

TECHNICAL RESEARCH REPORT

Characterization of the Surface Cracking Formed during the Machining of Ceramic Material

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Abstract

This paper presents a method to characterize the surface cracking formed during the machining of ceramics material. Ceramic specimens are prepared under two different machining environments, dry and submersion. An environmental scanning electron microscope is used to obtain high-magnification images of machined surfaces. Reconstruction of the surface texture in a three-dimensional space is made by scanning the images and using graphics software to obtain detailed and informative spatial views of the machined surface. The visualized surface cracks provide quantitative information on their size and shape. Two performance indices are proposed to characterize the distribution of surface cracks induced by machining in terms of the density and crack depth with reference to the machined surface. As a case study, the developed nondestructive evaluation method is used to assess the effectiveness of using the submerged machining to process ceramic material. The obtained results present a clear picture illustrating the capability of controlling the crack formation during the submerged machining.

1. Introduction

High-performance ceramics have many superior properties such as high strength, excellent wear resistance and exceptional corrosion resistance. The capability of ceramics to be manufactured to near net shape by pressing and sintering processes also makes economic production of ceramics possible. These intrinsic properties have led ceramics to be prime candidates for many applications ranging from engineering components to dental restorations.

Manufacturing of ceramic parts requires dimensional and geometrical accuracy. Machining has played a key role in this respect to ensure the functional surfaces of ceramic parts, especially after sintering. Due to the hard and brittle nature, ceramic materials are difficult to machine. The high wear rate of cutting tools or grinding wheels during

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machining gives rise to high production cost. Fracture occurs during machining and leaves cracks on/beneath the machined surfaces, forming surface and subsurface damage and leading to a shortened product life cycle. Research on ceramic machining 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. In the first area, new technologies to process ceramics have been developed. For example, ductile grinding of optical glass without cracks was reported in [1-3] 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 [4-6]. However, the high investment costs associated with these machining techniques limit their applications. In the second area, methods to characterize surface and subsurface structure present in the ceramics after machining have been developed [7-10]. Ultrasonic measurements are used to study the surface texture formed during machining by monitoring the amplitude of the generated surface waves. Indentation techniques are used to investigate the residual stress in the machined ceramics. Researchers have recognized the importance of having nondestructive evaluation methods that are effective and sensitive in detecting the surface and subsurface damage formed during machining.

In this paper, a new method to machine ceramics under a submersion environment is present. The material removal process is complicated by co-existence of a high stress field near the cutting zone and a chemically interactive environment which surrounds the cutting tool and workpiece material. The chemical, mechanical, and metallurgical interactions introduce the stress-corrosion cracking which promotes the chip formation process during machining. To evaluate the effectiveness in controlling the surface cracking formed during machining, an experimental procedure is developed. Images of the machined surface are obtained under an environmental scanning electronic microscope. Surface texture as well as surface cracks are visualized in the three-dimensional space using computer graphics. The crack distribution on the machined surface is characterized by its density and depth beneath the machine surface. The stress-intensity factor is estimated based on the crack size and shape measured for each of the two machining environments for the purpose of comparison. Results from this investigation present a clear picture illustrating the reduction of the cracks formed during machining when the submersion machining is being applied.

2. Basic Methodology

In the machining of ceramics, the presence of chips, the formation of surface texture, and the tool wear observed on rake and flank faces support the existence of the three deformation zones observed during the machining of conventional materials such as metals. However, cracks formed on the machined surface, which are in micro-scale, give distinction to the fundamentals of material removal mechanisms during the machining of ceramics. To gain a basic understanding, experiments using sliding microindentation between a diamond indenter and ceramics have been performed. The experiments simulate the direct contact between the cutting tool and the part material during the machining process. Observations made from these experiments have indicated that a diversity of cracks, such as median cracks, lateral cracks, and cone cracks, are generated in the vicinity of the scratched groove, or along the "tool path", as illustrated in Fig. 1. Based on a recent study [11], the cracks formed on the machined surface are mainly related to the median cracks, which propagate in the direction of the applied cutting force. The lateral cracks, which propagate in the direction of the applied cutting force. The lateral cracks, that run parallel to the machined surface, play a dominant role in the chip formation process. The cone cracks emanating from the edge of the contact impression are surface ring cracks. They grow incrementally downward and disappear in the catastrophic failure mode at instants when chips are formed.

