TECHNICAL RESEARCH REPORT

Submerged Precision Machining of Ceramic Material

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T.R. 95-5

INSTITUTE FOR SYSTEMS RESEARCH

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

SUBMERGED PRECISION MACHINING OF CERAMIC MATERIAL

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ABSTRACT
The brittle nature of ceramics makes them difficult to machine. This paper presents a study to explore a new method to machine ceramic material. The method is based on the stress-corrosion-cracking behavior of ceramic material under certain aggressive environments. An apparatus is designed to create a machining environment where workpiece and cutting tool are submerged in a bath filled with cutting fluids. Observations on the surface texture formed during machining have been made to investigate the effectiveness of submerged machining on quality and efficiency of the machining operation. The obtained results strongly suggest that the chemo-mechanical interactions occurred during machining have great influence on the stress distribution produced in the ceramic material being machined, thus having direct effects on crack initiation and propagation. By controlling the machining parameters, higher material removal rate with less surface damage can be achieved, showing the potential of submerged machining as an innovative technology for machining ceramic material

1. INTRODUCTION*
Over the last two decades, extensive research has been done in the development of advanced ceramic material. Superior properties of ceramic materials include unique hardness and high resistance to heat, wear, and corrosion. Ceramic materials have provided great opportunities to develop new products with unique performance capabilities.

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* This work is supported by the Department of Defense through the Defense Acquisition Scholarship Program

Most of today's parts made of ceramics are manufactured to a near net shape through pressing and/or sintering processes. However, limitations, such as geometric accuracy, pose the need for machining. In fact, machining is an area of research that is vital to realize the material potential and bring it within the access of engineers. Unfortunately, due to the hardness and brittleness, ceramic materials are difficult to machine, not only for a low machining efficiency, but also for a high cost associated with machining. More important is the fact that ceramic material is highly susceptible to failure due to cracks formed on, or beneath, the machined surface. Therefore, developing an innovative machining technology to effectively process ceramic material represents the need and a new challenge to the manufacturing community.

During the last two decades, a large amount of research in the area of ceramic machining has been carried out. The pioneering work towards understanding the fundamentals behind the machining of ceramics was conducted by Evans and Marshall in 1980 [1]. They applied indentation fracture mechanics to interpret the material removal mechanisms observed during the grinding of ceramic material. They suggested a lateral fracture threshold loading limit. Below the limit, plastic flow crushing occurs during machining, and above the limit, lateral cracking occurs. Research of fracture mechanics has provided strong evidence that cleavage fracture is the most common mode responsible for material removal during the machining of ceramic material [2-6]. A five stage model to describe the material removal process during machining was proposed by Zhang et al. in their investigation of machining aluminum oxide [6]. The model depicted a process starting from crack initiation, crack propagation, chip formation, to surface texture formation. Data on machining ceramics have also been accumulated for effective utilization in both basic research and practical applications [7]. It has been recognized that high-performance materials, such as ceramics, have to be machined using adapted conventional machining techniques.

This paper presents a method which employs the concept of submersion as an adapted conventional technique to machining ceramics. In this investigation, a device is designed and constructed so that the ceramic material to be machined is placed in a bath filled with cutting fluid. During machining, the cutting tool removes material in an environment where the supply of cutting fluid is sufficient. By controlling the type of cutting fluid and three machining parameters, namely, depth of cut, feed, and cutting speed, the temperature in the cutting zone and the tribological effects on the tool-workpiece and tool-chip interfaces are brought into action of material removal. It has been observed that the submerged machining environment promotes stress-corrosion-cracking through high penetration induced by chemical reactions. Experimental results strongly support the potential of using submerged machining to improve quality and efficiency of the machining operation.

2. BASIC METHODOLOGY OF SUBMERGED MACHINING

Reasons to use cutting fluid during machining have been known for, at least, a century. Reducing friction at the contact interface and removing the heat generated during machining are two among the many. During the machining of ceramic material, special attention should be paid to behaviors of ceramic material when it is subjected to a high stress field and surrounded by cutting fluid, or a corrosive media.

