

TECHNICAL RESEARCH REPORT

Assessment of Non-Linear Dynamics of Material Removal on Surface Integrity

by G. Zhang, S.J. Ng, D.T. Le

T.R. 97-30



*Sponsored by
the National Science Foundation
Engineering Research Center Program,
the University of Maryland,
Harvard University,
and Industry*

Assessment of Non-Linear Dynamics of Material Removal on Surface Integrity

Guangming Zhang, Stanley J. Ng, and Dung T. Le
Department of Mechanical Engineering & the Institute for Systems Research
University of Maryland
College Park, Maryland 20742

1. INTRODUCTION

Advanced ceramics offer many desirable characteristics for industrial and commercial use in terms of their high temperature tolerance, wear and abrasive resistance, and corrosion resistance. These intrinsic properties have led ceramics to be prime candidates for many applications ranging from engineering components to dental restorations. However, the machining of ceramics into practical forms presents a challenge because of the non-linear dynamics involved in the material removal process inherent by its high hardness and high brittleness.

Manufacturing of ceramic parts requires dimensional and geometrical accuracy. Machining has played a key role in this respect to ensure the functionality of surfaces of ceramic parts, especially after sintering. However, due to their hard and brittle nature, ceramic materials are difficult to machine. The fracture-dominated material removal process in ceramics machining leaves cracks on and beneath the machined surfaces, forming surface and subsurface damage and leading to a shortened product life cycle. Moreover, the high wear rate of cutting tools or grinding wheels during machining gives rise to high production cost. The non-linear dynamics can be best described by the basic five stages of the material removal mechanism in advanced ceramic material, as illustrated in Figure 1.

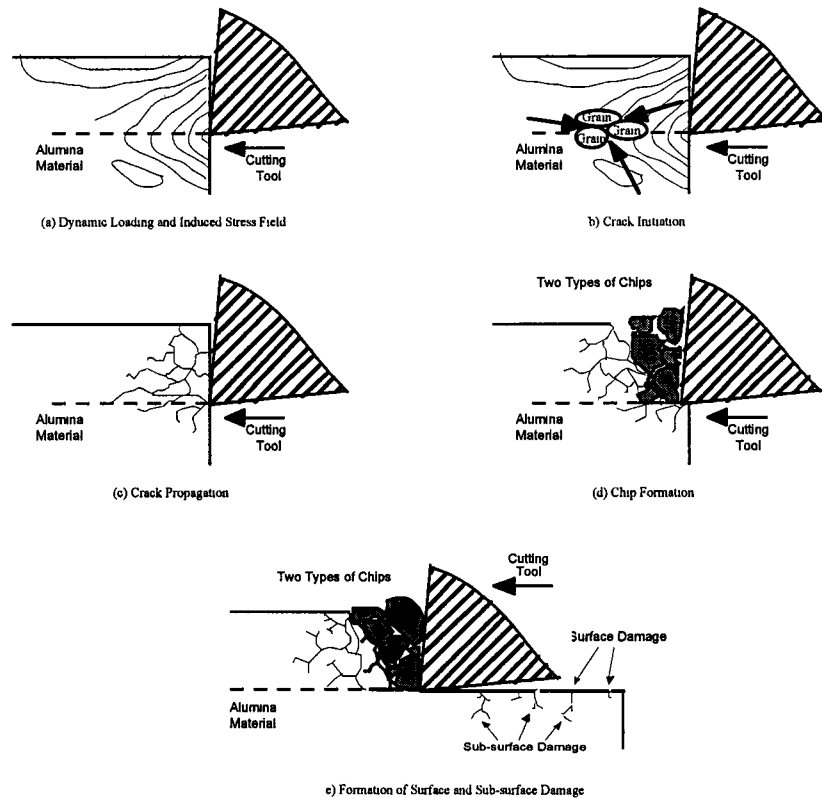


Figure 1. Five Essential Stages of the Material Removal Mechanism in Ceramics

To overcome these difficulties associated with ceramic machining, research has been extensive with focus on two areas: 1) searching innovative machining technologies that maintain the materials' special features while being as cost-effective as possible, and 2) developing evaluation methodologies to assess the machining performance, especially to characterize the non-linear dynamics of the material removal process. In the first area, new technologies to process ceramics have been developed. For example, ductile grinding of optical glass without cracks was reported by Evan and Marshall (1980), Inasaki (1987), and Konig et al (1991), although the material removal rate had to be restricted at a very low level. High speed grinding, electro discharge machining, and laser assisted machining have been exploited for machining ceramics with success, e.g, Mazurkiewicz (1991), Nakagawa et al (1985), and Zhang et al (1994). However, the high investment costs associated with these machining techniques limit their applications. In the second area where research on ceramic machining has been extensive, methods to characterize surface and subsurface structures present in the ceramics after machining have been developed by Lawn (1994), Slotwinski et al (1993), Jahanmir et al (1992), and Groenou et al (1979). Ultrasonic measurements have been used to study the surface texture formed during machining by monitoring the amplitude of the generated surface waves. Indentation techniques have also been used to investigate the residual stresses in the machined ceramics. These trends in ceramic machining research show the importance of having non-destructive evaluation methods that are effective and sensitive in detecting the surface and subsurface damage formed during machining.

In this chapter, we present our research on the study of non-linear dynamics observed during the machining of ceramic materials. We will focus on both innovation in machining technology and development of non-destructive evaluation methods to assess machining performance. Three aspects of our work are presented in the following sections. They are, 1) Submerged Precision Machining, and 2) Scanning Electron Microscopy Analysis. Aspect 1 relates to an innovative approach to machining, while aspects 2 relates to evaluation methodologies for surface characterization. These methods and techniques have been developed to achieve cost-efficient machining as well as high-quality surface finish in ceramic material.

2. SUBMERGED PRECISION MACHINING

We first present a new method of machining based on the stress-corrosion behavior of ceramic materials. This method, as a passive manner to control the non-linear dynamics, utilizes a submerged machining environment to assist in the material removal process. Results from our research have indicated that reducing friction at contact surfaces and removing heat generated during machining, thereby changing the stress field distribution in the immediate cutting zone. The advantages of this process can be further enhanced through proper choice of industrial machining coolants and chemical additives may provide a better control over strength and fracture toughness of ceramic material. It is assumed that the submersion environment would have effects on a marked improvement of surface quality and reduction of sub-surface damage can be achieved using the above technique .

2.1 Basic Methodology

The method presented here employs the concept of submersion as an adapted, conventional technique to machine ceramics. A submerged machining apparatus is designed and constructed, as shown in Figure 2, so that the ceramic material to be machined is placed in a bath filled with cutting fluid. In particular, the device consists of three parts, namely a container for cutting fluid, a vice to hold the workpiece, and a base on which force sensors are mounted for the purpose of measuring the cutting force during machining. During machining tests, the apparatus is fixed on the table of a CNC

machining center. The workpiece is tightened in the vice before the filling of cutting fluid. By controlling the type of cutting fluid and machining parameters, namely the depth of cut, feed, and cutting speed, and the temperature in the cutting zone, the tribological effects on