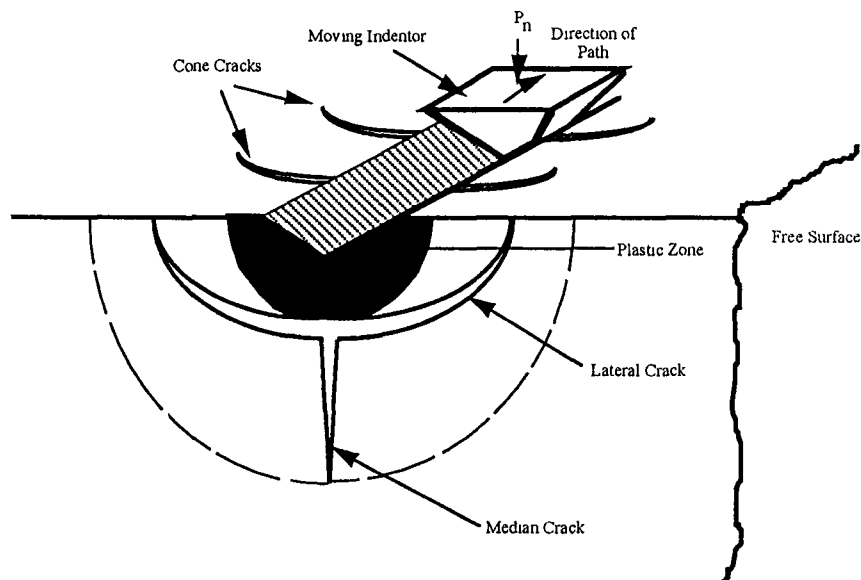


Figure 1 Cracks formed during the Sliding Microindentation of Ceramic Material

2.1 Specimen Preparation Using Submerged Machining

As guided by these observations, the stress field generated during machining will have direct influence on the crack distribution present in the ceramic material being machined. Machining ceramics under a submersion environment is proposed in this research. As illustrated in Fig. 2, a device is designed. It consists of three parts, namely, a container for cutting fluid, a vice to hold the workpiece, and a base on which strain gages are mounted to measure the cutting force during machining. The device is fixed on a CNC machining center during machining. Both the workpiece and cutting tool are submerged in the cutting fluid. This machining environment may create a unique opportunity to bring chemical interaction and tribological action into the kinetics of fracture, or the crack initiation and propagation in the chip formation process. For the purpose of making comparison, specimens are prepared under two different machining environments, namely, a dry machining environment where only compressed air is used to clear up chips from the machining zone and a submerged machining environment where cutting fluid is used to surround the tool and ceramic part material.

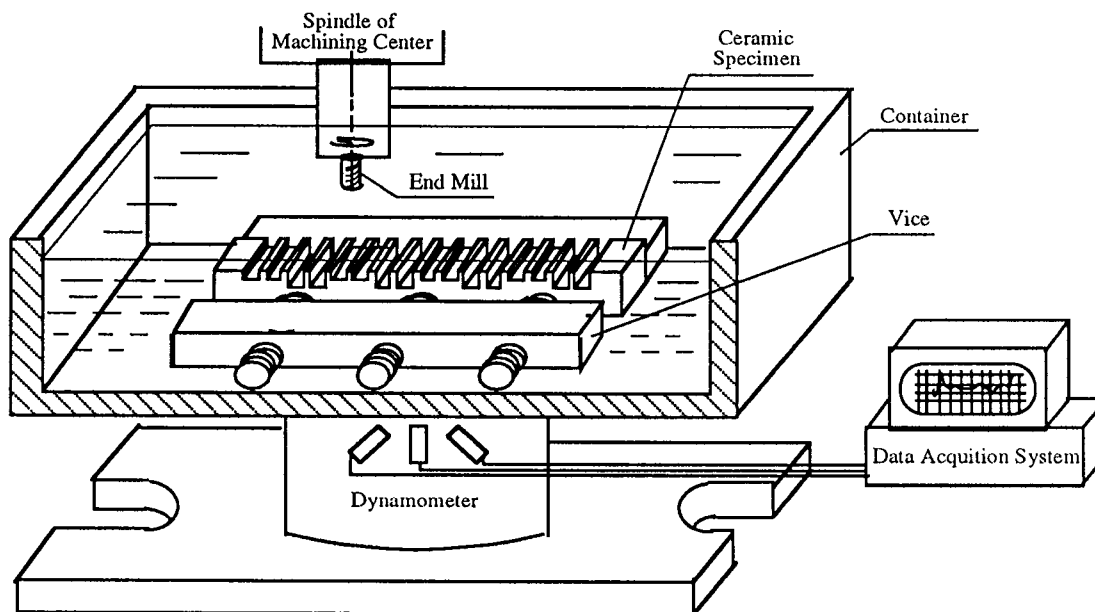


Figure 2 A Submerged Machining Device to Prepare Ceramic Specimens

In this study, the ceramic material used is Dicor-MGC. It is a two phase tetrasilicic mica glass-ceramic material and designed for use in dental restorations [12]. It has a micro structure consisting of mica flakes of approximately 70 volume percent dispersed in a non-porous glass matrix. The cleavage fracture along the planes of mica flakes makes the material machinable. As illustrated in Fig. 2, the machined surfaces are prepared on a specimen which is a 152.4 mm long bar with a rectangular cross-section, each side equal to 12.7 mm. The cutting tool is an end mill of high speed steel. The cutting fluid used is a commercially available emulsifiable oil, called LS-A-14H [13]. 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 is written to prepare the machined surfaces under selected machining conditions, first at the dry environment, and then at the submersion environment.

2.2 Stereophotogrammetric Examination of the Machined Surfaces

Currently, three experimental procedures predominate in studies of the fracture surface. They are based on the SEM fractograph, stereophotogrammetry, and profilometry [14]. SEM photomicrographs are used almost universally in fractographic studies. However, they are two-dimensional projected images obtained by reflection. Because of the absence of the third dimension, the usual interpretations on the crack formation are largely qualitative. Methods of using profilometry are useful to evaluate surface smoothness, but fail to detect the cracks formed on the machined surface which are in micro-scale. Stereoscopy offers a direct and nondestructive procedure to determine the elevation of a fracture surface at selected regions. However, a calibration process is needed to determine the graduations of the measurements.

In this study, an integrated system is developed for the evaluation of surface cracking induced by machining. As illustrated in Fig. 3, a machined surface is first undergone through a surface profilometry subsystem, in which the smoothness of the machined surface is evaluated in terms of the roughness average. In the second step, high-magnification images are taken under an environment electron microscope to provide details about the machined surface. Immediately following the second step, surface topographies are constructed using computer graphical software tools [15]. In the meantime, the graduations used in the reconstruction of surface topographies are calibrated using the data provided by the surface profilometry subsystem. Based on the calibrated surface texture, cracks formed on the machined surface are visualized to display their size and shape. Using contour plots, quantitative information on the crack distribution can be obtained.

