e., above the ductile-to-brittle transition temperature, dislocations become active and assist in the plastic deformation of these nominally brittle (covalently bonded) materials [11]. However, as has been demonstrated in the past [1, 14, 15], the observed ductile response of these materials can occur at or near room temperature, without the assistance of dislocation-based plasticity. Of course, it is assumed that the actual plastic deformation of the high-pressure metallic phase is based on dislocation activity. However, due to the amorphous state of the postprocessed material, the exact nature of this assumed metallic phase dislocation activity is not observable (either in situ or postprocess). High temperatures, achieved through high-speed cutting, or augmented with external heating sources [16, 17], may also produce ductile machining as a result of thermal softening. Current work is being performed by one of the authors (Pat-ten) to evaluate the cutting temperatures in situ during actual machining of silicon carbide.

2 Experiments

Single-point diamond turning (SPDT) of single-crystal SiC (6H) was performed on a diamond turning machine (DTM), as shown in Figs. 1 and 2. The details of the experiment equipment design are reported elsewhere [18]. Single-crystal cutting tools were used for all experiments. The cutting tools have a nominal 2 mm nose radius, and cutting edge sharpness in the range of 20–250 nm. To conform to a two-dimensional (2D) orthogonal cut, the edge (250 μm thick wafer) or circumference of the 2 in. single crystal wafer (SiCrystal AG, Germany) was machined rather than the polished face. The edge is only ground and not polished like the finished wafer surface, therefore some preliminary cutting (preparation was performed using incremental cuts of...
100 nm until a round surface was obtained) was performed to true the sample and partially remove the surface damage layer caused by the grinding process used in the production of the wafer. A unique method of varying the tool’s rake angle was also implemented. The centerline of the tool’s cutting edge was adjusted to create an effective rake angle (see Fig. 3) from 0 deg (where the tool’s rake face is perpendicular to the workpiece) to a negative 90 deg (where the tool’s rake face is tangent to the workpiece, however at this extreme no cutting is possible as the depth of cut is zero). At the midpoint between these two extremes, 45 deg below the horizontal plane, the effective rake angle is −45 deg, other effective rake angles, such as −15, −30, and −60 deg, are also available by adjusting the tool height. Based upon previous work [14,19], a rake angle of about −45 deg is optimal to achieve ductile machining conditions and minimum ductile machining force conditions. This rake angle produces a sufficient zone or volume of the high-pressure phase of the material, due to the large compressive and shear stresses developed in the chip formation zone, to accommodate chip generation and ductile material removal. Less-negative rake angles (more positive) do not produce a sufficient extent of the high-pressure phase to maximize the ductile depth of cut, i.e., produce the maximum critical depth of cut. More-negative rake angles do not further enhance the ductile chip formation (as the entire chip is already formed within the high-pressure phase), but do tend to increase forces (particularly thrust force, if the clearance angle is kept constant, which is not the case in the current work), leading to greater tool wear [20].

The depth of cut, chip thickness or in-feed, was adjusted over a range of 100–500 nm to cover the ductile and brittle material removal behavior and encompass the ductile-to-brittle transition. A PZT translation mechanism, with a total stroke of 3 μm, was used to establish the feed [18]. Material removal in excess of this (a 2x reduction in the wafer diameter) was achieved by multiple plunge cuts, using the machine’s x-axis slide to reposition the tool prior to each plunge cut of the PZT feed device.

The speed of the DTM was maintained at 20 rpm, providing a very slow surface or cutting velocity of about 3 m/min. This slow cutting speed results in low temperatures in the process or cutting zone, thereby minimizing the influence of thermal softening of the workpiece material. The average temperature in the chip formation zone is expected to be less than 500 °C [21], while the local maximum temperature is on the order of 1000 °C.

During each cut, at the various chip thickness and rake angle combinations, the cutting and thrust forces were monitored by a three-axis dynamometer (Kistler MiniDyne). The voltage output having been previously calibrated to the input force [18]. During machining, the process was monitored to detect signs of tool chipping or breakage. If tool breakage occurred, the process was interrupted and the tool was either indexed to a new section of the cutting edge or replaced with another tool. As the wafer has two flats ground onto the circumference, as is typical with wafers to identify crystal orientation, this provided a convenient “zeroing” of the force sensors twice during each revolution, and provided for orientation of the cutting process mechanism (ductile-brittle) relative to crystal orientation. After each cutting condition, depth and rake angle, the chips/debris were collected and, along with the machined surface, analyzed for ductile machining conditions.