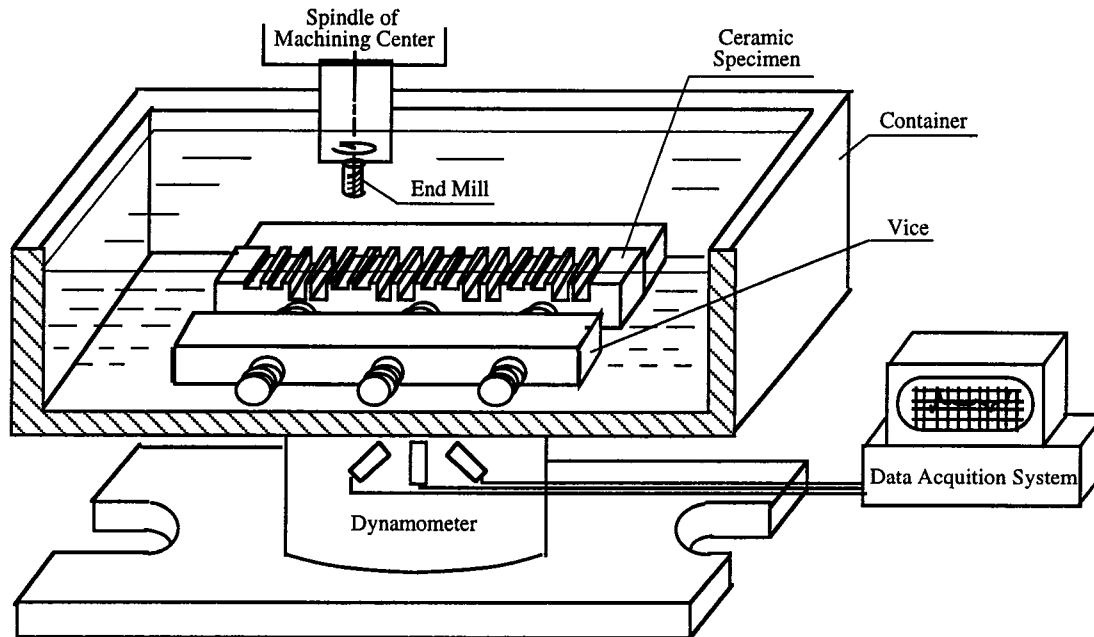


Figure 2 Submerged Machining Apparatus

the tool-workpiece and tool-chip interfaces are brought into play in the material removal process. It has been observed that the submerged machining environment promotes stress-corrosion cracking as induced by chemical reactions through high penetration of the cutting fluid. Experimental results strongly support the potential of using submerged machining to improve quality and efficiency of the machining operation.

2.2 A Case Study of Submerged Machining

To demonstrate the effectiveness of submerged machining, a case study is presented. The ceramic material used in the study is a machinable glass ceramic (MGC) from Corning. Its chemical formula is $K_2O-MgF_2-MgO-SiO_2$. It is a two-phase tetrasilicic mica glass-ceramic material and has a micro structure consisting of mica flakes of approximately 70 volume percent dispersed in a non-porous glass matrix. The hardness of this material is about 3.4 GPa. The cleavage fracture along the planes of mica flakes makes the material machinable. This MGC has been widely used as a new material in dental restorations. Figure 3 illustrates the specimen used in the machining tests. It is a 100 mm long bar with a rectangular cross-section, each side equal to 12.7 mm. The material of the end mill, which has a diameter of 3.175 mm, was high speed steel with hardness of about 18 GPa, which is 5 times as hard as the MGC material under the investigation.

The four parameters considered in this study are the type of cutting fluid used and the three machining parameters (depth of cut, feed rate and cutting speed), whose settings are implemented through a numerically controlled (NC) program. A design of experimentation method, as shown in Figure 3 from Box et al (1978), is used to set each of the four variables at two levels, namely, high and low. Table 1 lists the values of the high and low levels of the three machining parameters. For the cutting fluid, a commercially

available emulsifiable oil, called LS-A-14H, is used from Tower Oil and Technology Co. (1994). The emulsifiable concentrate is mixed with water in a ratio of 9:1. The pH ranges from 9.7 to 9.9. An NC program was prepared to carry out the machining tests, first at the dry environment, and then at the submersion environment.

Table 1. Value Settings for Design of Experimentation

Parameters	Cutting Speed	Feed Rate	Depth of Cut	Environment
High (+1)	6 m/min	10 mm/min	0.16 mm	Submerged
Low (-1)	4 m/min	5 mm/min	0.08 mm	Dry

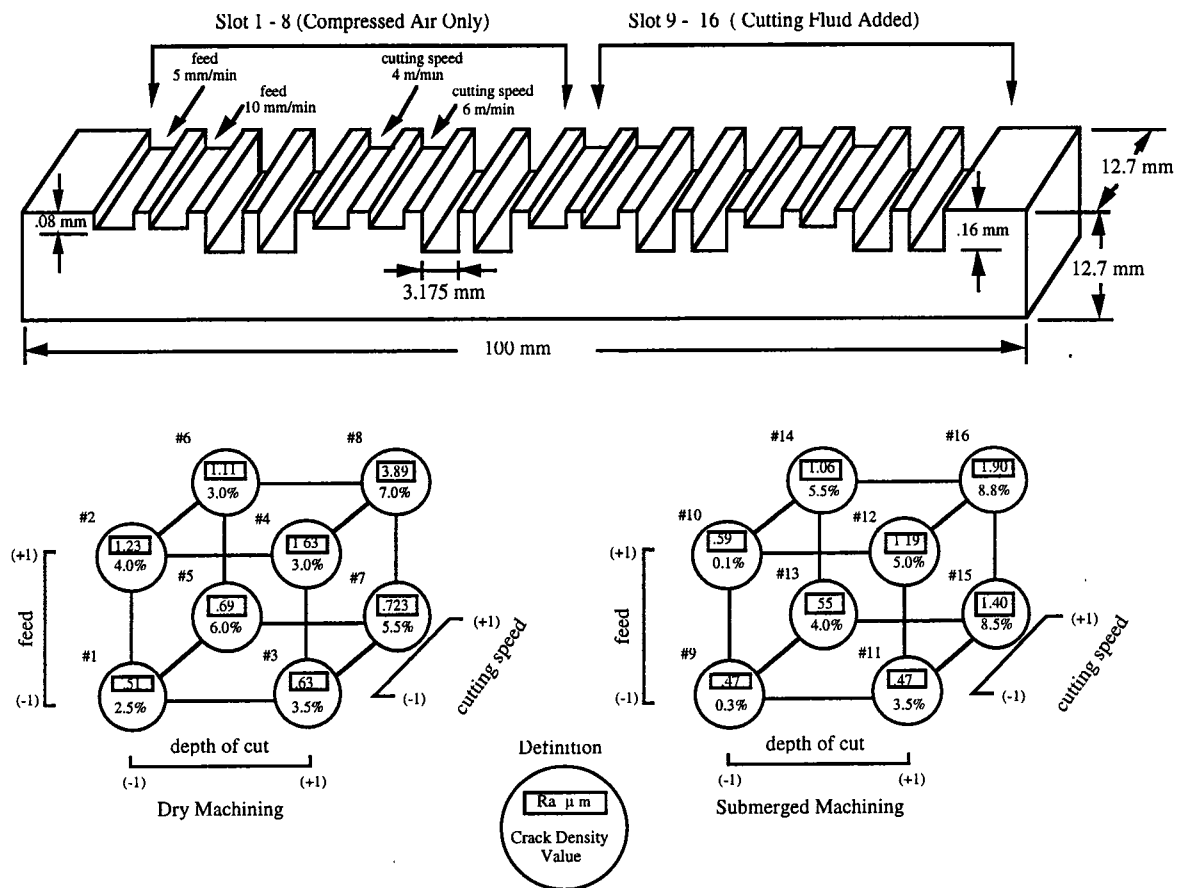


Figure 3. Ceramic Specimen And Settings Of The Machining Conditions

Assessment of experimental data obtained from the submerged machining investigation is based on the requirements set for the preparation of dental restorations using ceramic material. One of these requirements is reliability or durability of a restoration during its service. In fact, any fabrication method will cause damage to the ceramic during the restoration preparation. It is believed that the smoother the surface produced, the less likelihood that the ceramic has been damaged sufficiently to compromise its clinical performance. In addition, quantitative information on the degree of the damage is essential to the assessment of machining performance. Observations indicate that failure of most of the ceramic components occurring during service initiates at the surface cracks, which grow and penetrate, leading to unstable failure.

