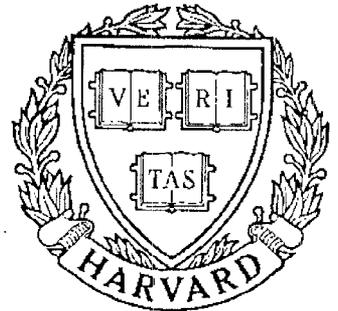


TECHNICAL RESEARCH REPORT



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Chemo-Mechanical Effects on the Efficiency of Machining Ceramics

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Chemo-Mechanical Effects on the Efficiency of Machining Ceramics

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Abstract

This paper presents an experimental study of the turning of a ceramic material - aluminum oxide (Al_2O_3). Emphasis is given to gain a comprehensive understanding of the cutting mechanism. This study explores the utilization of cutting fluids with chemical additives to develop a novel machining process. The machining tests were performed on a CNC lathe. Polycrystalline diamond compact tools were used. The cutting force during machining was measured using an instrumented tool holder as a dynamometer. The surface finish was inspected using a profilometer. SEM technique was used to study the mechanism of the surface formation in microscale. Results from this experimental study provides rich information on the cutting mechanisms during ceramics machining and the chemo-mechanical effects on the machining efficiency.

1. Introduction

The need for high-strength materials at high temperature applications has led to the development of advanced ceramics. Today industries, such as aircraft, automotive, and micro-electronics, are finding increasing applications for ceramic materials. Machining of ceramics has been a rapidly growing field. However, ceramic materials are hard to be machined. Although most of ceramic parts are manufactured to near net shape size by pressing and sintering processes, precision machining is now required to achieve a high degree of the geometrical accuracy of ceramic parts after the pressing and sintering processes.

The traditional technology to machine ceramics is grinding. By means of making very small chips produced by the cutting edges of abrasive particles, the grinding process removes ceramic material with a low productivity. With the ever increasing number of ceramic materials in the market place, there is a pressing need to improve traditional methods to machine ceramic materials for cost reduction and quality assurance in order to achieve the full potential of ceramics. As reported in [1], a "laser lathe" was developed in MIT where the dual beam principle was applied to remove ceramic materials in liquid form. However, the surface damage and sub-surface damage induced during machining are issues remaining unsolved. In abrasive jet machining, the high pressure abrasives wash and pierce ceramic materials away [2]. But, the availability of new equipment and economic factors have limited its wide use on the shop floor. With the availability of making abrasive grain consistently to high levels of performance and accurate size, the grinding process has maintained its popularity in a world of machining operations. Grinding wheels made of hard structural ceramic materials such as Si_3N_4 , SiC and alumina (hot pressed silicon nitride ceramics) are capable of achieving high quality of microfinishing. It was reported that the roughness average value (R_a) of the surface ground by wheels of #140-200 mesh size diamond abrasive was about 0.1 to 2 μm [3]. However, little work has been conducted in the study to gain a comprehensive understanding of the cutting mechanism during the machining of ceramic materials. Lack of such knowledge has slowed down the development of new and innovative machining processes that may revolutionize the machining technology of advanced ceramic materials.

The work presented in this paper is an experimental study of the cutting mechanism during the machining of ceramics. The experimental work is based on a single-point turning process, a fundamental element of machining operations. In this study, the workpiece material used was aluminum oxide (Al_2O_3). The cutting tools used were polycrystalline diamond compact tools. Method of a two-level experimentation design was employed to study the effects of machining parameters such as feed, depth of cut, and cutting speed on the machining performance with respect to surface finish quality. Special attention was paid to the collection of evidence which can support the theories assumed to be the cutting mechanisms in the material removing process. To apply these findings, or more importantly, to develop new and innovative machining methods based on these findings, chemical-assisted machining processes were explored to achieve a better machining performance. The paper is organized as follows. Section 2 of this paper describes the experimental procedures. The experimental evidence and results are reported in Section 3. Section 4 presents the study of cutting mechanism with emphasis on the tribological interactions in machining aluminum oxide (Al_2O_3) when selected chemicals were added to the applied cutting fluid. Section 5 contains concluding remarks.

2. Experimental Procedures

2.1 General Description of Experimental Setup

In this study, the ceramic material selected to be machined is aluminum oxide (Al_2O_3). The purchased 99.8% Al_2O_3 is a cylindrical bar with diameter = 19.0 mm and the length = 76.2 mm. The material is noted as a strong, dense recrystallized high-alumina ceramics. In order to machine aluminum oxide (Al_2O_3), the tool insert material selected is polycrystalline diamond compact. Some material properties of the ceramics are listed below. Note that the hardness of polycrystalline diamond compact is, at least, five times as hard as that of aluminum oxide material to ensure that the cutting tool will have sufficient length of tool life to perform the experimental study.

property item	unit	aluminum oxide	polycrystalline diamond compact
Hardness	kg/mm ²	1100-1200	6000-9000
Modulus of Elasticity	GPa	345	725-1049
Compressive Strength	Mpa	2071	8200
Fracture Toughness	MPa*√m	4.0	3.4

Figures 1a and 1b show the experimental setup. The machine tool used was a CNC Slater lathe. The aluminum oxide bar was mounted in the spindle. The cutting tool was fixed on the rotatory tool post attached to the lathe. Strain gages were attached to the tool holder which convert the strain induced by the cutting force generated during machining into an electrical signal for the cutting force measurement. As illustrated in Fig. 1b, a pc-based computer data acquisition was used for on-line recording the cutting force signal.