3 Results

3.1 Force Plots, Cutting, Thrust, and Force Ratio Versus Depth and Rake Angle. Force plots for rake angles of 0, −30, and −45 deg, at 100, 300, and 500 nm depth of cut (chip thickness or feed/rev) are shown in Figs. 4 and 5. The forces increase as the depth of cut is increased, as expected. At 0 deg rake angle, the force fluctuations (indicating ductile and brittle material removal) are significant; compare Fig. 4(a) to Fig. 5(a). As the rake angle is made more negative, or as the depth of cut is reduced, the force fluctuations are reduced (suggesting more of a ductile cut as indicated again by comparing Figs. 4(a) and 5(a)). The thrust forces are not significantly (or systematically) affected by the rake angle (this is partly due to the constant included angle of the tools).

3.2 Surface Finish, Depth of Cut, and Rake Angle. The machined surface shows evidence of both brittle and ductile material removal; rough and smooth, respectively. This was most obvious at the less-negative rake angles and larger depths of cut, where brittle fracture is most likely (rougher surface and lower forces). For smaller depths of cut and more-negative rake angles, the cutting became more ductile (smoother surface and higher forces). For example: The 100 nm depth of cut (chip thickness) with −45 deg rake angle tool produced a surface without significance.
cant fracture damage in the ductile region, whereas machining with the 0 deg rake angle at 500 nm depth of cut resulted in a mostly brittle fracture, as shown in Figs. 6 and 7.

The regions of ductile-brittle cutting and the ductile-to-brittle transitions correlated to the sample crystalline structure, i.e., there are six regions of ductile and brittle behavior (six transitions) that match the sixfold coordination of 6H SiC. The regions of ductile material removal are where the surface roughness is smoother, i.e., minimum fracture and less cracks. The regions of brittle material removal result in a rougher surface with many cracks, voids, and broken or chipped pieces. This is most clearly seen with the 0 deg rake angle tool as shown in Figs. 6 and 7.

3.3 Chips. The machining process generated chips indicative of both ductile and brittle machining. All cuts showed signs of both ductile (Figs. 8(a) and 8(b)) and brittle chips (Fig. 8(c)). The ductile debris tends to be long and narrow, similar to metal machining, chips. The brittle-fracture debris is mostly small fragments, chips, or powder. This fracture or brittle debris could be balled up into larger agglomerates (collected on the tool or sample) that were loosely held together and quite fragile. Whereas the ductile chips retained their strength and could be easily handled (moved or picked up) without being broken. The individual single grains of fractured material retained their strength and could be manipulated without additional fracture.

Some ductile chips also remained attached to the surface, especially noticeable for the ~45 deg rake angle and 500 nm depth of cut, as shown in Fig. 8(a). These “metal machining-like” chips are clearly evidence of a ductile or plastic deformation process.

A burr was formed at the trailing edge of the flats on the circumference of the wafer. These burrs, consisting of chips or debris, are similar in appearance to those formed with ductile metal cutting. Generally, in metal cutting, these burrs are found when the cutting edge is dull or large compared to the uncut chip thickness. A similar situation may occur during ductile machining of SiC at small depths of cut, where the chip thickness is comparable to the cutting edge radius [14,21].

3.4 Tool Wear and Chipping. Tool wear was not addressed in this initial study, but some observations have been made. The total length of cutting, or total material removed, was not large (millimeters and cubic micrometers, respectively) and therefore...
tool wear was not significant. Tool breakage or chipping was also not a major problem for the cutting reported herein, i.e., none of the results reported in this paper involved significant tool breakage or chipping. (Note: one tool was significantly chipped during some preliminary cutting tests and debugging of the experimental procedure.) Generally, the tool edge shows signs of some micro-chipping after cutting the samples. This chipping, which can and does affect the resultant surface finish (chipped tools obviously produce a rougher surface), is a problem with single-crystal tools during interrupted cutting such as performed in the subject experi-

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**Fig. 5** Force data plots for −45 deg rake angle tool: (a) 100 nm depth of cut; (b) 300 nm depth of cut; (c) 500 nm depth of cut