In fact, the sensitivity of strength and fracture toughness of ceramics to reactive chemicals is well known [??]. The presence of a chemically active species at a crack tip can alter the interfacial energy and change fracture behavior or alternatively react, forming new phases with different behaviors. Therefore, solutions that etch, dissolve or form new phases could enhance machining rates. This research is aimed at obtaining more fundamental knowledge about this aspect.

2.1 Design of Submerged Machining Apparatus

In this research, the potential for chemically-assisted machining of ceramics by selection of cutting fluids is explored in milling operations. As illustrated in Fig. 1, an apparatus is designed to carry out submerged machining. The apparatus 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 for the purpose of measuring the cutting force during machining. During the 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. The cutting tool used in this investigation is an end mill with diameter equal to 3.175

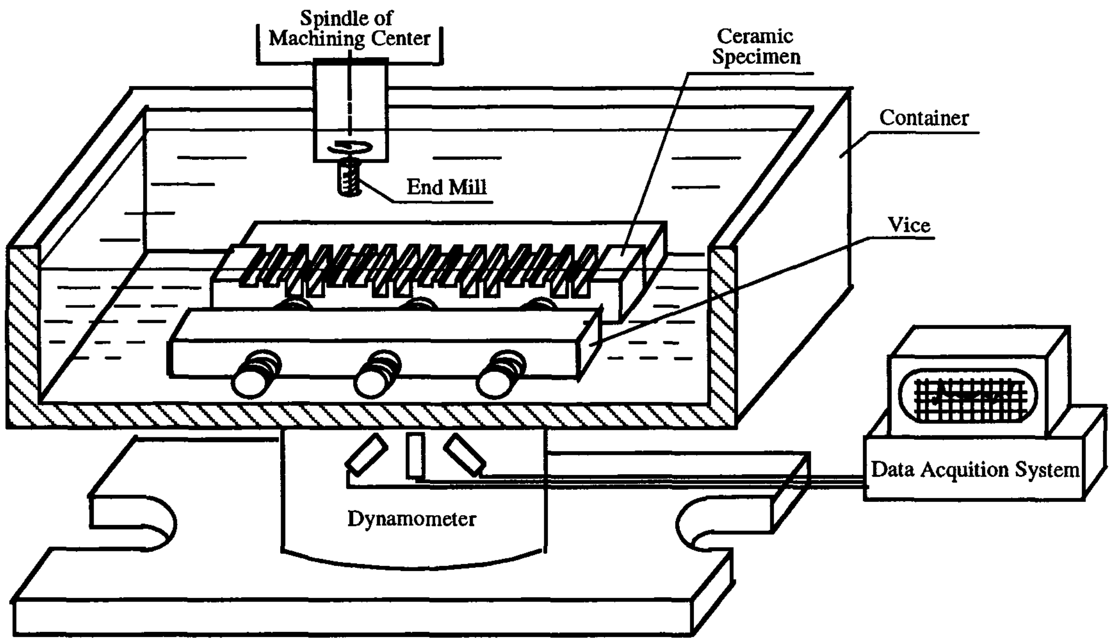


FIGURE 1 SUBMERGED MACHINING APPARATUS

mm. All the settings of depth of cut, feed, and cutting speed are implemented through an numerically controlled (NC) program.

2.2 Selections of Ceramic Material, Tool Material and Machining Conditions

In this investigation, the ceramic material used is Dicor-MGC. 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 Dicor-MGC is about 3.4 GPa. The cleavage fracture along the planes of mica flakes makes the material machinable. Dicor-MGC has been widely used as a new material in dental restorations [8-9]. Figure 2 illustrates the specimen used in the machining tests. It is a 152.4 mm long bar with a rectangular cross-section, each side equal to 12.7 mm. The material of the end mill selected was high speed steel with hardness of about 18 GPa, which is 5 times as hard as the Dicor-MGC material under the investigation.