The assessment performed in this study consists of two aspects. The first aspect is to measure finish quality of machined surfaces using the traditional profilometer method. A surface profilometer, Perthometer-S5P (resolution 40×10^{-9} m), is used to take traces from each of the 16 machined surfaces, and values of roughness average, R_a , are obtained. They are listed in Figure 3. The second aspect is to quantify cracks formed on the machined surface through visualization of the surface texture formed during machining. In order to do so, an environmental scanning electron microscope is used to obtain high-magnification images of localized areas of surface texture, which are representative of the machined surface, as detailed by Goldstein et al (1992). Figure 4 presents a set of electron micrographs taken from the 16 machined surfaces. From these images, reconstruction of the surface texture formed during machining is realized using an image processing method, which is discussed in detail in the next section on scanning electron microscopy analysis. The two reconstructed 3-dimensional surface topographies shown in Figure 5 are taken from the two pictures marked as test 2 and test 10 in Figure 4. To quantify the damage induced under different machining conditions, a performance index is introduced to characterize the machined damage in terms of surface cracking (results are also shown in Figure 3). The performance index is called the density of surface cracking, and is defined as the percentage of the area occupied by cracks formed on a machined surface. As illustrated in figure 6, two contour plots are taken from the two reconstructed surface topographies for evaluating the density of surface cracking. As illustrated in Figure 6, surface cracks have a cone-shaped geometry. The crack density depends on the level of depth with which a contour plot is being taken. Figure 5 illustrates that the two contours shown in Figure 6 are taken at a level of depth marked as $(CP - 1.7\sigma)$ where parameter σ represents the standard deviation of the height variation about the center plane CP. To further clarify the two parameters, CP and σ , formulas for determining them during the evaluation are listed as follows:

$$CP = \sum_{i=1}^n \sum_{j=1}^n \frac{y_{ij}}{n \times n} \quad (1)$$

$$\sigma = \sqrt{\sum_{i=1}^n \sum_{j=1}^n \frac{(y_{ij} - CP)^2}{n \times n}} \quad (2)$$

where y_{ij} represents the height of an individual point with respect to a reference plane, and n represents the number of points taken on each side of the squared area for the evaluation. Results obtained from evaluating the density of surface cracking for the 16 machined surfaces at several levels of depth are plotted in Figures 6a and 6b, for the dry and submerged machining environment, respectively. The data listed in Figure 3 represent the crack density values evaluated at the level of depth set at 1.7σ below the central plane, CP.

2.3. Analysis of Results

Data obtained from a factorial design, such as the one used in this study, offers an unique opportunity to derive empirical models capable of describing effects of the four parameters on the machining performances of dry and submerged environments.

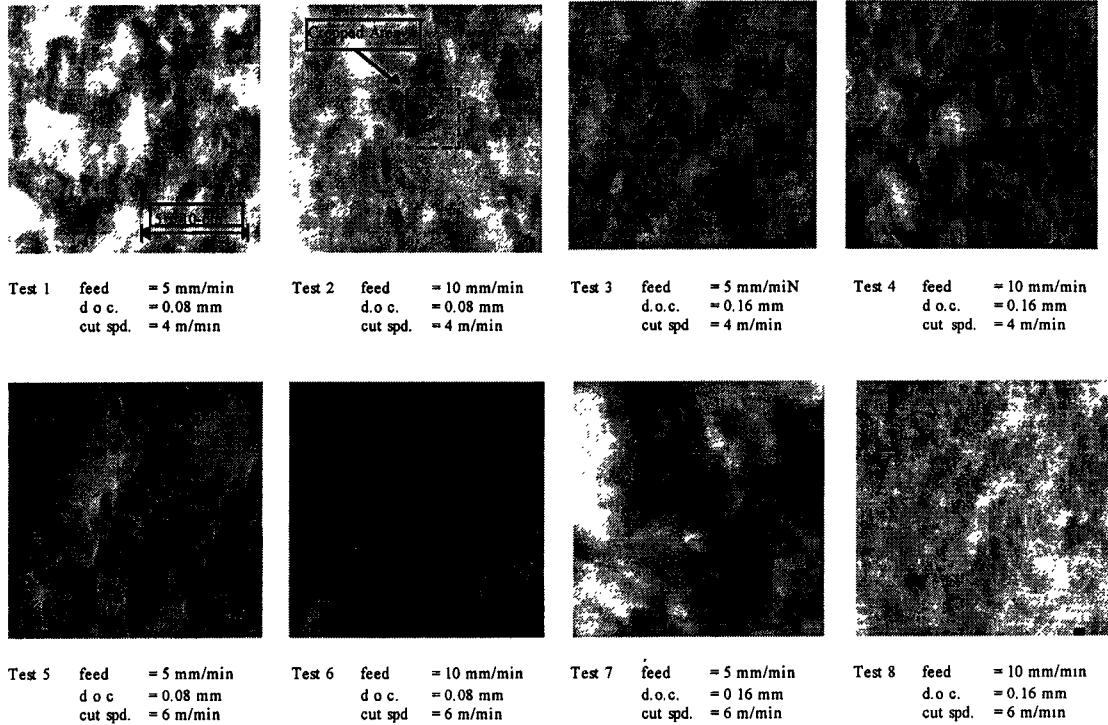


Figure 4A

Sem Micrographs of the 8 Machined Surfaces (Dry Machining Environment)

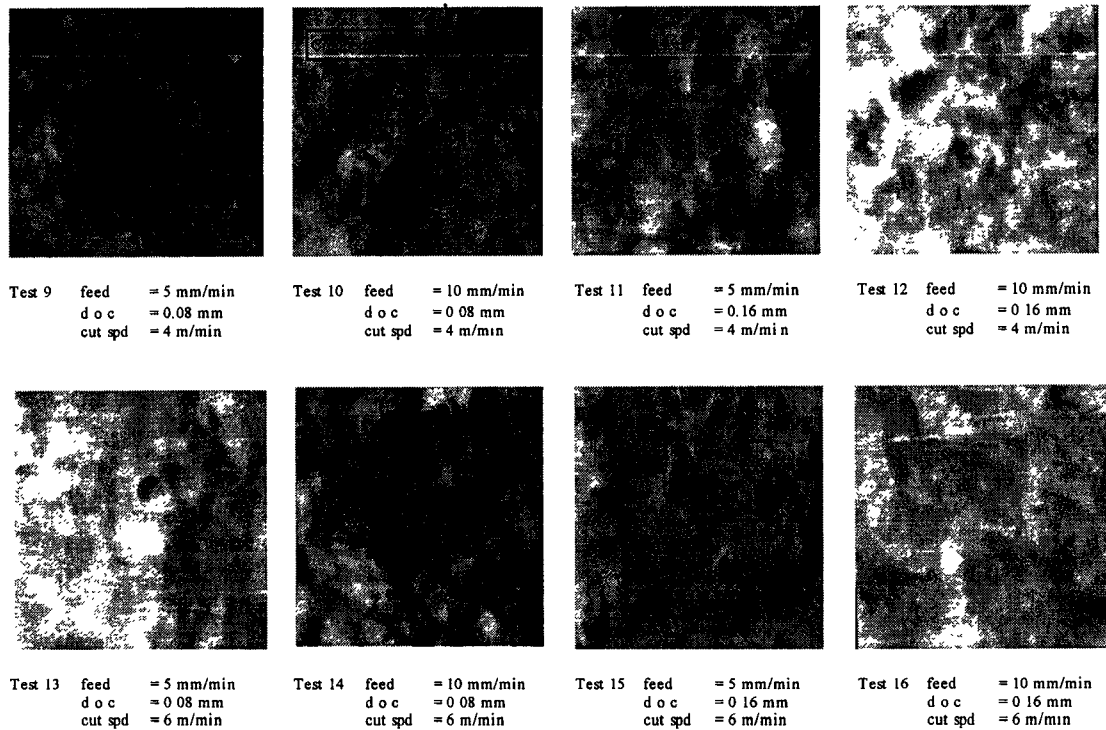


Figure 4B

Sem Micrographs of the 8 Machined Surfaces (Submerged Machining Environment)