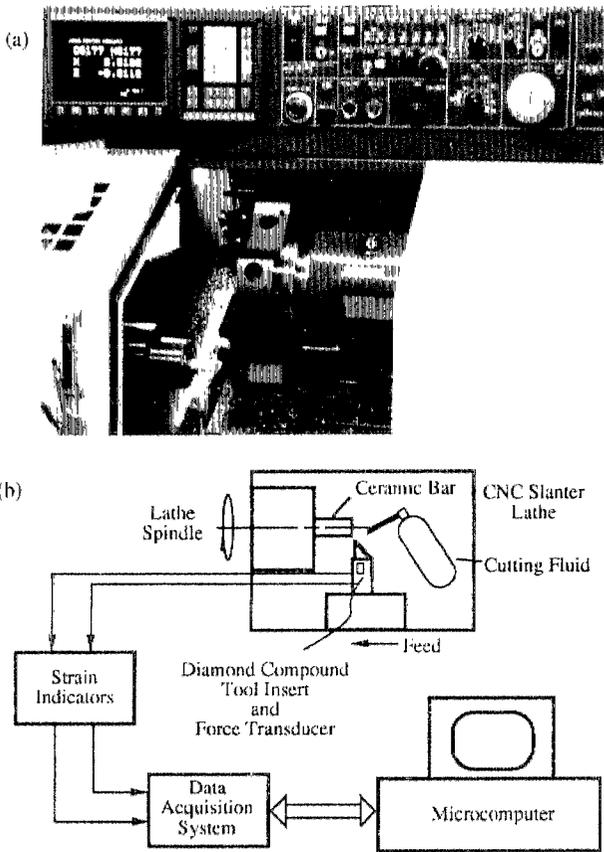


Figure 1 Experimental Setup and Its Schematic Diagram

2.2 Setting of Machining Conditions

In order to investigate the cutting mechanism, the factorial design, based on the principle of orthogonal array, was employed. The three parameters under investigation were feed, depth of cut, and cutting speed. The following design matrix lists their settings used in the experimental study.

In order to explore the possibility of using cutting fluids as an efficient means to achieve satisfactory machining performance, four types of cutting fluids were used during the study. They are a type of traditional mineral oil, an oil-based water soluble coolant, pure distilled water, and a mixture of distilled water and a selected chemical additive. In this experimental study, our finding was that the cutting fluid with the selected chemical additive performed surprisingly well regard the machining performance. Therefore, in the paper we present the experimental results from two types of cutting fluids. These two types are the cutting fluid of pure distilled water and the cutting fluid with the selected chemical additive.

test condition number	depth of cut (mm)	feed rate (mm/min)	spindle speed (rpm)	tool insert		
				1	2	3
1	-(0.1)	-(5)	-(400)			
2	+(0.2)	-(5)	-(400)			
3	-(0.1)	+(10)	-(400)			
4	+(0.2)	+(10)	-(400)			
5	-(0.1)	-(5)	+(600)			
6	+(0.2)	-(5)	+(600)			
7	-(0.1)	+(10)	+(600)			
8	+(0.2)	+(10)	+(600)			

In order to block experimental errors due to the variation among the tool insert quality, a single tool insert was used to cut 16 tests, 8 tests for the pure distilled water conditions and 8 tests for the chemical added conditions. To get fair estimates, three tool inserts were used to duplicate the 16 tests. Whenever a new tool insert was used, the method of tossing a coin was employed to determine which of the two sets of 8 tests should be performed first to randomize the effect of tool wear on the machining performance when the experimental study was in progress.

3. Experimental Results and Evidence

The experimental study consisted of three phases. In the first phase, the cutting force generated during machining at each of the 8 tests for a give cutting fluid was on-line recorded. Figure 2 presents two cutting force signals measured during machining and indicates that the average value and its standard deviation are calculated from the recorded data. Figure 3a and Figure 3b display the measured cutting force at each of the 8 tests for the distilled water cutting fluid and the cutting fluid with the selected chemical additive, respectively. A comparison between two corresponding corners reflects the effect of the selected chemical additive on the magnitudes of the two cutting force components measured during machining.