The four machining parameters under this study are type of the cutting fluid used, and three machining parameters. They are depth of cut, feed and cutting speed. A design of experimentation method is used to set each of the four variables at two levels, namely, high and low [10]. Table 1 lists the 16 combinations of these four parameter settings. For example, the machining condition set for Test 1 is a combination of depth of cut = 0.08 mm, feed = 5 mm/min, and cutting speed = 4 m/min at a dry cutting environment where compressed air is used to assist in chip removal. On the other hand, the machining condition set for Test 8 is a combination of depth of cut = 0.16 mm, feed = 10 mm/min, and cutting speed = 6 m/min at a dry cutting environment. Note the machining environment for Tests 9 - 16 where cutting fluid is used. The fluid used in this investigation is a commercially available emulsifiable oil, called LS-A-14H [11]. The emulsifiable concentrate is mixed with water in a ratio of 9:1. The pH ranges from 9.7 to 9.9. As described in section 2.1, an NC program (see appendix) is prepared to carry out the machining tests, first at the dry environment, and then at the submersion environment.

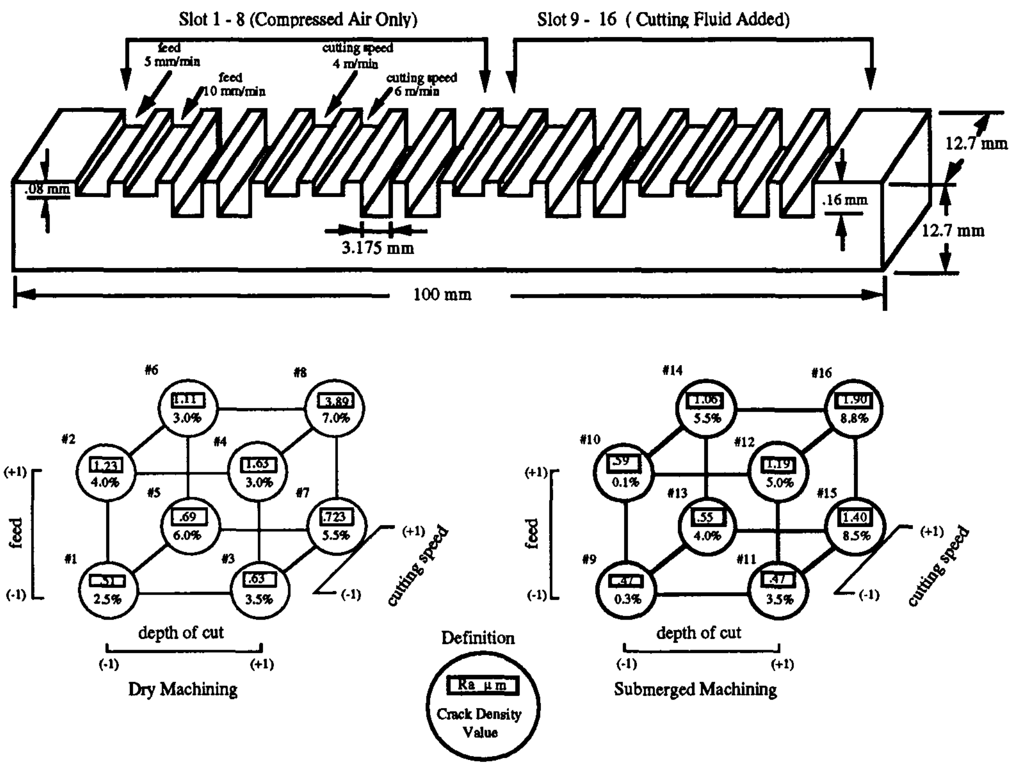


FIGURE 2 CERAMIC SPECIMEN AND SETTINGS OF THE MACHINING CONDITIONS

3. ASSESSMENT OF EXPERIMENTAL DATA

Assessment of experimental data obtained from this 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, all of the fabrication methods damage the ceramic during the restoration preparation. It is believed that the smoother the surface produced, the less likely it is damaged sufficiently to compromise its clinical performance [10]. In addition, quantitative information on the degree of damage which has been induced to the ceramic material during the preparation is essential to the assessment of machining performance. Observations indicate that most of the ceramic components failure occurred during service initiate at the surface cracks, which grow and penetrate, leading to unstable failure.