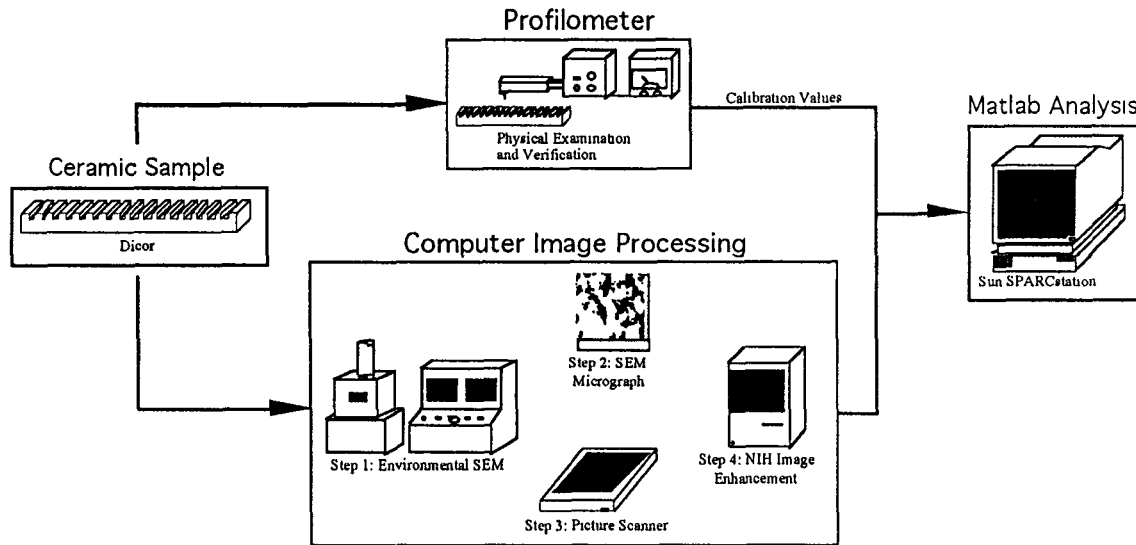


Figure 3 A Computer-Based System for the Evaluation of the Machining-Induced Surface Cracking

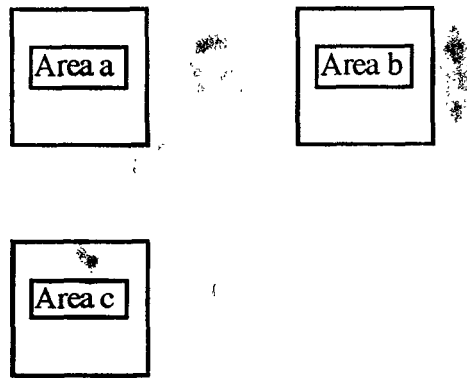
Figure 4 provides the results obtained from these experiments. Figure 4a presents the images of two machined surfaces, one prepared under the dry machining environment and the other under the submerged machining environment. Figure 4b are the scaled surface topographies, that are reconstructed through image processing of the SEM photomicrographs of the machined surface. Figure 4c are contour plots to depict the surface cracks formed during machining.

3. Characterization of the Crack Distribution

3.1 Definition of Surface Cracks

Results obtained from the stereophotogrammetric examination has provided rich information about the surface texture generated during machining. The surface texture mainly consists of two components: surface irregularities and surface cracks. The focus of this research is to gain a comprehensive understanding on the surface cracking. Therefore, it is necessary to draw a line to distinguish the surface irregularities from the surface cracks.

The two graphs shown in Figure 5 are two-dimensional projections of the three-dimensional surface texture images illustrated in Fig. 3b. They depict the height variation



Dry Machining Cutting Speed = 4 m/min
 Depth of Cut = 0.08 mm
 Feed Rate = 5 mm/min

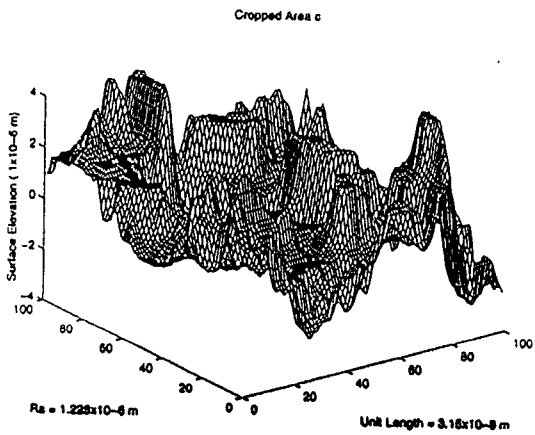
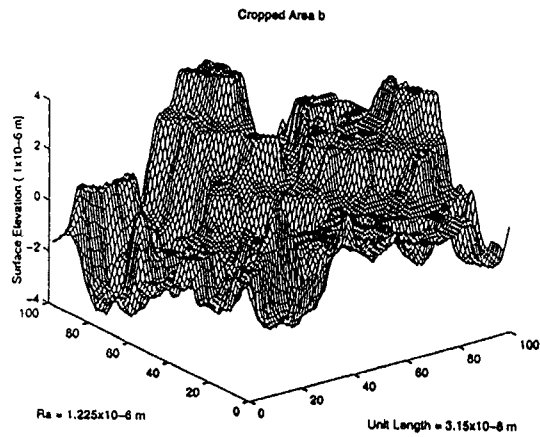
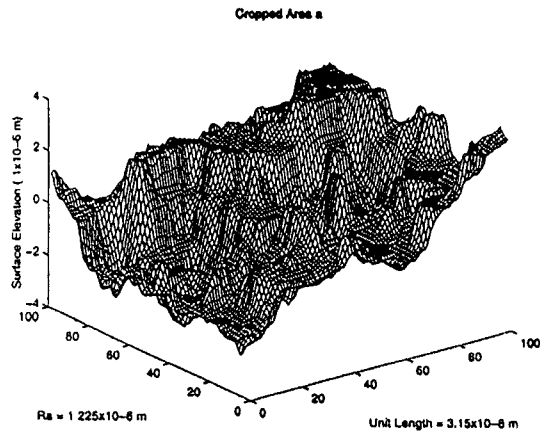