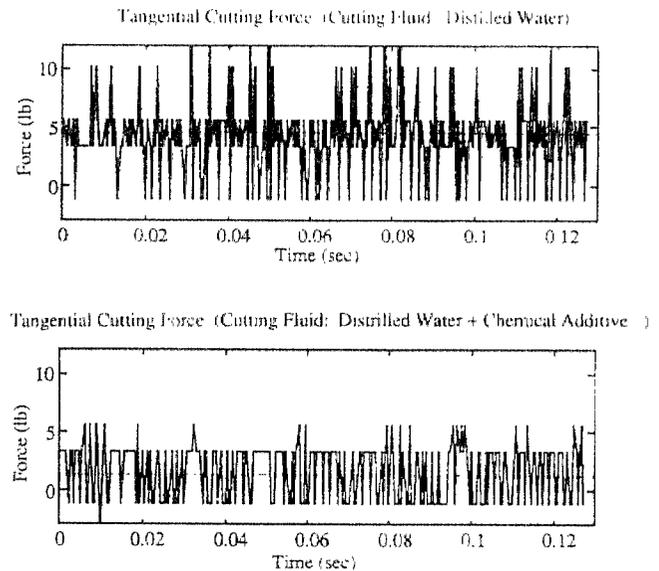


Figure 2 Cutting Force Signals Recorded during Machining

In the second phase, the machined surface of the ceramic bar was examined using a scanning electronic microscope. Photos were taken to gain a qualitative information on topography of the machined surface in micro-scale. Figure 4 displays the appearances of two machined surfaces under an identical machining conditions except the cutting fluid type. The picture depicted in Fig. 4a show the topography of the surface formed during the machined with pure distilled water, and the picture depicted in Fig. 4b with the selected chemical additive. The geometrical shape and size of the visible marks and the contrasts between the lightest and darkest parts of these two pictures signify a fact that the surface conditions shown in Fig. 4b are

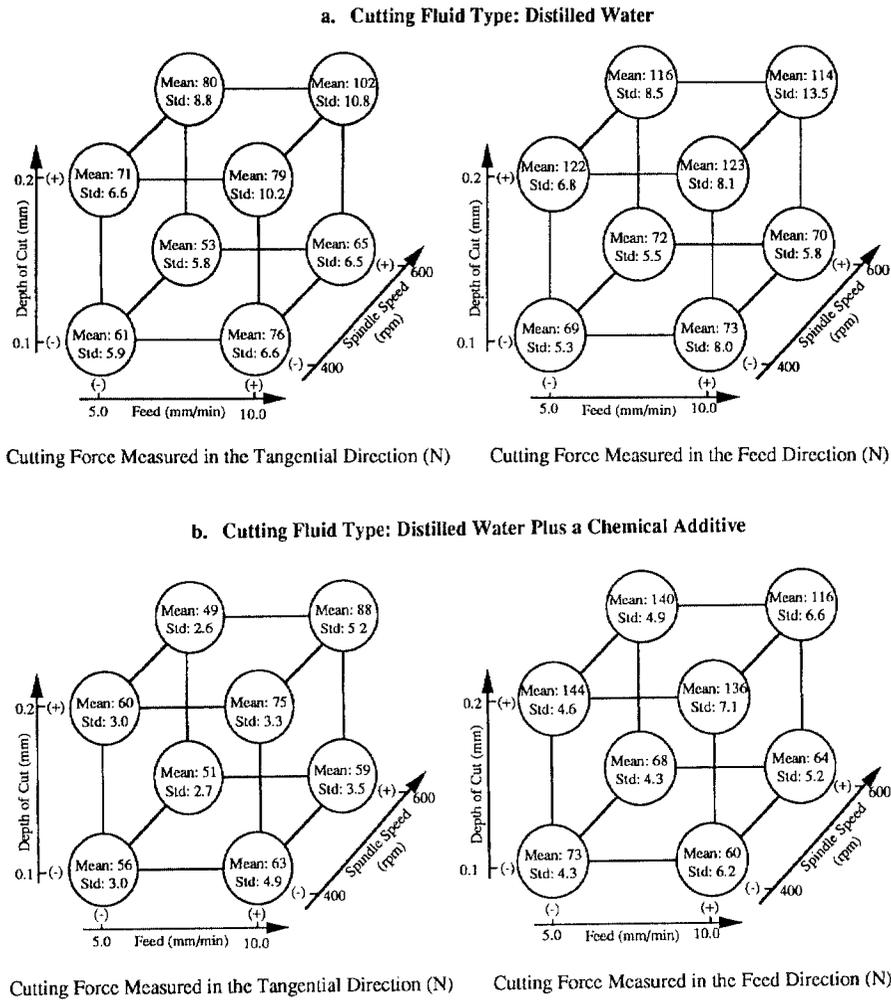
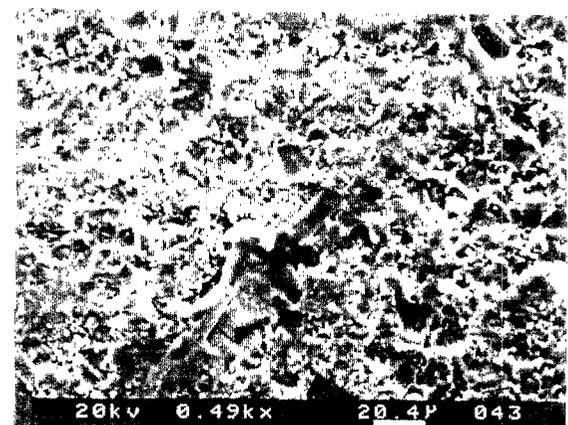
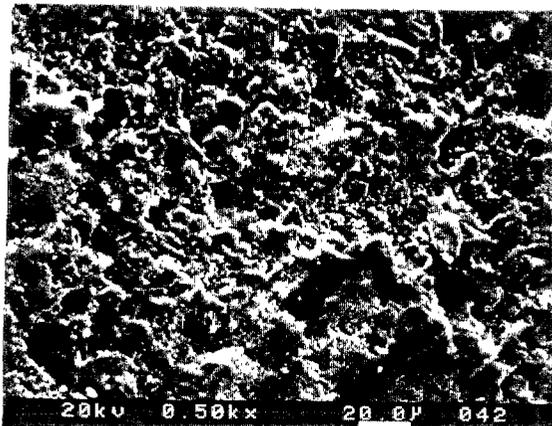