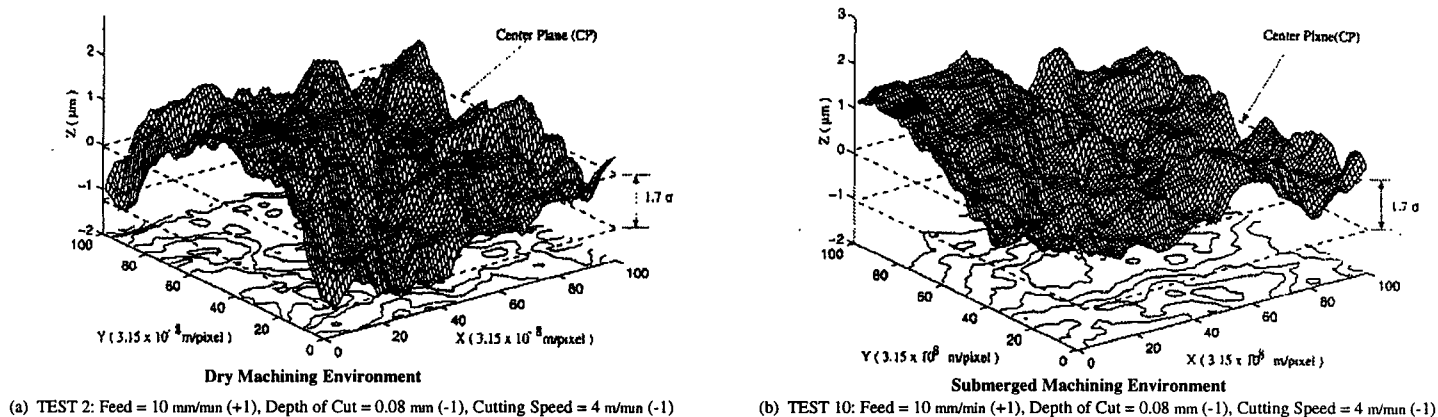


Figure 5. Two Reconstructed Surface Topographies

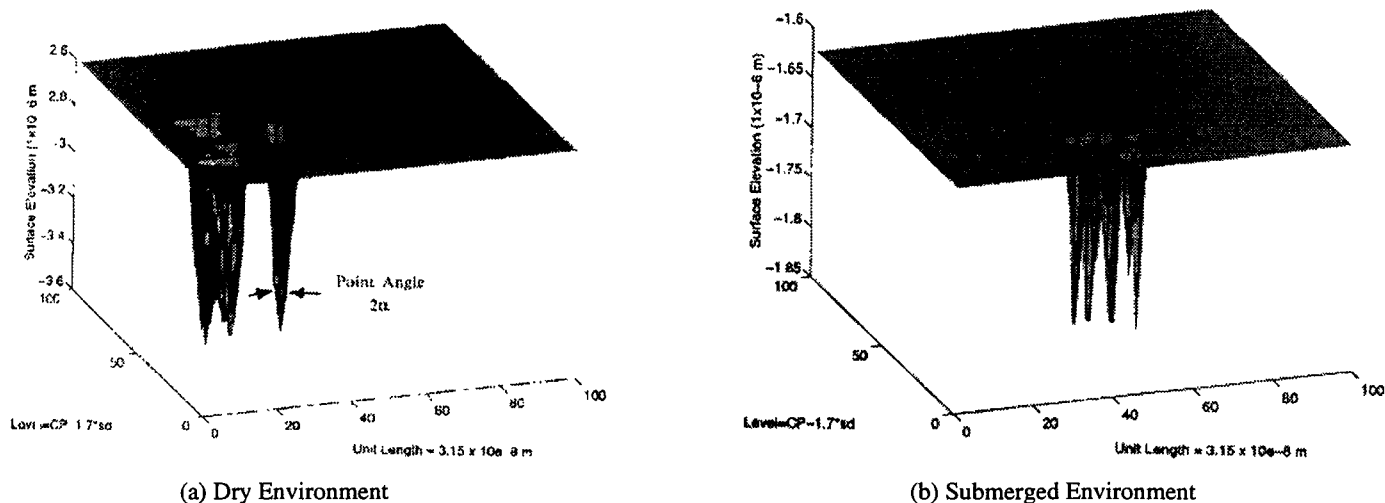


Figure 6. Contour Plots for the Evaluation of Surface Cracking Obtained from Stereophotogrammetric Examination of Two Machined Surfaces

2.3.1 Main Effects of the Four Machining Parameters

Using the algorithm, proposed by Box et al (1978), averaging the 8 pairs of roughness measurements for each of the four machining parameters provides an estimate of the main effect of each of the four parameters on finish quality in terms of surface roughness. For example, the main effect of the machining environment can be identified by

$$\bar{R}_a = \frac{1}{2} \left[\frac{0.47 + 0.59 + 0.47 + 1.19 + 0.55 + 1.05 + 1.40 + 1.90}{8} - \frac{0.51 + 1.23 + 0.63 + 1.63 + 0.69 + 1.11 + 0.72 + 3.89}{8} \right] = -0.18 (\mu\text{m}) \quad (3)$$

In a similar manner, the three main effects of feed, depth of cut, and cutting speed can also be obtained. An empirical model to describe the main effects of these four parameters on finish quality is represented by

$$\begin{aligned} \bar{R}_a = & 1.13 + 0.45(\text{feed}) + 0.35(\text{depth of cut}) + 0.28(\text{cutting speed}) - 0.18(\text{machining Environment}) \\ & + (\text{combinational effects}) \quad (\text{unit : } \mu\text{m}) \end{aligned} \quad (4)$$

Note that the first term in Eq. (4), 1.13 μm , is the grand average, or the average of the 16 R_a measurements, serving as an indication of the order of surface finish under this investigation, which is about 1 μm . When using Eq. (4), numerical values of the four parameters used for prediction have to be either (+1) representing a high level setting or (-1) representing a low level setting. For the qualitative parameter representing the machining environment, (-1) means dry machining and (+) submerged machining. For example, replacing all the parameters by (-1) in Eq. (3) corresponding to a combination of using smaller depth of cut, smaller feed, lower cutting speed, and a dry machining environment.

Examining Eq. (4), the four values associated with the four machining parameters characterize their main effects on the surface finish. The three positive values indicate that large R_a values, or a degrading trend of surface finish, can be anticipated when feed, depth of cut and cutting speed are set at the high level. On the other hand, the negative value, -0.18 μm , is associated with the submersion machining environment parameter, strongly indicating the benefit of improving finish quality. The ratio of 0.18 to 1.13 quantifies a 16% of reduction from the mean Level of roughness average when the submersion is being used to machine the Corning-MGC material.

2.3.2 Interaction Effects between and/or among the Four Parameters

The benefit of using submerged machining can be further exploited when the experimental results are analyzed in two separated sets, one with the dry machining environment and the other with the submerged machining environment. For each data set, the grand average, main effects, and combinational effects among feed, depth of cut, and cutting speed are calculated to obtain the two empirical models. It is important to note that these combinational effects characterize the non-linear behavior of the material removal in the surface texture formation.