Submerged Machining Cutting Speed: = 4 m/min
 Depth of Cut: = 0.08 mm
 Feed: = 5 mm/min

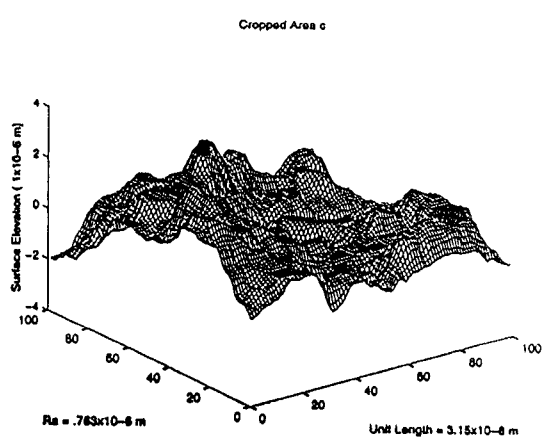
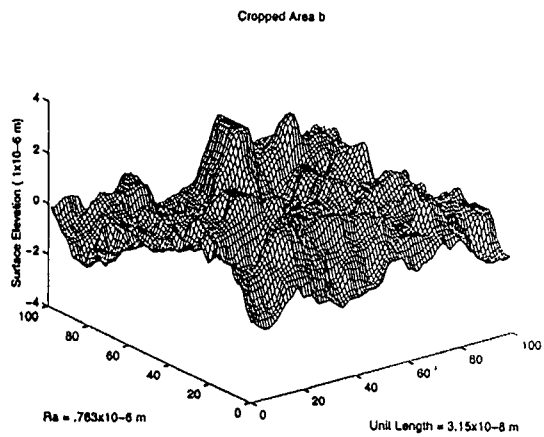
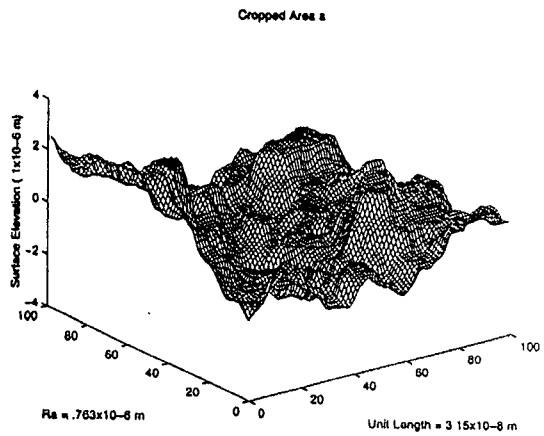
(a) SEM Micrographs

Figure 4 Results Obtained from the Stereophotogrammetric Examination of Two Machined Surfaces

Dry Machining



Submerged Machining



(b) Reconstructed Surface Topographies

Figure 4 Results Obtained from the Stereophotogrammetric Examination of Two Machined Surfaces (Continued)