**Fig. 6** Typical smooth (ductile) surface
ments. Polycrystalline diamond tools (PCD) and/or non-
interrupted or continuous cutting conditions do not result in as
much edge chipping of the tool. These conditions (PCD and con-
tinuous cuts) will be exploited in future machining experiments.
Much success has been demonstrated using PCD tools for ma-
chining of silicon nitride, where tool edge chipping can be greatly
reduced compared to single-crystal diamond tools [21]. Figure 9
shows the various tools after machining was concluding.
The 0 and −30 deg rake angle tools showed more edge wear/
damage than did the −45 deg rake angle tool.

3.5 Postprocess Analysis. A number of postprocess inspec-
tion techniques were used to evaluate the ductile-brittle nature of
the cutting process. These included optical, TEM, SEM, and Ra-
man. Only a cursory review of the pertinent results will be pre-

tained here. A separate paper is being prepared to cover the TEM
results and the implications of a phase transformation in more
detail [22].

The optical microscope images (Figs. 6–8) reveal evidence of
both ductile and brittle machining (surface and debris/chips). The
brittle machining was evidenced by small broken pieces of single-
crystal SiC. The size of these fragments was generally on the
order of a few micrometers, and appears similar to powder (not
round pieces, but more irregular and rough/jagged pieces). These
small pieces could also be balled up or agglomerated into larger
globules during the machining process as shown in Fig. 8(c).

TEM observation confirmed the ductile nature of the chips and
showed evidence of a phase transformation. The ductile chips are am-
orphous, although the typical amorphous halo ring is lacking.
Thus, the original or starting single-crystal material was eventu-
lally transformed into an amorphous material, which has under-
gone significant ductile or plastic deformation during the machin-
ing process. The brittle or fractured material is found to be single-
crystal SiC as evidenced by the diffraction pattern.

EDAX evaluation during TEM, as shown in Fig. 10, indicates
the ductile chips are indeed SiC, as are the brittle debris (and not
debris from some other source).

SEM observation, as shown in Fig. 8(b), also confirms the duc-
tile metal-like machining debris.

3.6 Fluid-Dry Cutting Conditions. All of the reported cut-
ting tests were done dry in room air. This facilitated collection and
inspection of the machining debris, i.e., chips. In the future, cut-
ting fluids will be utilized in an attempt to improve the machining
process. This may necessitate an increase in the rpm and thus
cutting speed, to increase the temperature high enough to produce
desirable thermal and chemical reactions. Doubling the speed to
40 rpm or 6 m/min may be sufficient to raise the workpiece tem-
perature. Based upon previous computer simulations, this higher
speed increases the temperatures above 500°C at the tool cutting
edge [21].

4 Discussion

The machining experiments and subsequent or postprocess
analysis clearly demonstrate ductile and brittle material removal,
and a ductile-to-brittle transition with increasing depth of cut
and/or the use of a less-negative rake angle tool. These results are
consistent with machining experiments of other nominally brittle
semiconductor and ceramic materials such as silicon, germanium,
and silicon nitride.

4.1 Forces, Surfaces, Chips, and Force Signature. For the
purposes of this discussion, and with regard to machining forces,
high forces are considered to be indicative of ductile machining
and lower forces are considered due to brittle material removal for
a given depth of cut. It generally takes less energy (lower forces)
to remove material via brittle fracture than by ductile or plastic
deformation on a per unit or volume basis, or at the same depth of
cut.

Due to the wide fluctuation in the cutting force (particularly at
the less-negative rake angle), maximum, minimum, and average
forces (Fig. 11) are reported in addition to the raw or instanta-
aneous data (Figs. 4, 5, and 12).

For the 0 deg rake angle tool: The minimum, maximum, and
average forces all increase with increasing depth of cut as ex-
pected, as shown in Fig. 11(a). Here, the minimum forces are due
to brittle cutting, and the maximum forces occur in the ductile
regime. The process appears dominated by brittle fracture at the
larger depths of cut. The force ratio reflects this trend as the
cutting/thrust ratio decreases with an increase in depth of cut. This
is expected when brittle cutting (lower cutting forces) dominate at
the larger depths of cut.