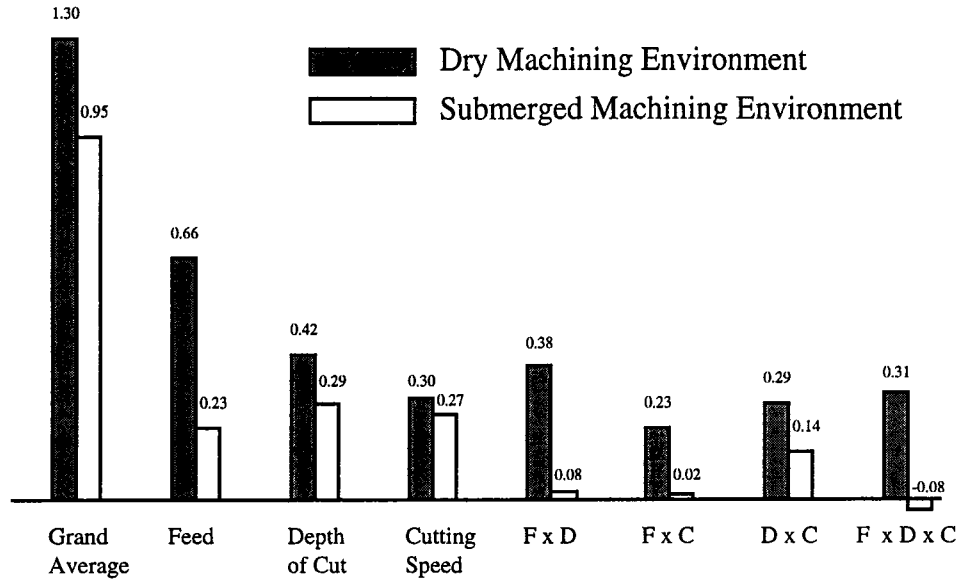


Figure 7. Comparison of Estimated Effects Between the Dry and Submerge Machining Environments

For the dry machining environment:

$$\begin{aligned}
 \bar{R}_a = & 1.30 + 0.66(\text{feed}) + 0.42(\text{depth of cut}) + 0.30(\text{cutting speed}) \\
 & + 0.38(\text{feed} \times \text{depth of cut}) + 0.23(\text{feed} \times \text{cutting speed}) + 0.29(\text{depth of cut} \times \text{cutting speed}) \\
 & + 0.31(\text{feed} \times \text{depth of cut} \times \text{cutting speed}) \quad (\mu\text{m})
 \end{aligned} \quad (5)$$

For the submerged machining environment:

$$\begin{aligned}
 \bar{R}_a = & 0.95 + 0.23(\text{feed}) + 0.29(\text{depth of cut}) + 0.27(\text{cutting speed}) \\
 & + 0.08(\text{feed} \times \text{depth of cut}) + 0.02(\text{feed} \times \text{cutting speed}) + 0.14(\text{depth of cut} \times \text{cutting speed}) \\
 & - 0.08(\text{feed} \times \text{depth of cut} \times \text{cutting speed}) \quad (\mu\text{m})
 \end{aligned} \quad (6)$$

Examining the eight values representing the grand average, main and combinational effects in Eqs (5) and (6), the following important observations are made:

- (1) The numerical values in Eq. (6), or associated with the submersion, are significantly smaller than those in Eq. (5), indicating that a better surface finish condition can always be expected when the submersion is applied. This can be further confirmed when examining the data presented in the two cubics shown in Fig. 2. For the identical machining parameter settings, the roughness value for test 1 is 0.51 μm for the dry machining, larger than 0.49 μm for test 9 under the submerged machining, 1.23 μm for test 2 which is larger than 0.47 μm for test 10, and so on.

- (2) The influence contributed by the submerged machining to improve finish quality is unevenly distributed to the eight effects estimated from the experimental data. Figure 7 presents a comprehensive picture to illustrate such distribution. The most significant reductions are associated with the combinational effect between feed and depth of cut, the combinational effect between feed and cutting speed, and the combinational effect among feed, depth of cut, and cutting speed. Those reductions almost eliminate these effects on degrading the finish quality statistically. Significant reductions includes the grand average, the main effect of feed, the main effect of depth of cut, and the combinational effect of depth of cut and cutting speed. The least reduction, which is 10%, is associated with the main effect of cutting speed. Statistically the following formula depicts the relationship between the roughness average of a machined surface and the three machining parameters under the submerged machining:

$$R_a = 0.95 + 0.23(\text{feed}) + 0.29(\text{depth of cut}) + 0.27(\text{cutting speed}) + 0.14(\text{depth of cut} \times \text{cutting speed}) \quad (\mu\text{m}) \quad (7)$$

The explicit format of Eq. (7) is an indication of the involvement of the stress-corrosion-cracking behavior of ceramic material in the process of material removal during machining. Because of the brittle fracture, the mechanics of material removal during the machining of ceramics is dominant by non-linear dynamics.

- (3) Because of the interplay between depth of cut and cutting speed, a combination of low cutting speed and low depth of cut may result in finish quality which is very compatible with the finish quality obtainable under the combination of low cutting speed and high depth of cut. This observation may bring practical interest that, when the submersion is applied, a combination of low cutting speed and large depth of cut could offer a higher material removal rate under the assumption of keeping satisfied finish quality of the machine surface.

Thus, experimental results have confirmed the validity of using submerged machining as an innovative machining technique to control the surface finish of ceramics. In the next section, an effort is made to explain the technique of using an environmental scanning electron microscope (ESEM) to obtain high-quality, high-magnification images of machined ceramic surfaces for the purpose of surface finish assessment. The use of an ESEM, together with computer graphics, represents an improvement over the traditional stylus for measuring surface roughness.

3. ASSESSMENT OF SURFACE INTEGRITY USING SEM

One of the methods we have developed in assessing surface integrity is through the use of Scanning Electron Microscopy (SEM) Analysis. A computer-based system has been developed to evaluate the condition of the machined surface. As illustrated in Fig. 3.1, a ceramic specimen with a machined surface is first examined under an environmental scanning electron microscopy (ESEM). SEM micrographs of representative locations on the machined surface are displayed on the screen, inspected, and digitized. Corresponding image files are then stored on computer. Numerical data in the image files are the recorded intensity of electron reflection on the surface texture. To obtain the height information on the surface images, a grayscale-height calibration process is performed using the stereo-pair method as reported by Slotwinski (1993). When the SEM image data files are transformed to the height variation data files, three-dimensional topographies in micro-scale can be reconstructed using computer graphics.

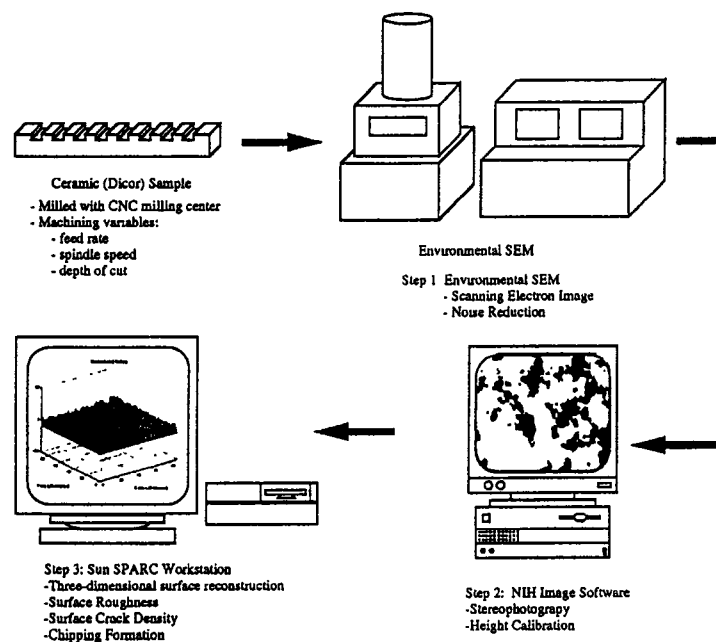


Figure 8. Computer-Based System for Surface Characterization

SEM photography is a well known method to obtain high resolution images with a great depth of field of machined surfaces. Through the use of advanced computer image processing techniques, qualitative information regarding surface morphology can be now extracted from the SEM micrographs and be evaluated quantitatively to describe surface characteristics such as surface roughness (R_a), residual stress distribution and the density of surface cracking in terms of the percentage of surface area. The use of this non-destructive evaluation (NDE) technique can provide important feedbacks to the user for optimization of machining parameters.

3.1 Applications: Study of Surface Texture and Surface Roughness

To demonstrate the procedure using the developed SEM-Stereophotography method to characterize the surface texture, a machinable dental ceramic, Dicor-MGC polycrystal, is used in preparing the specimens with machined surfaces. It is the same material used in the previous case study. According to Groenou et al (1979), the material matches the physical

properties of human enamel in terms of translucency, thermal conductive, density, and hardness.