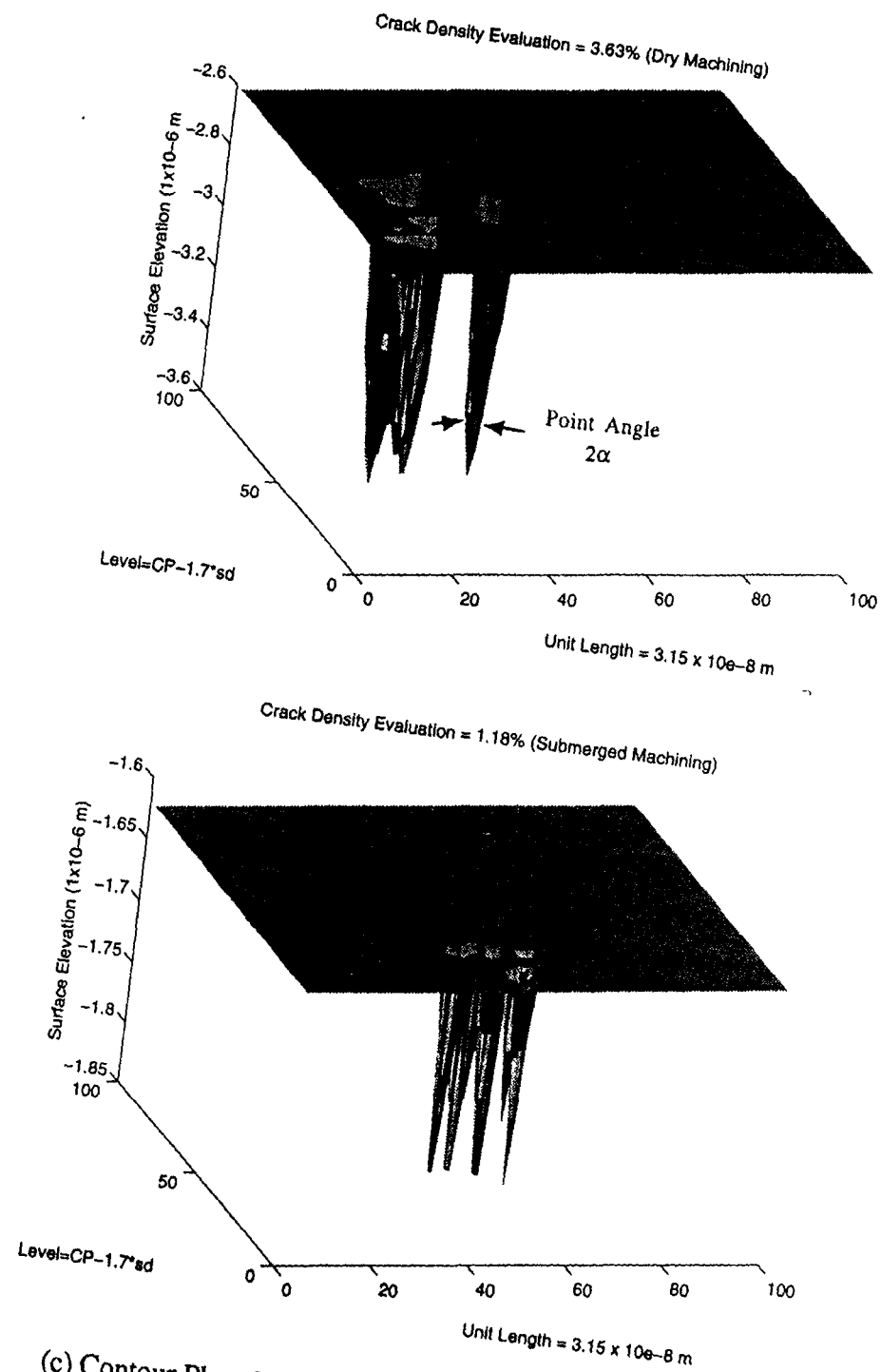
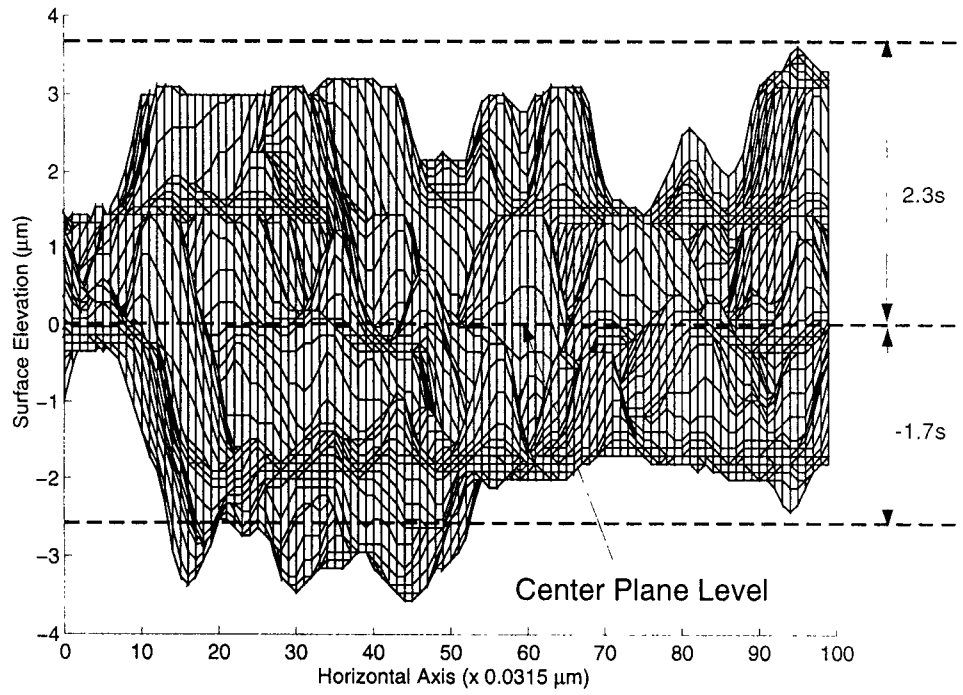
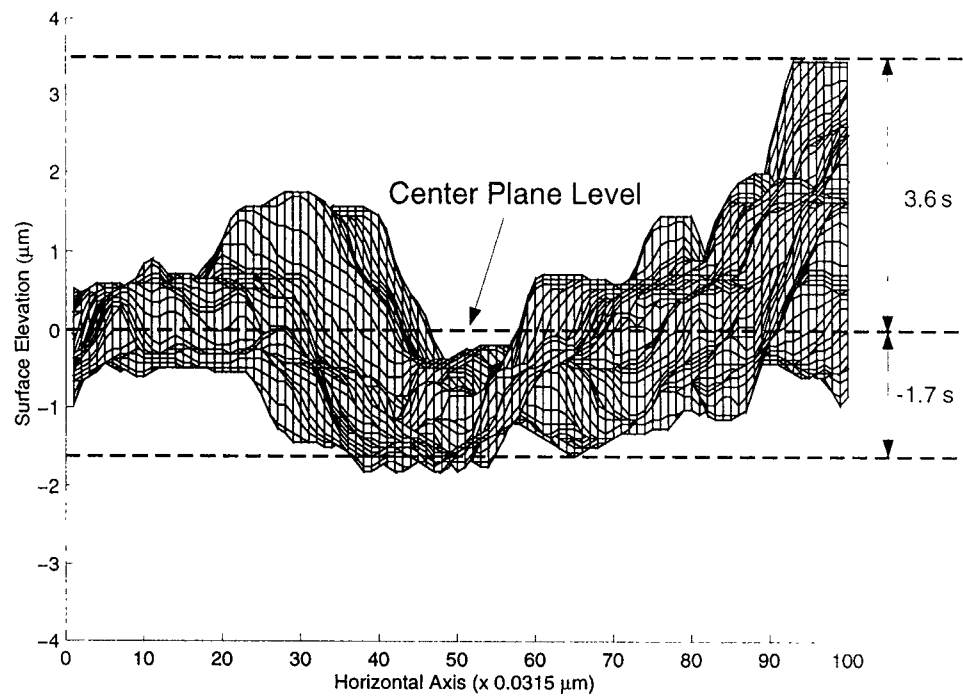