For the −45 deg rake angle tool: The 100 nm cut appears
mostly ductile, based on the force signals, and the 300 nm depth
of cut may represent a transition to brittle cutting, i.e., lower
forces, compared to ductile cutting as shown in Fig. 11(b). At
500 nm depth of cut brittle behavior dominates.

The force fluctuations (most noticeable at 0 deg rake angle as
shown in Figs. 4, 11(a), and 12, reflecting high ductile machining
forces and lower brittle machining forces, suggest a ductile-to-
brittle transition in accordance with the sixfold symmetry of the
crystal structure.

The thrust force data is more difficult to compare due to the
fixed included angle, i.e., the clearance angle changes with the
change in rake angle, as indicated in Fig. 3. Also, the cutting
forces are higher for the more-negative rake angle tool for a given
depth of cut. In traditional metal cutting, this is explained by a

at small depths of cut, the thrust force dominates over the
cutting force due to the rather large or significant influence of the

Journal of Manufacturing Science and Engineering
AUGUST 2005, Vol. 127 / 5
rubbing and plowing component of the friction force. The coefficient of friction $\mu$ is typically less than 1, as is the case for frictional behavior as represented in Eq. (1).

$$F_f = \mu F_n$$

where the cutting force $F_c$ corresponds to the friction force $F_f$, and the thrust force $F_t$ is represented by the normal force $F_n$.

In the case of diamond on SiC, $\mu = 0.4$; therefore, the cutting force would be about one-half the thrust force at small depths of cut, where the cutting edge radius is on the same size scale as the depth of cut. These values are consistent for the 0 deg rake angle tool, where presumably the thrust force component is largely generated by frictional contact of the clearance face. At larger depths of cut, the cutting force is larger than the thrust force [21] and is most clearly shown with the $-45^\circ$ deg rake angle tool at 300 and 500 nm depths of cut. At the critical depth of cut, where the ma-
Material removal becomes brittle rather than ductile, the cutting force will be less than the corresponding ductile regime cutting force but may still be comparable to the thrust force [21]; this condition appears for the −45 deg rake angle tool at the 300 and 500 nm depth of cut conditions. This is most clearly shown in the case of the 0 deg rake angle tool if one considers the valleys of the force plots to be representative of brittle material removal and the peaks to represent ductile material removal.

As the rake angle is decreased from 0 to −45 deg, the relative amount of ductile cutting increases and the brittle fracture contribution decreases. Also, the cutting mechanism transitions from a more ductile to a more brittle behavior as the depth of cut is increased from 100 to 500 nm.

The −45 deg rake angle does not result in a significantly larger thrust force as might be expected, because the clearance angle is also large. As the tool’s included angle is fixed at 85 deg due to the method used to vary the rake angle, the clearance angle is also changed. Therefore, most of the thrust force is generated on the rake case for the −45 deg tool, whereas for the 0 deg rake angle tool, the thrust force is substantially generated on the clearance face. Therefore, a direct comparison of the influence of the cutting conditions on the thrust force is not straightforward due to the tool geometry employed. But in general, at −45 and −30 deg rake angles, the thrust force is mainly generated along the rake face (a combination of plastic deformation, chip formation, and friction), whereas for the zero degree rake angle tool, the thrust force is mostly due to frictional contact on the clearance face.

4.2 Crystal Orientation. The force signature reported herein included a periodic component that indicates a crystallographic effect. As the workpiece material is single crystal, the tool is exposed to various (continually varying) cutting planes and cutting directions as the part is rotated about its axis. Previous work with machining single-crystal silicon and germanium [23,24] had shown that these periodic and regular variations were due to the crystal orientation effects, i.e., varying fracture toughness of the
crystal planes and directions. Furthermore, the roughness of the resultant surface could also manifest itself with “zones” characteristic of both ductile and brittle material removal that aligned with the crystal planes and directions, characterizing orientations of easily fractured atomic arrangement, as shown in Figs. 4–7.

The force peaks show a number of very interesting features. The crystallographic plots are clearly revealed for the 0 deg rake angle (Fig. 4) where a combination of ductile and brittle cutting occurs. The high force peaks are believed to be due to either ductile machining conditions and/or resulting from higher material property values in the crystal orientations at these locations. Similarly, the low forces (valleys) are due to brittle material removal and/or lower material property values at these locations. The contribution of the varying material properties, with crystal orientation, will be the subject of a future publication.