Figure 3 Comparison of the Cutting Force Components Measured During Machining, (a) Distilled Water and (b) Chemical Additive



(a) Machined Surface Using Distilled Water

(b) Machined Surface Using a Chemical Additive

Figure 4 SEM Micro Graphs of Two Machined Surfaces

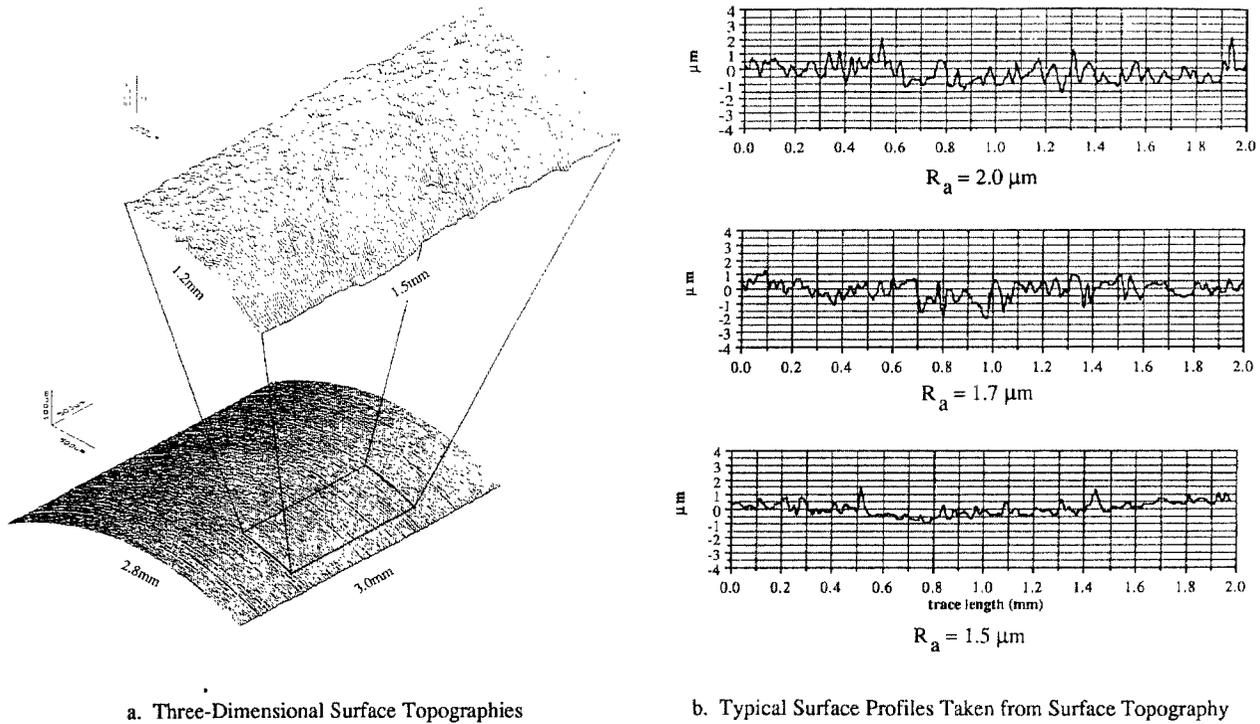


Figure 5 Three-Dimensional Visualization of the Surface Topography

better than those in Fig. 4a, indicating the effectiveness of using the selected chemical additive for improving quality of the machined surface. To quantify such effectiveness, the topography of a machined surface in macro-scale was constructed in a 3-dimensional space from the measurement on a surface profilometer. Figure 5a depicts the surface topography of a portion of the machined surface. To clearly visualize the characteristics of surface roughness, an enlarged view of the area chosen from the 3-dimensional display is also presented in Fig. 5b. The three traces shown in Fig. 5b were taken from the chosen area, representing the best, median, and worst traces regarding the roughness characteristics, that are possibly taken from the selected area.