The assessment performed in this investigation 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 Table 1. 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 on the machined surface [12]. Figure 3 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 [12]. The two reconstructed 3-dimensional surface topographies shown in Fig. 4 are taken from the two pictures marked as test 2 and test 10 in Fig. 3. To quantify the damage induced under different machining conditions, a performance index is introduced to characterize the machined damage in terms of surface cracking. It

TABLE 1 DESIGN MATRIX FOR THE EXPERIMENTATION AND MEASURED DATA

Test No.	Parameter Settings				Surface Roughness (mm)	Crack Density (%) at 1.7σ Level
	Feed (mm/min)	Depth of Cut (mm)	Cutting Speed (m/min)	Machining Environment		
1	5 (-1)	0.08 (-1)	4 (-1)	Dry Machining	0.51	2.5
2	10 (+1)	0.08 (-1)	4 (-1)	Dry Machining	1.23	4
3	5 (-1)	0.16 (+1)	4 (-1)	Dry Machining	0.63	3.5
4	10 (+1)	0.16 (+1)	4 (-1)	Dry Machining	1.63	3
5		0.08 (-1)	6 (+1)	Dry Machining	0.69	6
6	10 (+1)	0.08 (-1)	6 (+1)	Dry Machining	1.11	3
7	5 (-1)	0.16 (+1)	6 (+1)	Dry Machining	0.72	5.5
8	10 (+1)	0.16 (+1)	6 (+1)	Dry Machining	3.89	7
9	5 (-1)	0.08 (-1)	4 (-1)	Submerged Mach.	0.47	0.3
10	10 (+1)	0.08 (-1)	4 (-1)	Submerged Mach.	0.59	0.1
11	5 (-1)	0.16 (+1)	4 (-1)	Submerged Mach.	0.47	3.5
12	10 (+1)	0.16 (+1)	4 (-1)	Submerged Mach.	1.19	5
13	5 (-1)	0.08 (-1)	6 (+1)	Submerged Mach.	0.55	4
14	10 (+1)	0.08 (-1)	6 (+1)	Submerged Mach.	1.05	5.5
15	5 (-1)	0.16 (+1)	6 (+1)	Submerged Mach.	1.4	8.5
16	10 (+1)	0.16 (+1)	6 (+1)	Submerged Mach.	1.9	8.8

is called density of surface cracking, and is defined as a percentage of the area occupied by cracks formed on a machined surface. As illustrated in Fig. 5, two contour plots are taken from the two reconstructed surface topographies for evaluating the density of surface cracking. As illustrated in Fig. 5, 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 4 illustrates that the two contours shown in Fig. 5 are taken at a level of depth marked as (CP - 1.7σ) where parameter σ serves as a normalized factor for evaluating the density of surface cracking with a variety of surface roughness values. To further clarify the two parameters, CP and σ, formulas for determining them during the evaluation are listed as follows:

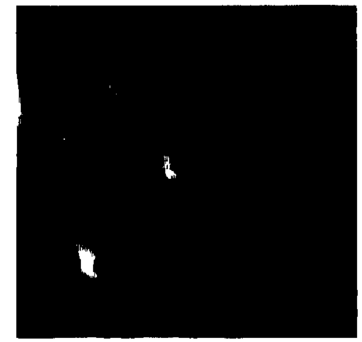
$$CP = \sum_{i=1}^{n}\sum_{j=1}^{n}\frac{y_{ij}}{n \times n} \qquad (1)$$