Figure 4
 (c) Contour Plots for the Evaluation of Surface Cracking
 Results Obtained from the Stereophotogrammetric Examination of
 Two Machined Surfaces (Continued)



(a) Under Dry Machining Environment ($s = 1.539 \mu\text{m}$)



(b) Under Submerged Machining Environment ($s = 0.956 \mu\text{m}$)

Figure 5 Two-Dimensional Projects of the Height Variations

of individual points on the two surface textures generated under the two machining environments. By calculating the arithmetic average of the heights, as indicated in Eq. (1), a central plane (CP) can be determined. It is marked by CP in Fig. 5 and is used as a reference plane to distinguish those heights which are located above the average height from those heights below the average height. Peaks and valleys can be counted with respect to the central plane. In a similar manner, the standard deviation, s , is also calculated with respect to CP using Eq. (2). This parameter provides a normalized factor to define the relative distance of a surface peak, or valley, from the central plane.

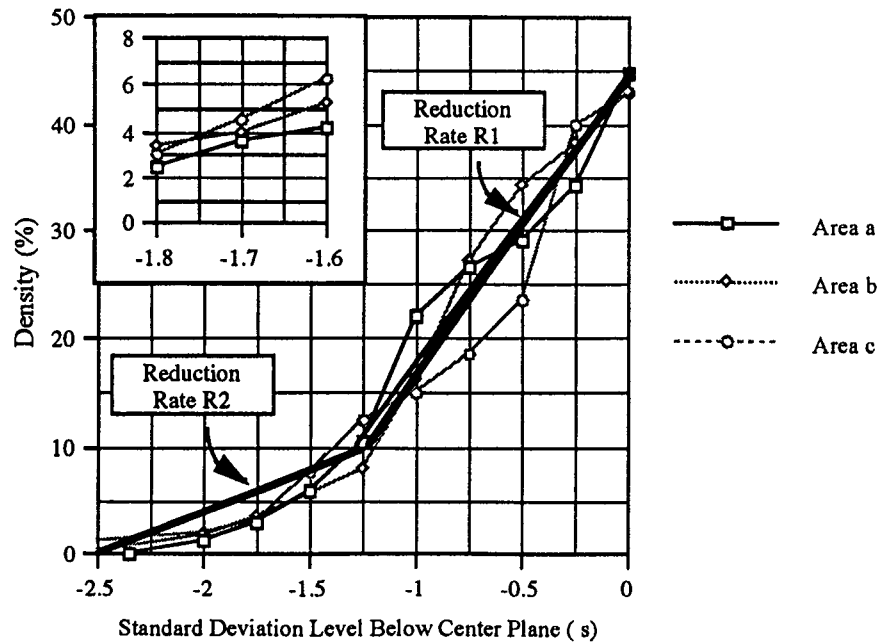
$$CP = \sum_{i=1}^n \sum_{j=1}^n \frac{y_{ij}}{n \times n} \quad (1)$$

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

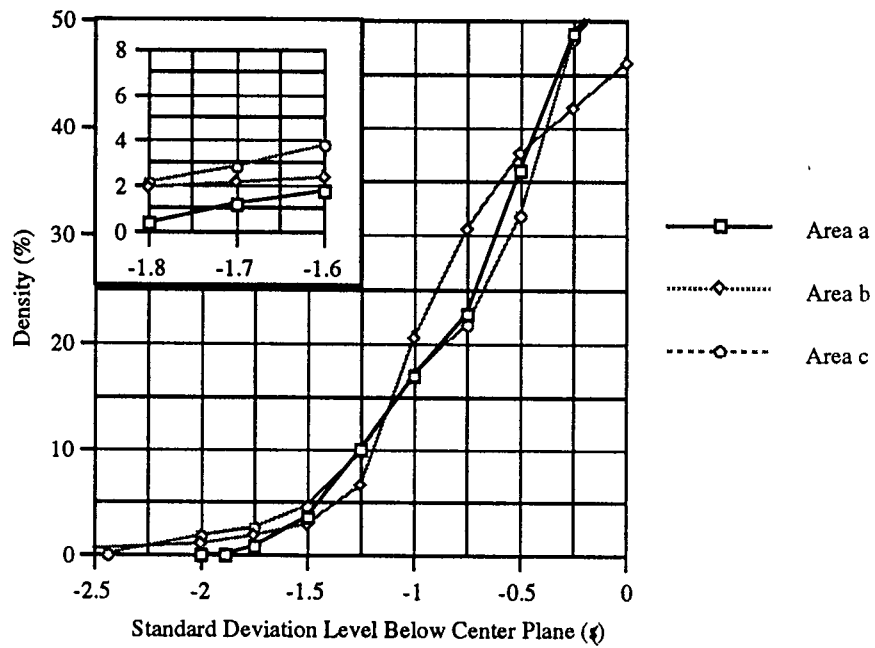
where y_{ij} = height of an individual point about a reference plane
 n = number of points taken on each side of the squared area for the evaluation.