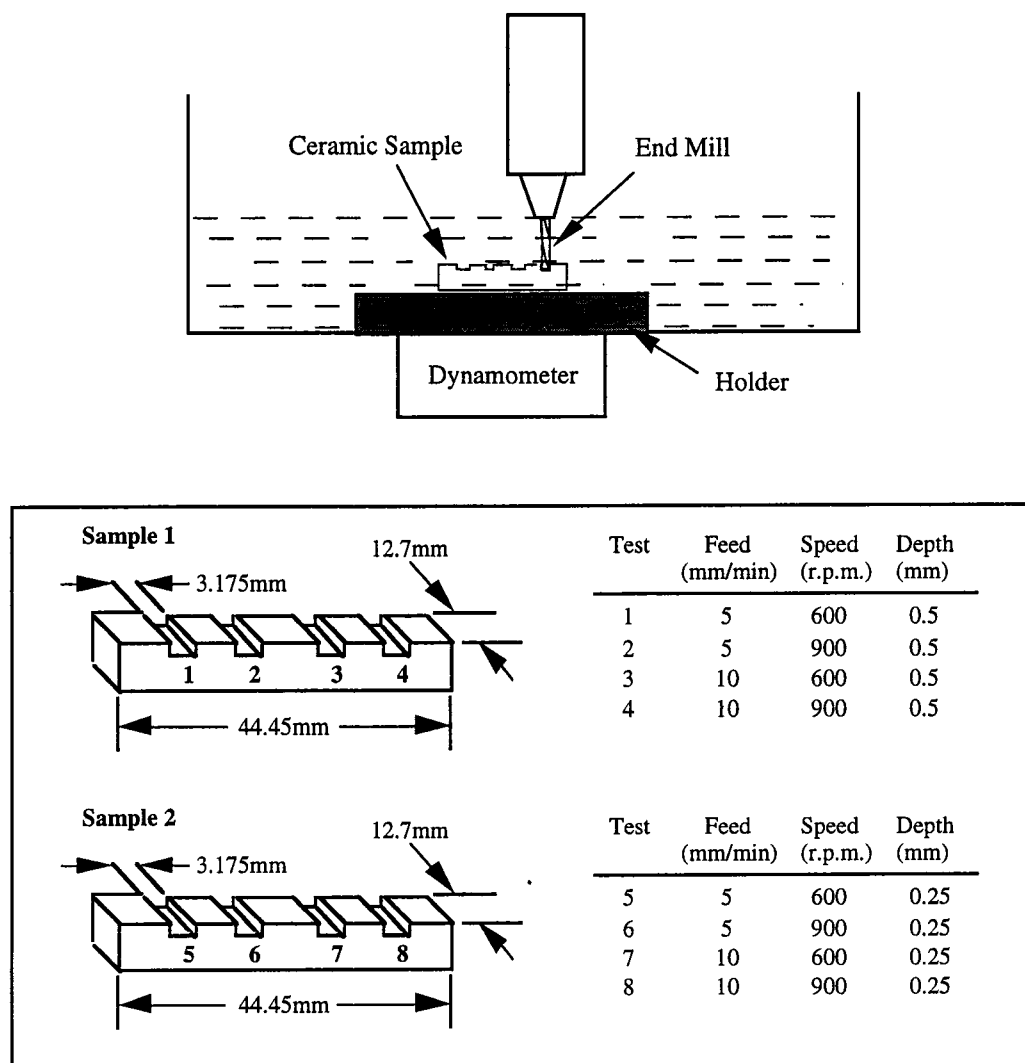


Figure 9. Preparation of Specimens with Machined Surfaces

The preparation of specimens with machined surfaces is illustrated in Figure 9. An end mill with a diameter of 3.175 mm cuts two blocks of 12.7 x 12.7 x 44.5 mm³. On each of the two blocks, four slots are machined under four different conditions. As reported in Zhang et al (1995), the four different machining conditions for slots 1-4 are combinations of two feedrate settings (5 and 10 mm/min) and two spindle speed settings (600 and 900 rpm) with the depth of cut set at 0.5 mm. When preparing slot 5-8, the feedrate and spindle speed settings remain unchanged, but the depth of cut is set at 0.25 mm.

The specimens after machining are examined using ElectroScan E-3 Environmental Scanning Electron Microscope. Figure 9 presents eight representative SEM micrographs obtained through image processing. Each of these eight graphs contains 125 pixels by 125 pixels, representing a scanning area of 0.10 x 0.10 mm². The image data is then transformed into height variation data using a defined calibration relation between the intensity of electron reflection and the micro-scale surface graduation. Figure 11 presents two surface topographs reconstructed in the three-dimensional space and their respective contour maps after the data transformation.

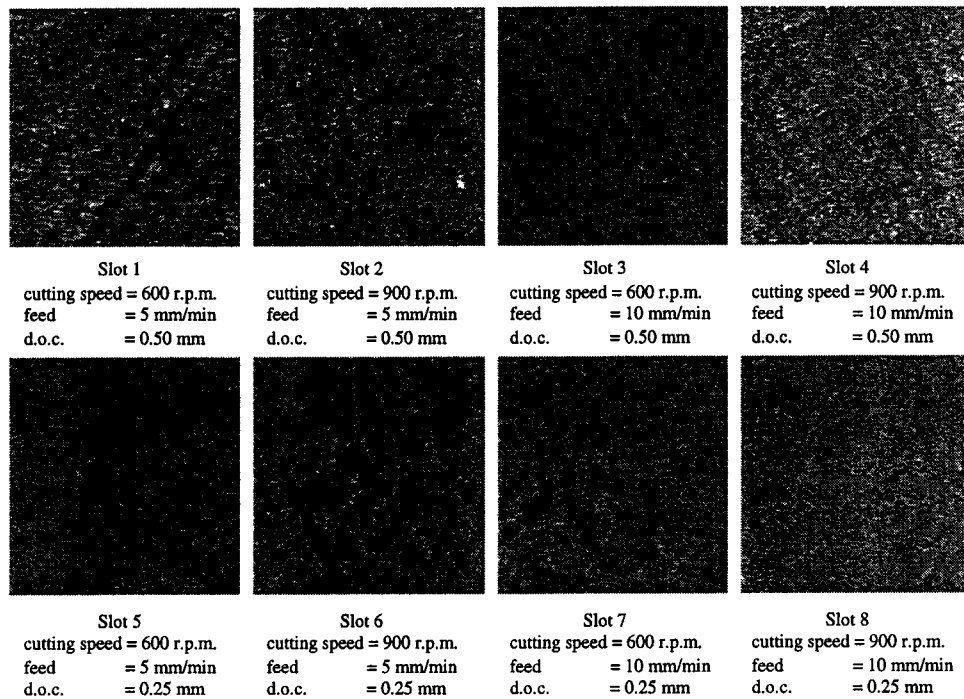


Figure 10. SEM Micrographs of Milled Surfaces of Dicor Specimen (Area = 0.10 x 0.10 mm)