For the case of a 0 deg rake angle tool, all of the cuts attempted (100, 300, and 500 nm) resulted in substantial brittle material removal and fracture. For this rake angle, the ductile-to-brittle transition, for all crystal directions sampled during machining of the circumference of the wafer, occurred throughout a larger range than that sampled. As the trend in the data suggest in Figs. 4 and 12, a purely ductile cut may only be achieved at depths less than 50 nm (certainly <100 nm), and a purely brittle cut may be produced at depths greater than 750 nm (the 50 and 750 nm are speculative and used only for discussion purposes). For the six zones of ductile machining (per revolution of the sample), the transition depth to brittle machining clearly appears to show up at 500 nm for all rake angles used, i.e. the ductile mode appears to be reduced and the fracture mode enhanced between 100 and 500 nm. It is important to keep in mind that there are, in reality, many crystal directions sampled during one revolution, and the crystal cutting direction is continuously varying. Likewise the ductile-brittle behavior also continuously varies around the wafer circumference. So, there are really zones or regions that dominate ductile and brittle behavior, and the edges of these zones are not well prescribed. From the data for the 0 deg rake angle tool, it appears that at some depth greater than 500 nm (perhaps 750 nm), the entire cutting process (for all crystal directions) would be brittle. Whereas for this same rake angle, a depth of cut of less than 100 nm (perhaps 50 nm or less) is required to produce a purely ductile cut.

In reality, there are three parameters to evaluate when determining the ductile-brittle cutting characteristics. The above discussion emphasizes the machining forces. But the machining debris, or chips, and the surface can also be ductile or brittle. To have a totally ductile cut, all three parameters (forces, surface, and debris) would exhibit ductile behavior. But this is not necessary to produce a finished surface free of brittle fracture. The machining process can involve a combination of ductile and brittle cutting; the forces may suggest ductile cutting (as is the case for ~45 deg and 300 nm), whereas the debris may include both ductile and brittle chips, as occurred for these conditions.

While the ductile response of single-crystal semiconductors such as silicon and germanium is not noticeably influenced by the crystal orientation or cutting direction (as it is presumed that the high-pressure phase transformation is not extremely sensitive to crystallographic orientation), the fracture characteristics are strongly influenced by crystallography. Therefore, during cutting of the circumference of the single crystal, similar to cutting on the planar face, during one revolution we can effectively machine or sample all of the crystal directions exposed on that particular face. This should lead to some areas or zones (crystal planes, orientations, and directions) more susceptible to fracture, as is found with planar face cutting operations [23,24]. Evaluation of this phenomenon can be directly used to assess the potential for ductile machining of polycrystalline material. Machining of polycrystalline material, with random crystal orientations, similarly samples all possible crystal orientations during the machining process. Typically, the worst-case “crystal orientation for fracture” dominates the machining of polycrystalline materials. This worst-case orientation can be readily determined from evaluating the resultant fracture damage during machining of single-crystal samples. The crystal orientations that do not readily fracture due to higher fracture toughness or lower resolved tensile stress, i.e., that produce ductile behavior, will perform similarly in both the single-crystal and polycrystalline materials, and as such do not limit the ability
to perform ductile regime machining. Of course, in the case of polycrystalline materials, the secondary or binder (sintering) phase may also play a role in the machining behavior of the material.

4.3 Chip Debris. All cutting conditions involved both ductile and brittle formed debris. The amount of each varied with the relative contribution from ductile/brittle material removal. For instance, at the −45 deg 500 nm cutting condition, much more ductile chip debris was generated compared to the less-negative rake angles at this same depth of cut. Similarly, or comparatively, at the 0 deg rake and 500 nm cutting condition, the majority of the chips were produced by brittle process mechanisms.

The ductile chips tended to exist as larger single pieces (up to several millimeters in length), whereas the brittle debris (micrometers in size and powderlike) tended to be balled up into larger agglomerates. Presumably this is due to the dry cutting conditions, as no fluid (not even compressed air) was used to clean or clear the cutting region, therefore the small chips tended to pile up on the sample and tool. This did have the adverse effect of causing the surface to be scratched by this accumulated debris during subsequent machining. Other researchers have reported the occurrence of brittle debris or a powderlike material during machining of nominally hard and brittle materials. However, the importance of the current contribution is in the existence of ductile chips or debris indicative of a ductile metal like machining process.