In the third phase, evidence relevant to the study of machining mechanism was collected in this experimental study. The evidence presented in this paper includes the geometrical shape and size of the chips formed during machining shown in Fig. 6, and characteristics of the tool wear progress during machining shown in Fig. 7. In Fig. 6, qualitative and quantitative information is depicted. A comparison within Fig. 6a or Fig. 6b indicates how the machining parameter feed influences the chip formation. It is evident that the larger the feed, the larger the size of the chips formed during machining. A corresponding comparison between Fig. 6a and Fig. 6b indicates how the type of the cutting fluid used during machining influences the chip formation. The evidence is the chemical added cutting fluid produced smaller and more uniform sizes of chips. In Fig. 7, the tool wear phenomena in two different stages are illustrated. The tool wear shown in Fig. 7a represents an initial wear stage. The tool wear shown in Fig. 7b represents a severe tool wear stage.

4. Discussion of Experimental Results

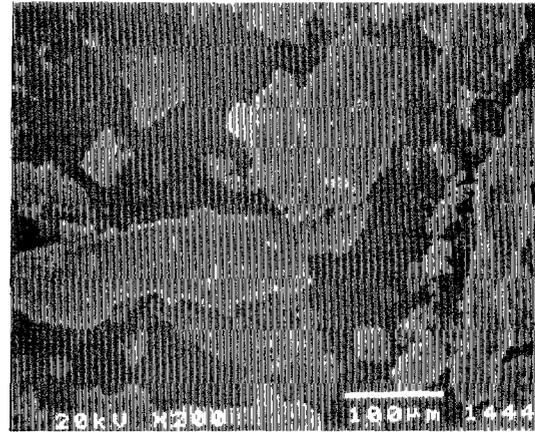
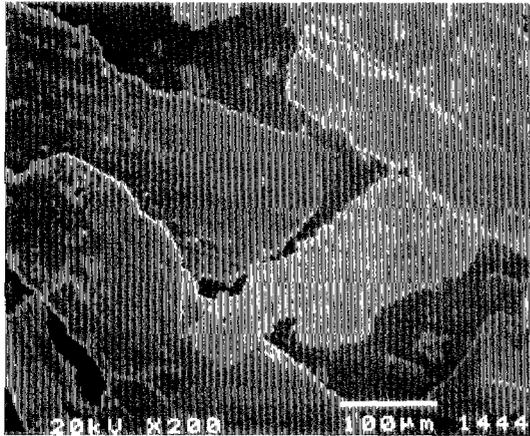
4.1 Interpretation of Cutting Mechanisms

In the machining of aluminum oxide (Al_2O_3), three types of cutting mechanisms were presented. They are brittle fracture, plastic flow, and elastic recovery. The tool, travelling across the workpiece surface, acts like an indenter to compress the material, thus inducing the stresses within the cutting zone. The propagation of the induced stress defines the three cutting mechanism boundaries. Crushing and

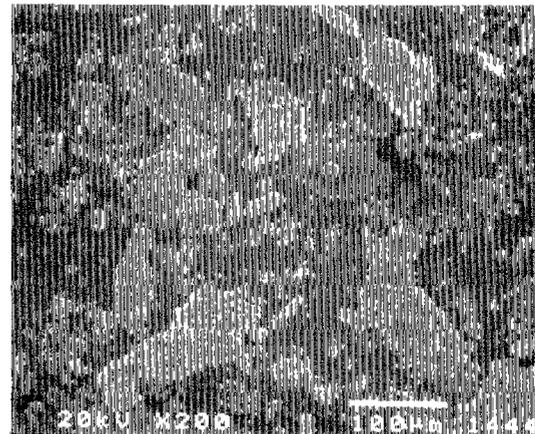
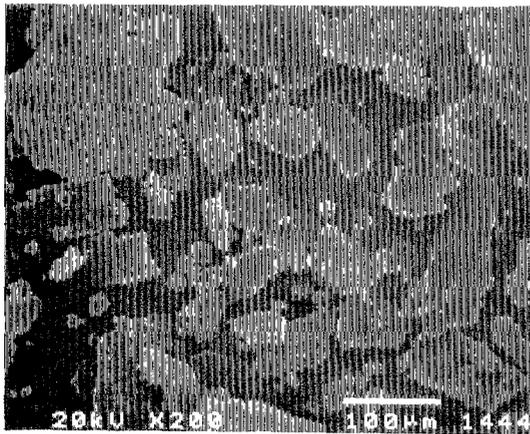
chipping were produced by brittle fracture. Therefore, it is anticipated that the indentation fracture mechanism of material removal will result in severe surface damage and sub-surface damage. Consequently, controlling this cutting mechanism and limiting it within a certain range is a key issue for any machining processes. The results from our experimental study strongly support this assertion. By examining the profiles shown in Fig. 5b, the height variations never constitute the outline of the cutting edge geometry such as the nose radius and never show any tendency of the side and end cutting edge angles. The random pattern of the height variation only explains the fact that brittle fracture is an essential mechanism to remove the ceramic material when it is being machined.