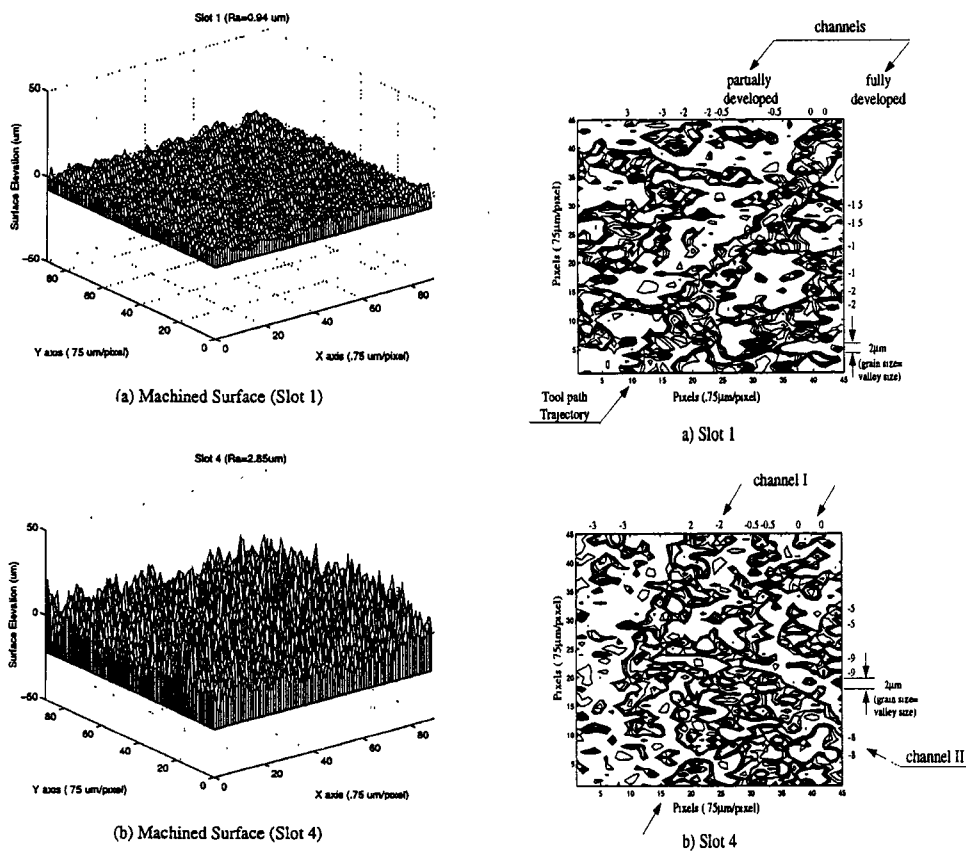


Figure 11. Reconstructed Surface Topography and Contour Map

Examining Figure 11, the two reconstructed surface topographies represent visualization of machined surfaces. The surface texture shown in Figure 11a characterizes the machined surface on slot 1 and the surface texture shown in Figure 11b characterizes the machined surface on slot 4. A comparison of the two surface topographies gives a vivid picture showing how the two surface textures are different from each other. The surface condition on slot 4 is much rougher than that on slot 1 because it has higher peaks and deeper valleys.

Note the scale used in the visualization. In the marked X and Y axes, each pixel represents $0.75\text{ }\mu\text{m}$, and the indicated 80 pixels represent a length of $60\text{ }\mu\text{m}$. The unit of the vertical axis is micrometer. To quantify the surface texture, contour plots are taken at six levels on the vertical direction. They are $2.0\text{ }\mu\text{m}$, $1.5\text{ }\mu\text{m}$, $1.0\text{ }\mu\text{m}$, $0.5\text{ }\mu\text{m}$, $0\text{ }\mu\text{m}$, and $-1.0\text{ }\mu\text{m}$ with the level of $0\text{ }\mu\text{m}$ representing the reference plane used for the R_a evaluation, as illustrated in Figure 5. Figure 7 presents two contour maps. Figure 11a is the contour map representing slot 1. The contour map is an assembly of the six contour plots at the six indicated height levels taken from the surface topography shown in Figure 5a. Similarly, Fig. 11b is the contour map representing slot 4. On these contour maps, the grain size of $2\text{ }\mu\text{m}$ is also indicated as reference for examination.

Examining the two contour maps, several important observations can be made. The first observation is the presence of isolated islands formed by clustered contour lines on the contour maps. These isolated islands represent valleys formed on the surface texture. The size of these isolated islands characterizes the geometric shape of their corresponding valleys. It is interesting to note that the smallest size of a valley on both maps is about $2\text{ }\mu\text{m} \times 2\text{ }\mu\text{m}$, which is about the grain size of the Dicor material used in this study. This observation suggests the existence of pullouts of a single grain during machining. It is well understood that grain boundaries in Dicor material represent a weak link when subjected to a tensile stress field due to the presence of second phase. The development of micro-cracking on the grain boundary enforces an entire grain to dislodge from the surface being machined. Valleys or cavities on the surface texture are formed as a result of these pullouts. The second observation is that most of the islands shown in Fig. 7a are larger than the $2\text{ }\mu\text{m} \times 2\text{ }\mu\text{m}$ islands. The average size of these islands is somewhere between $10\text{ }\mu\text{m} \times 5\text{ }\mu\text{m}$ and $10\text{ }\mu\text{m} \times 10\text{ }\mu\text{m}$. The $10\text{ }\mu\text{m}$ is about one dimension related to the size of mica-flakes. We note that the Dicor material used in this study contains mica-flakes as a second phase. Addition of these mica flakes is designed to improve the machinability, a mechanism similar to free-machining steel where inclusions are added. This observation indicates that the easy-cleavage properties of mica flakes create the weak boundaries which promote the micro-cracking propagation. By closely examining those large islands shown in Fig. 7a, small islands can also be identified within them, indicating that the co-existence of the pullouts of single grains and the progressive development of micro-cracking between the neighboring grain boundaries.

The third observation is the presence of cavity channels. Some of them are fully developed and some are partially developed, as illustrated in Fig. 7a. The formation of these cavity channels is closely related to the internal stress field developed on/near the machined surface during machining. The most noticeable characteristic of the cavity channels is that their orientation follows the tool path trajectory. This suggests that the tensile stress induced by machining is along the cutting speed direction. Under high internal stresses, micro-cracks merge along the tensile stress direction while releasing the strain energy accumulated under the buildup of hydro-static stresses. As long as a sufficient amount of the released energy is available, cavity channels will be formed in a completed form during the material removal process. Otherwise, partially completed channels will be formed.

Traditionally, surface texture formed during machining is examined using profilometers. By taking profiles, surface characterization indices, such as roughness average and peak-to-valley, are evaluated from the measured heights along the profiles. Figure 12 presents four profiles which are constructed using the data stored in the height variation data file. The two profiles with $R_a = 0.83$ and $0.88\text{ }\mu\text{m}$ in Figure 12a represent

the surface roughness condition of slot 1 and the two profiles with $R_a = 3.25$ and $2.97 \mu\text{m}$ in Fig. 12b are representations of slot 4. Note the "cut-off length", which is $0.68 \mu\text{m}$, used in the roughness average evaluation. It is $0.68 \mu\text{m}$, representing a total of 90 data (pixels) used in the evaluation. Table 2 lists the roughness average values evaluated from the eight machined surfaces. The smallest R_a value is $0.21 \mu\text{m}$ associated with slot 8. The corresponding machining conditions are feedrate: 5 mm/min , spindle speed: 600 rpm , and axial depth of cut: 0.25 mm . Numerical values of the standard deviation are also presented in Table 2, indicating the variation range of the R_a evaluation. In general, the standard deviation remains at $0.03 \mu\text{m}$. As the R_a mean value increases, the standard deviation value increases accordingly.