4.4 Cutting Tools and Fluids. Chipping or fracture of single-crystal diamond tools is a potential problem with machining of hard-brittle materials, especially with interrupted cuts. However, with continuous cuts, such as during a facing operation, or nearly continuous cuts, such as in the current work (there are two continuous cuts per revolution, resulting from four edges—produced by the two flats), the number of tool-workpiece impacts are greatly diminished, leading to less tool damage and prolonged tool life. Some limited tool edge chipping did occur during the machining tests conducted for this study.

Once tool breakage is under control, i.e., as with a continuous cutting operation, then wear of the cutting edge is the next likely tool issue to be addressed. In essence, you have two very hard materials (two of the hardest materials known) coming into intimate contact and wearing each other away. If the temperatures are low enough to prevent or minimize diffusion wear, as we suspect it is for the present case, then abrasive wear is the likely dominant wear mechanism. Cutting fluids or lubricants provide a protective

Fig. 11 (a) Max, min, avg forces, (b) force ratios (depth and rake angle)
barrier that may be useful to reduce friction and protect the tool from adverse wear. Particularly noteworthy is an experimental cutting fluid developed by NIST [25] that forms a protective coating via a thermally activated chemical reaction. This alcohol-based fluid is purported to chemically react with the diamond tool and creates a "sacrificial" surface layer that coats and protects the diamond from wear (probably providing a diffusion and abrasion wear barrier). It is this thin protective layer that is subsequently worn away during the machining process, and then is replenished via the thermally activated chemical reaction, and the cycle is continued.

Previously, fluids have not been found that improved upon the machining process (reduced cutting forces or longer tool life) for machining semiconductors and ceramics. Rather, certain fluids tended to make the ductile machining process worse, generally by promoting brittle fracture or increasing tool wear (notably water, and bases and acids—high and low pH chemical based fluids [26,27]). Whereas oils seemed to be the least benign and provided some lubrication benefit [28]. Therefore, in the past, selecting a cutting fluid or coolant was mostly based upon the fluid that produced the least detrimental effects. Of course, water for cooling and washing (with appropriate rust inhibitors and cleansing agents) and oils (particularly mineral oil) for lubricating are often chosen for machining these difficult materials.

4.5 Phase Transformation. The occurrence of a high-pressure phase transformation of semiconductors and ceramics is often characterized by the amorphous remnant that exists, on the surface and within the chip, after processing. This amorphous remnant is a result of a back transformation from the high-pressure phase to an atmospheric pressure phase due to the rapid release of the pressure in the wake of the cutting tool, i.e., the high-pressure phase only exists while the pressure is applied—when the pressure is relieved, the material reverts to another phase. The rate at which the pressure is released, along with the maximum pressure imposed, can also affect the resultant back transformed phase [2]. It is believed by the authors that a high-pressure phase transformation of SiC is responsible for the ob-
served ductile machining behavior, as has been found with other hard-brittle materials such as silicon, germanium, and silicon nitride.

5 Conclusion

Ductile regime machining of single-crystal silicon carbide has been demonstrated to occur at penetration depths or chip thicknesses less than 500-nm. This ductile behavior has been confirmed by production of smooth surfaces, and chips indicative of ductile machining similar to metals. The ductile machining characteristics are enhanced by more-negative rake angles and smaller depths of cut. It is believed that the plastic nature attributed to the ductile machining is a result of the material undergoing a high-pressure phase transformation to a metallic state in which the deformation occurs. The investigation of these high-pressure phase transformations is currently under investigation [29].

Acknowledgments

The authors deeply appreciate the financial assistance of JSPS (Grant No. PU02210), which provided for the collaboration on which this paper is based. J. Patten also gratefully acknowledges the financial assistance of NSF (DMR) for funding of the High-Pressure Phase Transformation-Focused Research Grant. The authors also thank the faculty and students at Tohoku University for assistance on this project, particularly Professor Kawahara for his help with the TEM analysis. W. Gao acknowledges the financial support for developing the instrument used to conduct the experiments reported herein, from JSPS (Scientific Grant-in-Aid No. 15360063).

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