Regarding the plastic flow mechanism, if one visualizes the chip removal process, the plastic and elastic boundaries should be compressed under the tool nose tip as the tool advances. Note that the part of the ceramic material in the cutting zone is under high loads, speeds and temperature. The fact that one of the material removal mechanisms is in plastic should not be surprised. Results from our experimental study also support this assertion. By examining Fig. 7a and Fig. 7b, the wear marks on the rake face reflect the contact length between the chip and tool insert. The observation of crater wear on the tool rake face is an alias of the chip plastic flow over the tool rake face. The existence of such a plastic flow can be further evidenced by the photo taken on the back of a ceramic chip, as shown in Fig. 8. The smoothness of the chip back surface and signs of plowing wear on the back surface indicate that the ceramic chip material once was softened under high cutting temperature when it passes through the tool cutting point.

Direct evidence to support the existence of elastic deformation and recovery mechanism during machining seems hard to find out because of the extreme low elasticity of aluminum oxide (Al_2O_3). However, the effectiveness of using a chemical additive with respect to reducing the friction might imply its existence. One of the lubricating functions of the chemical additive is to form layered structure on the tool insert flank surface and workpiece material. The atoms within the layered structure, separating the two contact surfaces due to the elastic recovery mechanism, shear and slide over each other with relative ease, and thus provide low friction.



(a) Cutting Fluid: Distilled Water Only and Cutting Conditions: Test 5 & Test 6



(b) Cutting Fluid: Chemical Additive Added and Cutting Conditions: Test 5 & Test 6

Figure 6 SEM Micro Graphs of the Chips Formed during Machining

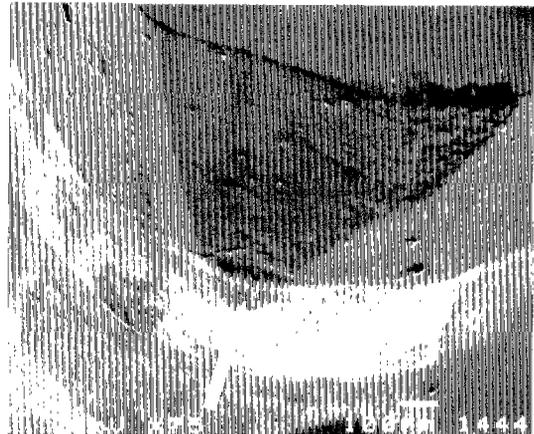
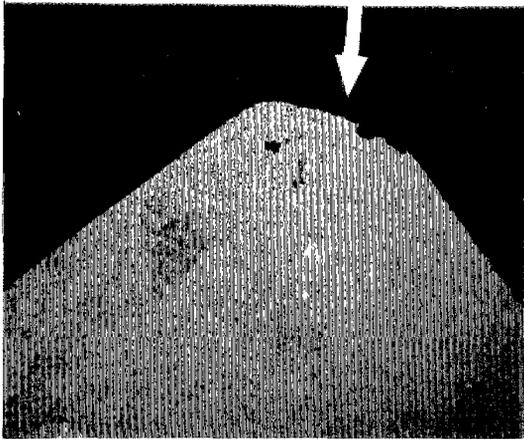
4.2 Tribological Interactions

In this experimental study, distilled water was used as a cutting fluid for the purpose of improving machining performance. In fact, water has been found to exhibit significant effects on the tribological behavior of alumina [4]. A film-like substance has been found on the surfaces of water lubricated alumina wear surfaces, suggesting the possibility of tribochemical reaction between water and alumina in the contact junction. It has been found that at high temperature ($\approx 200^{\circ}\text{C}$) aluminum oxide hydroxide (boehmite, $\text{AlO}(\text{OH})$) is formed, while at lower temperature ($\approx 100^{\circ}\text{C}$) the formation of aluminum trihydroxide (bayerite, $\text{Al}(\text{OH})_3$) is favored.

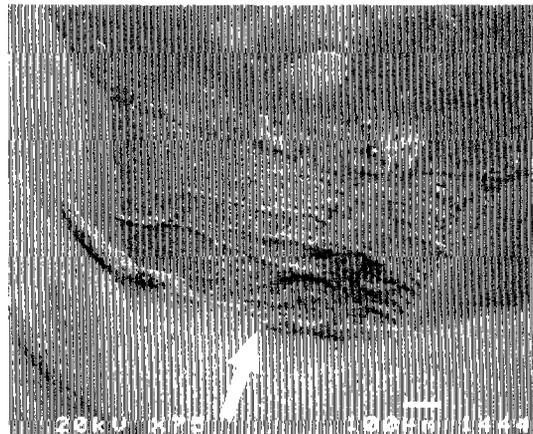
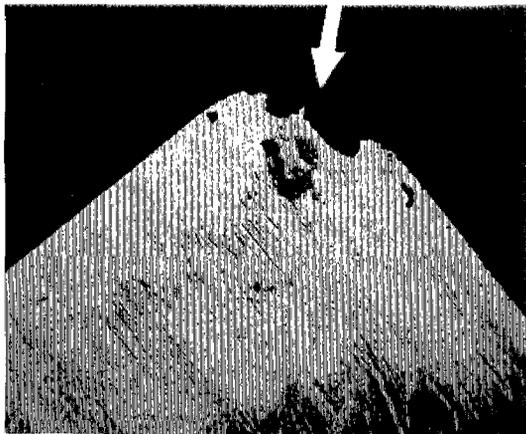
The tribochemical interactions between water and alumina provide a series of reactions. The "tribo" part serves two functions. First, it provides anisotropic shear stresses and high pressures which induce the phase transformations. Second, it provides high temperatures through frictional heating which are necessary to drive the subsequent "chemical" reactions at the proper rates.