Table 2. Results of R_a

Slot Number	1	2	3	4	5	6	7	8
R_a (μm)	0.94	0.80	2.85	1.73	1.43	0.53	1.21	0.21
Standard Deviation (μm)	0.03	0.03	0.13	0.15	0.11	0.04	0.09	0.03

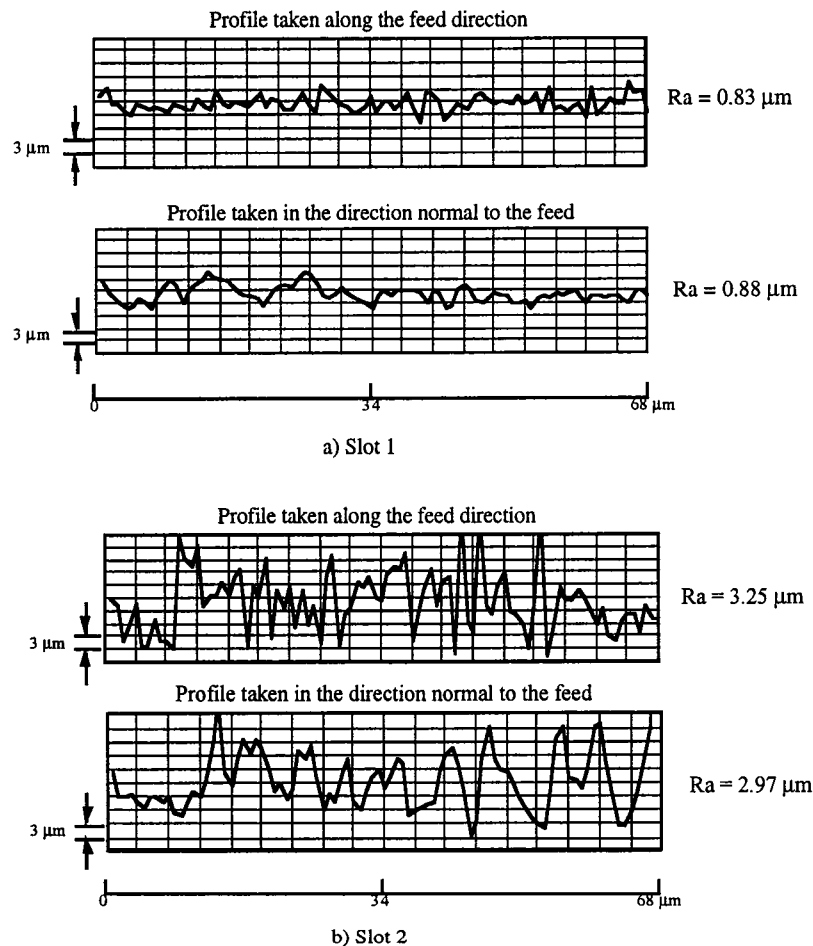


Figure 12. Profiles Reconstructed from Height Variation Data Files

4. CONCLUSIONS

In this chapter, the non-linear dynamics observed during the machining of advanced ceramic materials is described. The brittle fracture dominates the chip formation during the material removal process. The machining mechanics is shifted from shear deformation to micro-scale crack initiation, crack propagation, and macro-scale fracture. As described in this chapter, investigation on the non-linear dynamics has been intensive and significant progress has been made.

4.1 Submerged Machining

An experimental investigation has been conducted to explore the advantage of using submerged machining to improve the surface integrity of ceramic parts. Surface finish and density of surface cracking are used as the two performance indices for the performance evaluation. Significant findings from this study are:

- (1) Submerged machining demonstrates a better performance in terms of improving surface finish and reducing the density of surface cracking. The chemo-mechanical effects contributed by stress-corrosion cracking assist in the chip formation process and increase the efficiency of material removal during machining.
- (2) In a submerged machining environment, special care has to be taken in setting the machining parameters in order to maximize the potential to achieve a smooth surface with a low density of surface cracking. It is recommended that low cutting speed and low depth of cut be used. The interaction between the depth of cut and cutting speed deserves special attention, due to the non-linear behavior displayed in the interaction between the two parameters.
- (3) Investigation with focus on fracture analysis should continue to further explore the potential of chemical-assisted machining as an effective technology to process ceramic materials.

4.2 Assessment of Surface Integrity

In order to understand the non-linear dynamics displayed during the machining of ceramic materials, quantitative measurements are critical. In this chapter, a non-destructive evaluation approach is demonstrated. The approach integrates SEM analysis, signal processing and computer graphics to visualize the surface texture formed during machining in micro-scale. Two performance indices are introduced to quantify the effects of the non-linear dynamics on surface integrity.

- (1) The SEM-stereophotography method developed in this study has been a great success in detecting the micro-scale surface texture. The high resolution of micrographs attainable ensures coverage of rich information on surface height variation in micro-scale at an accuracy conventional profilometry methods can never achieve.
- (2) Identification of surface cavities provide strong evidence of the material removal mechanisms present during machining. Pullouts of individual grains due to dislodgment from the neighboring contact area and cavities formed through the progressive development of grain boundary microcracking are two among the possible material removal mechanisms.

- (3) Factors including material microstructure and three machining parameters, namely, feedrate, depth of cut, and spindle speed, are studied with respect to their influence on the surface texture formation. To quantify these effects, a new parameter, denoted as cavity density, is introduced. It is found that feedrate and depth of cut are the two most influential factors in controlling the cavity density, and the spindle speed has the least influence because of the conflicting effects on the crack toughness of ceramic material contributed by loading rate and temperature.
- (4) It is expected that the interplay between microstructure and machining parameters will have its unique effect on the surface texture formation because of its unique effect on the microcracking activities during machining. Further research in this direction is urgently needed.

5. REFERENCES

Box, G., et al. (1978). *Statistics for Experimenters, An Introduction to Design, Data Analysis, and Model Building*. John Wiley & Sons, Inc.

Evan, A.G., and Marshall, D. B. (1980). "Wear Mechanisms in Ceramics," In *Fundamentals of Friction and Wear*, Ed. D. A. Rigney, Metals Park, Ohio, American Society of Metals, pp. 439-452.

Goldstein, J., Newbury, D., and Echlin, P. (1992). *Scanning Electron Microscopy and X-Ray Microanalysis*, Plenum Press: New York, Second Edition.

Groenou, B., Maan, N., and Veldkamp, J. (1979). "The Science of Ceramic Machining and Surface Finish," edited by B. Hockey and R. Rice, National Bureau of Standards, SP-562, P. 43.

Inasaki, I. (1987). "Grinding of Hard and Brittle Materials," *Annals of the CIRP*, Vol. 36 (2).

Jahanmir, S., Ives, L., and Ruff, A. (1992). "Ceramic Machining: Assessment of Current Practice and Research Needs in the United States", National Institute of Standards and Technology, Report SP-834.

Konig, W., et al (1991). "Machining of New Materials," *Processing of Advanced Materials*, Vol. 1, pp. 11-26.

Lawn, B. (1994), *Fracture of Brittle Solids*, Second Edition, Cambridge University Press.

Mazurkiewicz, M. (1991). "Understanding Abrasive Waterjet Performance," *Machining Technology*, Vol. 2, No.1, pp. 1-3.

Nakagawa, T., Suzuki, K., and Uematsu, T. (1985). "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, pp. 1-7.

Slotwinski, J., et al (1993). "Ultrasonic Measurement of Surface and Subsurface Structure in Ceramics," Proceedings of the International Conference on Machining of Advanced Materials, Maryland, pp. 117-124.

Tower Oil & Technology Co. (1994). "LS-A-14H Specification", Chicago, Illinois.

Zhang, G., Satish, K., and Ko, W. (1994). "The Mechanics of Material Removal Mechanisms in the Machining of Ceramics," ASME Winter Annual Meeting Proceedings, pp. 121-135.

6. SUGGESTED READINGS

Rekow, D., Zhang, G., and Thompson, V. (1993). "Machining Ceramic Materials for Dental Restorations," Proceedings of the International Conference on Machining of Advanced Materials, Maryland, pp. 425-435.

Stout, K. J., ed. (1994). *Three Dimensional Surface Topography: Measurement, Interpretation, and Applications*, Penton Press: London, England.

Zhang, G., Ko, W., and Ng, S. (1995). "Submerged Precision Machining of Ceramic Material," 1995 ASME Conference on Advanced Material Processing, Los Angeles.

Zhang, G., Ng S., Le, D. T. (1995). "Characterization of Surface Texture Formed During Machining of Ceramics", NAMRC Publication.

Zhang, G., Ng, S., Le, D.T. (1995). "Characterization Of The Surface Cracking Formed During The Machining Of Ceramic Material", ASME Winter Annual Meeting Proceedings, Vol. 1, pp. 415-429.