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

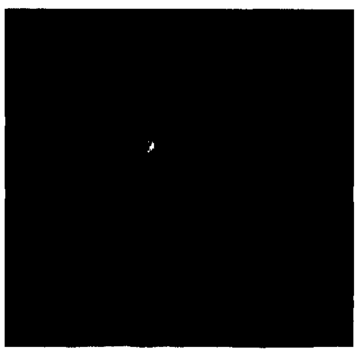
Test 1 feed = 5 mm/min
d.o c = 0.08 mm
cut spd. = 4 m/min

Test 2 feed = 10 mm/min
d.o c = 0 08 mm
cut spd. = 4 m/min

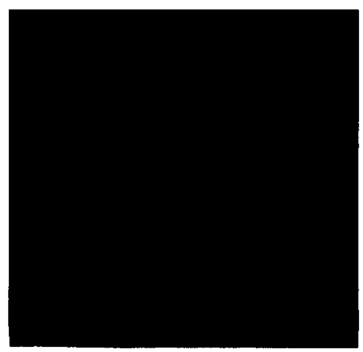
Test 3 feed = 5 mm/miN
d.o.c. = 0.16 mm
cut spd. = 4 m/min



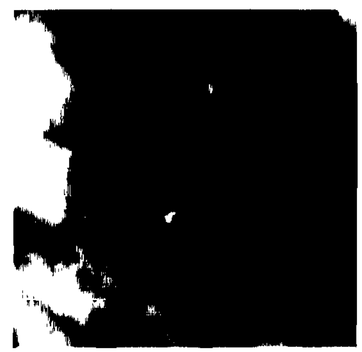
Test 4 feed = 10 mm/min
d.o c. = 0 16 mm
cut spd = 4 m/min



Test 5 feed = 5 mm/min
d.o.c = 0 08 mm
cut spd. = 6 m/min



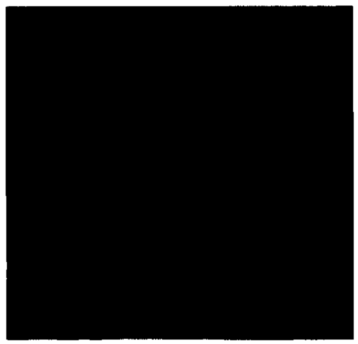
Test 6 feed = 10 mm/min
d.o.c. = 0 08 mm
cut spd = 6 m/min



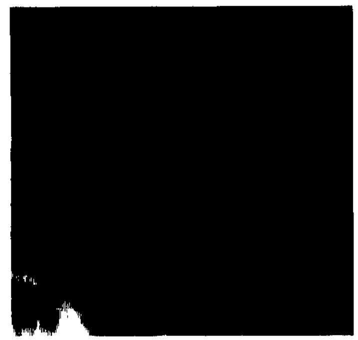
Test 7 feed = 5 mm/min
d o c = 0.16 mm
cut spd. = 6 m/min

Test 8 feed = 10 mm/min
d.o c. = 0 16 mm
cut spd = 6 m/min

FIGURE 3A SEM MICROGRAPHS OF THE 8 MACHHINED SURFACES (DRY MACHINING ENVIRONMENT)

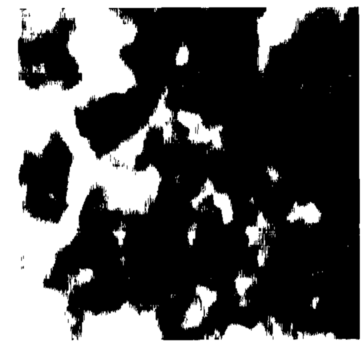


Test 9 feed = 5 mm/min
d o c. = 0 08 mm
cut spd = 4 m/min



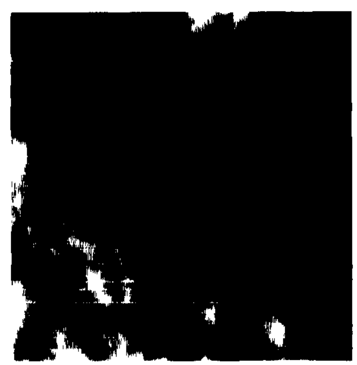
Test 10 feed = 10 mm/min
d.o c = 0.08 mm
cut spd = 4 m/min