The chemical additive selected in this experimental study plays a role of being a self-replenishing solid lubricant to achieve lower friction and wear in the two moving pairs, i.e. the pair of chip and tool rake face and the pair of tool flank face and machined workpiece surface. By examining the cutting force data displayed in Fig. 3a and Fig. 3b, two important observations from comparison between the machining process using distilled water and the addition of the selected chemical additive can be made.

1. The tangential cutting force is reduced and the feed cutting force is increased, while maintaining a constant level of the resultant cutting force. As illustrated in Fig. 9, the change in the direction of the resultant cutting force keeps the tool staying in the cutting zone and attenuates tool vibration effectively.



(a) Tool Wear at the Initial Stage where the Arrows Show the Direction of Projection under Microscope



(b) Tool Wear at the Severe Stage where the Arrows Show the Direction of Projection under Microscope

Figure 7 Evidence of Tool Wear in Two Different Stages
(a) an initial stage; (b) a severe stage

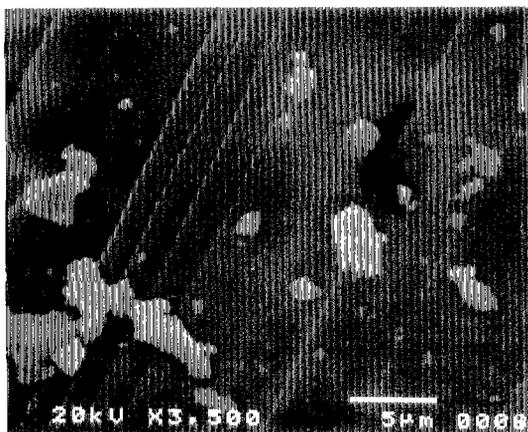
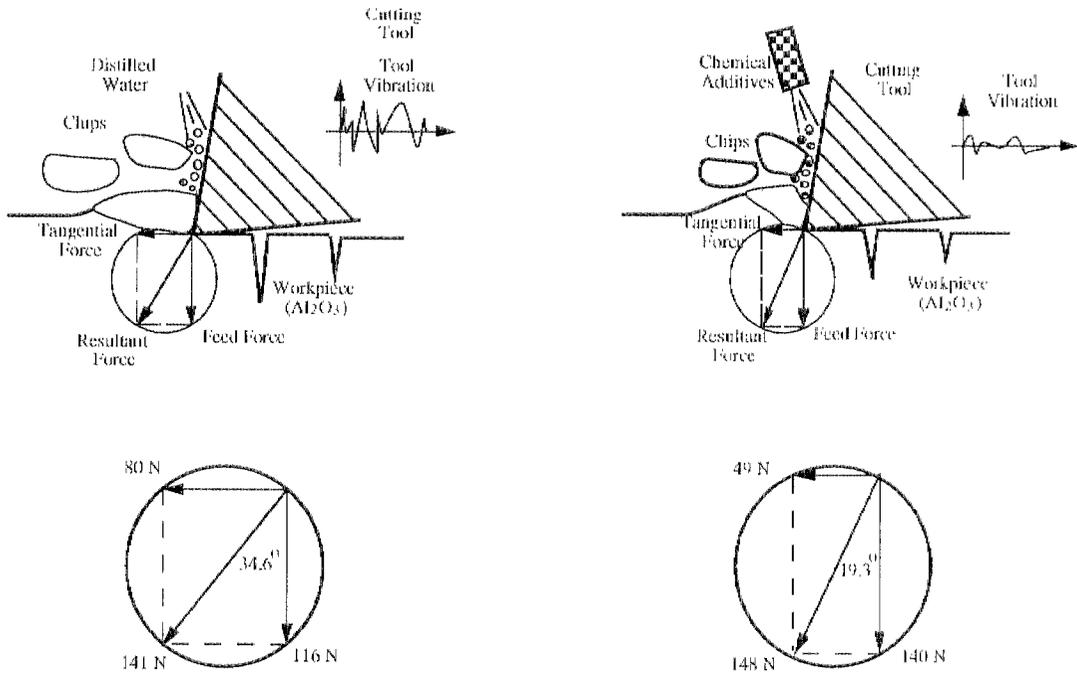


Figure 8 Smooth Back Surface and Plowing Marks Identified on Chip

2. A stabilized tool motion leads to a better surface quality such as surface finish. Figure 10 displays the measured roughness average R_a values from the surfaces machined under the 16 tests when the two cutting fluids were used. It is interesting to note that the main effect of the chemical additive is the improvement of surface roughness significantly. It seems that cutting speed has the least effect on the surface finish improvement while decreasing feed leads a better surface finish. A combination of low feed, high cutting speed and small depth of cut will result in an excellent surface finish.