With these two parameters, a graphic method is used to calculate the percentage of the areas which are occupied by the surface valleys. First, contour plots are constructed at different levels, starting from the CP level, then CP-0.25s level, to the level at which the valley-covered area vanishes. Then, the areas covered by the surface valleys are identified, evaluated and summed up. The two plots shown in Fig. 6 presents the evaluation results for the two surface textures illustrated in Fig. 4b. Each of the two plots contains three curves which correspond to the three local areas selected for the evaluation. Examining these curves closely, the following three observations can be made:

- (1) The percentage of the valley-covered areas decreases as the contour plot level goes downward from the central plane.
- (2) There are two distinguishable rates of decrease, characterized by R_1 and R_2 , and $R_1 > R_2$. The slow decrease rate, R_2 , is a strong evidence indicating that the variation of valley-covered areas has reached a stage that its reduction is solely contributed by the area reduction due to the cone-shaped



(a) Under Dry Machining Environment



(b) Under Submerged Machining Environment

Figure 6 Plots of the Percentages of Valley-Covered Areas at Different Height Levels

median cracks. As the contour level goes downward, the area of the cross section of a cone-shape crack decreases accordingly.

- (3) There exists a critical point on the curve of valley-covered areas vs level depth. It serves as the key level of the surface texture to separate surface cracks from those surface valleys formed on the machined surfaces, which should be dealt with primarily as surface irregularities.

These observations represent significant findings in characterizing the surface cracking phenomenon related to machining. In this study, the critical level of depth to define cracks formed on the machined surfaces is selected at CP-1.7s. Numerical values of 1.7s are $2.5 \mu\text{m}$ and $1.7 \mu\text{m}$ for the two surface textures shown in Fig. 5, respectively.

3.2 Distribution of Surface Cracks

Examining the identified surface cracks shown in Figs. 4C and 5, the distribution of surface cracks can be characterized by two parameters. They are the crack density in terms of the percentage of the valley-covered areas, and the crack depth in terms of the standard deviation of the height variation, serving as the normalized factor. Using the experimental results provided in Figs. 4C and 5, the two distributions of surface cracks for the dry and submerged machining environments can be represented as follows:

Table 1 Distributions of Surface Cracks (Dry and Submerged Machining)

Parameters Type of Machining	Crack Depth Distance below CP unit: μm	Crack Density Mean (STD) unit: % of Area
Distribution Dry Environment $s = 1.5 \mu\text{m}$	$2.25 \mu\text{m}$ (1.5 s)	7.9% (1.9%)
	$2.55 \mu\text{m}$ (1.7 s)	4.1% (0.7%)
	$2.85 \mu\text{m}$ (1.9 s)	2.0% (0.1%)
	$3.15 \mu\text{m}$ (2.1 s)	0.5% (0.08%)
Distribution Submersion Environment $s = 1.0 \mu\text{m}$	$1.50 \mu\text{m}$ (1.5 s)	3.6% (0.9%)
	$1.70 \mu\text{m}$ (1.7 s)	2.1% (0.8%)
	$1.90 \mu\text{m}$ (1.9 s)	1.2% (1.1%)
	$2.10 \mu\text{m}$ (2.1 s)	0.3% (0.06%)

As indicated by the listed data, the crack densities at the CP-1.5s level are 7.9% and 3.6% for the dry and submerged machining cases, respectively. The crack density

approaches zero at the depth of 3.15 μm below the center plane for the dry machining, and at the depth of 2.10 μm for the submerged machining. Such comparison means that both the crack density and the height variation of surface cracks under the submerged machining environment are significant less than those under the dry machining environment. Accordingly, efforts to eliminate these surface cracks using a post process, such as polishing, would be more substantial for the dry machining than the efforts for the submerged machining in order to remove the damaged surface layer. Such removal may also lead to high cost as well as degrading the geometric and dimensional accuracy of the machined part.

4. Performance Evaluation of Submerged Machining

4.1 Effect of Surface Cracking on Stress Intensity Factor

To explain the low measured strength values of brittle material under a stress field, the crack formation is well accepted. According to Griffith, fracture under tensile stress of a brittle solid is always initiated by a crack. The stress-intensity factor, a parameter characterizing the effects of the applied stress, the crack shape and size on stress-concentration at the crack tip is given by

$$K_I = 1.12\sigma\sqrt{\pi a / Q} \quad (3)$$

where σ = applied stress, a = depth of a surface crack, and Q = crack-shape parameter as a function of the ratio $a/2c$ where $2c$ stands for the width of a surface crack. For surface cracks on ceramic materials, an empirical model to estimate the Q value is given by [15]

$$Q = 2.23 + 0.20 \frac{\frac{a}{2c}}{0.05} \quad \text{for } 0.50 \leq \frac{a}{2c} \leq 2.0 \quad (4)$$

Table 2 lists the measured depth and width of the five surface cracks illustrated in Figs. 4C and 5. It also provides the Q values estimated by Eq. (4) and the K_I values estimated by Eq. (3). Two important observations can be made from the data:

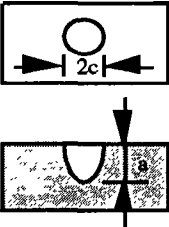
- (1) A large depth of a surface crack corresponds to a high stress-intensity factor. The average depth of surface cracks for the dry machining is about 0.59 μm . This corresponds to the stress-intensity factor ranging from 8.48σ to 19.09σ . The

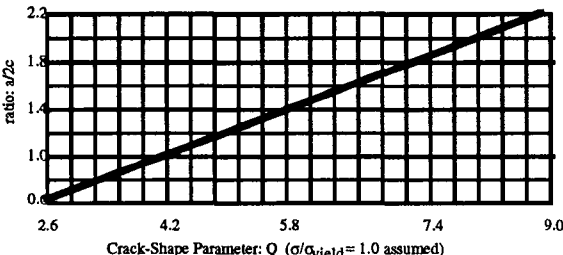
average depth of surface cracks for the submerged machining is about 0.21 μm . This corresponds to the stress-intensity factor ranging from 8.95σ to 11.20σ , which is about 30% lower than the stress-intensity factor estimated for the dry machining environment, illustrating the crack shape effect on the stress-intensity factor.

- (2) A large width of a surface crack, or a large crack, gives a low Q value, which turns to a high stress-intensity factor. For example, four cracks formed under the submerged machining have the same depth of 0.188 μm , but different width values. The crack with a larger width (0.20 μm) has a high stress-intensity factor of 11.2σ as compared with 9.51σ for the crack with a smaller width of 0.13 μm , illustrating the crack size effect on the stress-intensity factor.

Table 2 Distributions of Surface Cracks (Dry and Submerged Machining)

Parameters Type of Machining	Crack Depth a (μm)	Crack Width $2c$ (μm)	Ratio $a/2c$	Crack Shape Parameter Q	Stress Intensity Factor K_I $1.12\sqrt{\pi a/Q}$	Crack Point Angle 2α
5 Cracks Dry Environment (Fig. 5a)	0.95	0.47	2.01	10.27	19.09σ	24.3°
	0.85	0.32	2.70	13.02	16.04σ	21.0°
	0.31	0.22	1.41	7.85	12.47σ	28.5°
	0.12	0.11	1.09	6.58	8.48σ	43.0°
	0.74	0.31	2.35	11.63	15.84σ	17.0°
5 Cracks Submersion Environment (Fig. 5b)	0.188	0.16	1.19	7.00	10.28σ	45.5°
	0.188	0.13	1.49	8.20	9.51σ	37.1°
	0.188	0.16	1.19	7.00	10.28σ	45.5°
	0.28	0.13	1.02	6.29	8.95σ	52.4°
	0.188	0.20	0.92	5.90	11.20σ	57.1°





4.2 Effectiveness of Submerged Machining

Results from assessing the surface cracking induced by machining indicate that the stress field present during machining interacts with the stress singularity points present in the ceramic material, such as triple point junctions (intersections of the grain boundaries) and dislocation pile-ups at the grain boundaries, to initiate cracks. During machining there exists a crack system, which promotes the material removal process, but at the same time, leaves micro-scale cracks on and beneath the machined surface. The effectiveness of using the submerged machining on improving the machining performance in terms of reducing the surface cracking can be seen, as compared with the dry machining, from having a lower crack density; a thinner layer containing the surface cracks; and a reduced stress-intensity factor. The mechanisms to achieve these benefits may need a further investigation, especially in the micro-scale to incorporate the microstructure of ceramics into the crack formation. Two contributors, however, are evident:

- (1) The change of surface chemistry due to the presence of chemical-based cutting fluid provides strong tribological reactions on the interface between the ceramic material and the cutting tool. These reactions have a direct influence on the stress field present in the machining zone. A significant impact is promoting the propagation of lateral cracks against the development of median cracks. This effect brings the thickness of the surface layer containing all micro-scale cracks under control.
- (2) Under a chemically interactive environment, such as the submerged machining, the environmental effects, such as stress-corrosion cracking, can never be neglected. An accelerated kinetic crack propagation features environmentally assisted (corrosion) crack growth during the submerged machining. Strong interactions between environment and microstructure for the enhancement of crack growth, such as transport of the chemical additive(s) to the crack tip and reaction of the chemical additive(s) with the newly produced crack surfaces, can be anticipated.

5. Conclusions

This paper presents an experimental investigation on the effectiveness of applying submersion to machine ceramics. A nondestructive evaluation method has been developed to characterize the surface cracking induced by machining. Results and significant findings gained from this investigation can be summarized as follows.

1. A crack system consisting of median, lateral, and cone cracks is generated during the machining of ceramic materials. The surface cracks formed during machining are mainly those of median cracks. The shallow lateral and surface ring cracks appear to be responsible for material removal as the cutting tool progresses its sharp contact with the ceramic material during machining.
2. The distribution of surface cracks can be described by two parameters, its density and depth with reference to the defined central plane. The cracking density is an indication of the degree of surface damage induced by machining. The cracking depth, characterizing the size of the surface layer containing all surface cracks, determines the critical stress-intensity factor of the ceramic parts during the service.
3. Machining environment and selection of machining parameters are directly related to both the cracking density and depth. The submersion method utilizes the stress-corrosion cracking growth to promote the crack propagation in the ceramic material during the material removal process. The obtained results demonstrate its effectiveness in the reduction of the cracking density and depth, strongly suggesting quality improvement of the machined surface.
4. The developed image-based cracking evaluation system is a technological integration of the SEM, image processing, and computer graphics. The system offers a nondestructive evaluation method to characterize the distribution of the surface cracking formed during machining.

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