Test 11 feed = 5 mm/min
d.o c = 0.16 mm
cut spd = 4 m/min

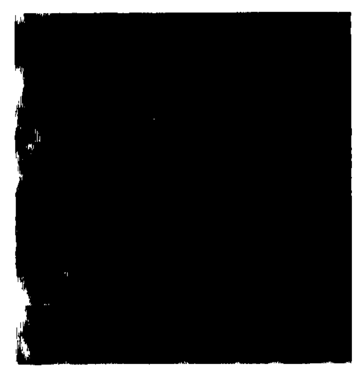


Test 12 feed = 10 mm/min
d.o.c. = 0.16 mm
cut spd = 4 m/min

Test 13 feed = 5 mm/min
d o.c = 0.08 mm
cut spd = 6 m/min



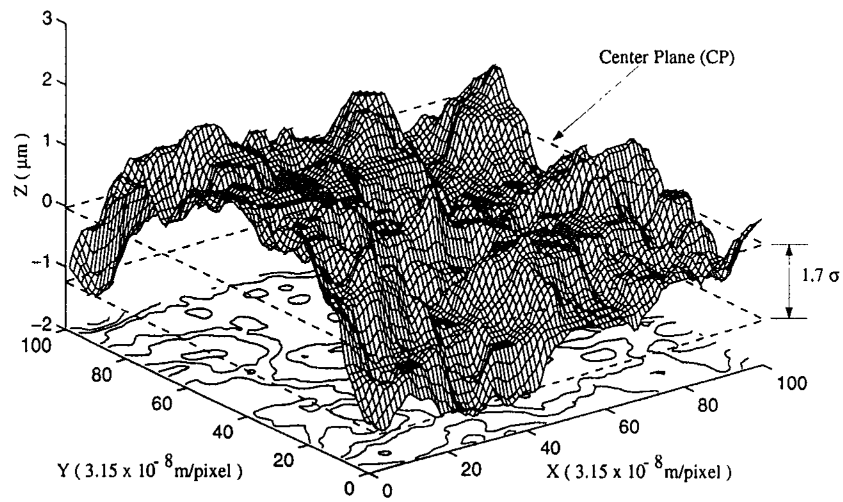
Test 14 feed = 10 mm/min
d.o c = 0.08 mm
cut spd = 6 m/min



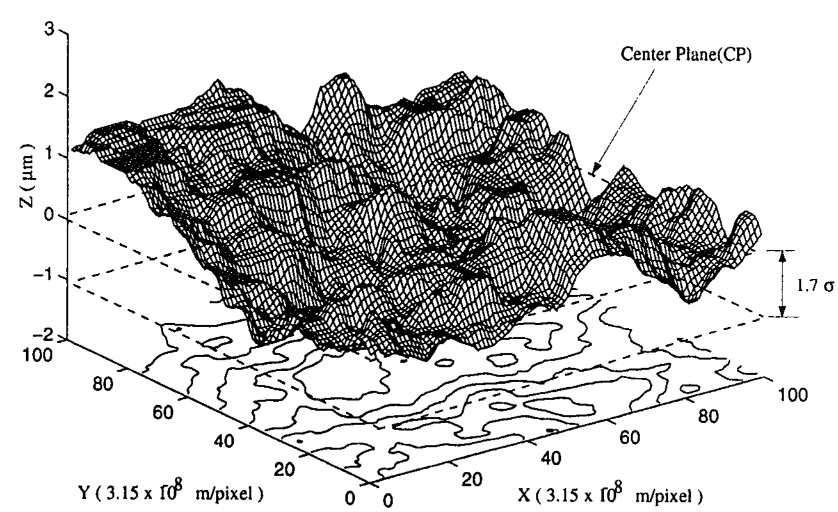
Test 15 feed = 5 mm/min
d o c. = 0.16 mm
cut spd = 6 m/min