(a) A Large Ratio of the Tangential Cutting Force to the Feed Cutting Force when Using Distilled Water as Cutting Fluid

(b) A Small Ratio of the Tangential Cutting Force to the Feed Cutting Force by Addition of the Selected Chemical to Distilled Water

Figure 9 Chemo-Mechanical Effects when Using the Selected Chemical Additive during Machining.

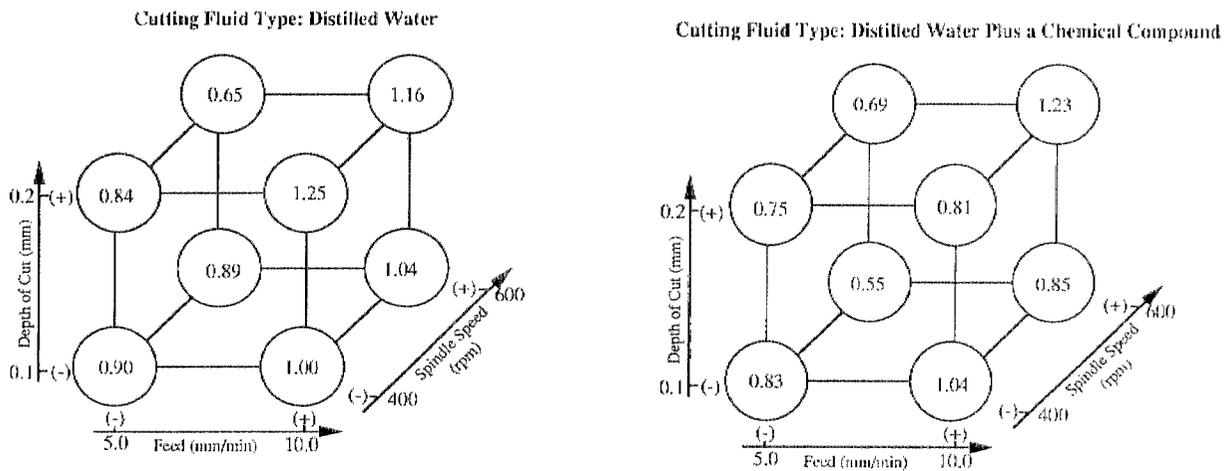


Figure 10 Comparison of Surface Roughness Averages (µm)

5. Conclusions

1. Three types of cutting mechanisms exist during the machining of aluminum oxide (Al_2O_3) in a single-point cutting process: brittle fracture, plastic flow, and elastic recovery. Although actual quantitative measurement of elastic recovery is difficult, evidence of plastic flow and brittle fracture during the ceramic material removal is strong. Controlling the brittle fracture during machining is a vital issue to control surface damage and sub-surface damage.
2. Machining parameters have significant effects on the machining performance. Increase of depth of cut or/and feed will induce a strong propagation of stress wave originated from the cutting zone. There is a pressing need to pursue experimental and analytical studies for the establishment of a machinability database and that would be a significant step in manufacturing precision components made from advanced engineering materials such as ceramics and composites.
3. The tribological interactions on the interfaces between the cutting tool and ceramic material have a strong effect on the cutting mechanism [5,6]. It has been observed that the feed cutting force increases while the tangential cutting force decreases when a selected chemical additive is added to distilled water. The chemo-mechanical effect enforces the cutting tool to stay in the cutting zone, and significantly reduces the tool vibration during machining; thus leading to a better surface quality. Further investigation is needed to clarify the details of the chemo-mechanical effects for the development of a new and novel machining technology.

Acknowledgements

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References

1. Chryssolouris, G., Bredt, J., Kordas, S., and Wilson, E., "Theoretical Aspects of a Laser Machine Tool," ASME Winter Annual Meeting Proceedings, PED 20, December 1986, pp. 177-190.
2. Mazurkiewicz, M., "Understanding Abrasive Waterjet Performance," *Machining Technology*, Vol. 2, No.1, 1991, pp. 1-3.
3. Nakagawa, T., Suzuki, K., and Uematsu, T., "Three-Dimensional Creep Feed Grinding of Ceramics by Machining Center," Report in *Machining of Ceramic Materials and Components*; Eds. K. Subramanian, Norton Company and R. Komanduri, General Electric Company, New York, NY, ASME, 1985, pp. 1-7.
4. Gates, R.S., Hsu, S.M. and Klaus E.E., "Tribochemical Mechanism of Alumina with Water", *Journal of Society of Tribologists and Lubrication Engineers*, vol. 32, no. 3, pp. 357-363, 1989.
5. Kramer, B., "Tribological Aspects of Metal Cutting," ASME Winter Annual Meeting Proceedings, PED-Vol. 54/TRIB-Vol. 2, December 1991, pp. 77-85.
6. Zhang, G., Hwang, T., Anand, D., and Jahanmir, S., "Tribological Interaction in Machining Aluminum Oxide Ceramics," *Proceedings of the Navy Tribology Workshop, Annapolis, Maryland, May 11-13, 1992*, pp. 9-13.