Test 16 feed = 10 mm/min
d o c. = 0.16 mm
cut spd = 6 m/min

FIGURE 3B SEM MICROGRAPHS OF THE 8 MACHINED SURFACES (SUBMERGED MACHINING ENVIRONMENT

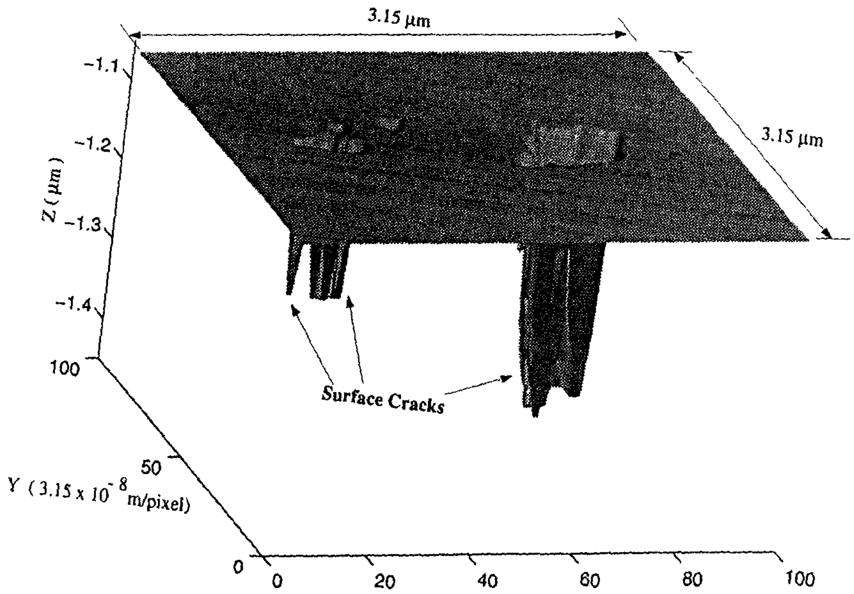


(a) Test 2. Feed = 10 mm/min (+1), Depth of Cut = 0.08 mm (-1), Cutting Speed = 4 m/min (-1), Machining Environment = dry machining

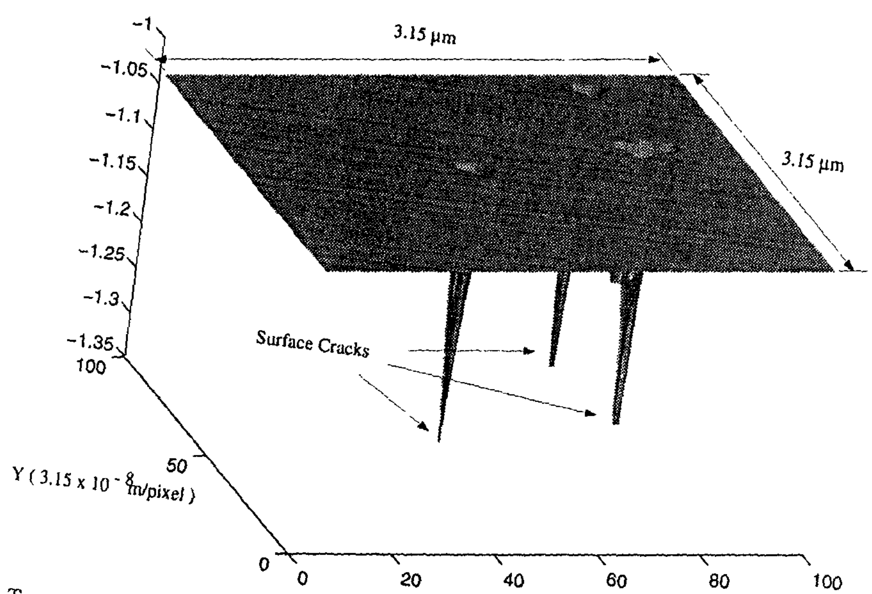


(b) Test 10: Feed = 10 mm/min (+1), Depth of Cut = 0.08 mm (-1), Cutting Speed = m/min (-1), Machining Environment = submerged machining

FIGURE 4 TWO RECONSTRUCTED SURFACE TOPOGRAPHIES



(a) Test 2: Feed = 10 mm/min (+1), Depth of Cut = 0.08 mm (-1), Cutting Speed = 4 m/min (-1), Machining Environment = dry machining



(b) Test 10: Feed = 10 mm/min (+1), Depth of Cut = 0.08 mm (-1), Cutting Speed = m/min (-1), Machining Environment = submerged machining

FIGURE 5 TWO CONTOUR PLOTS ILLUSTRATING THE CONCEPT OF DENSITY OF SURFACE CRACKING where y_{ij} represents the height of an individual point about 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 Figs. 6a and 6b, for the dry and submerged machining environment, respectively. The data listed in Table 1 represent the crack density values evaluated at the level of depth set at 1.7σ below the central plane, CP.

4. DISCUSSION OF RESULTS

Data obtained from a factory design, such as the one used in this investigation, offers an unique opportunity to derive empirical models capable of describing effects of the four parameters on the machining performance.

4.1 Main Effects of the Four Machining Parameters

Using the algorithm, proposed by Box [10], 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

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

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

$$\bar{R}_a = 1.13 + 0.45(\mathit{feed}) + 0.35(\mathit{depth\ of\ cut}) + 0.28(\mathit{cutting\ speed}) - 0.18(\mathit{machining\ Environment}) + (\mathit{combinational\ effects}) \quad (\text{unit: } \mu\text{m}) \qquad (3)$$

Note that the first term in Eq. (3), 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 mm. When using Eq. (3), 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. (3), 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 Finnish, 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 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 Dicor-MGC material.

4.2 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 [10]:

For the dry machining environment:

$$\bar{R}_a = 1.30 + 0.66(\textit{feed}) + 0.42(\textit{depth of cut}) + 0.30(\textit{cutting speed})$$
$$+ 0.38(\textit{feed} \text{ x } \textit{depth of cut}) + 0.23(\textit{feed} \text{ x } \textit{cutting speed}) + 0.29(\textit{depth of cut x cutting speed})$$
$$+ 0.31(\textit{feed x depth of cut x cutting speed}) \quad (\text{unit: } \mu\text{m}) \qquad (4)$$

For the submerged machining environment:

$$\bar{R}_a = 0.95 + 0.23(\textit{feed}) + 0.29(\textit{depth of cut}) + 0.27(\textit{cutting speed})$$
$$+ 0.08(\textit{feed} \text{ x } \textit{depth of cut}) + 0.02(\textit{feed} \text{ x } \textit{cutting speed}) + 0.14(\textit{depth of cut x cutting speed})$$
$$- 0.08(\textit{feed x depth of cut x cutting speed}) \quad (\text{unit: } \mu\text{m}) \qquad (5)$$

Examining the eight values representing the grand average, main and combinational effects in Eqs (4) and (5), important observations are

(1) the numerical values in Eq. (5), or associated with the submersion, are significantly smaller that those in Eq. (4), 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 6 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:

$$\bar{R}_a = 0.95 + 0.23(\textit{feed}) + 0.29(\textit{depth of cut}) + 0.27(\textit{cutting speed})$$
$$+ 0.14(\textit{depth of cut x cutting speed}) \quad (\text{unit: } \mu\text{m}) \qquad (6)$$

The explicit format of Eq. (6) is an indication of the involvement of the stress-corrosion-cracking behavior of ceramic material in the process of material removal during machining.

(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.

4.3 Density of Surface Cracking Induced during Machining

The data obtained from evaluating the density of surface cracking based on the criterion described

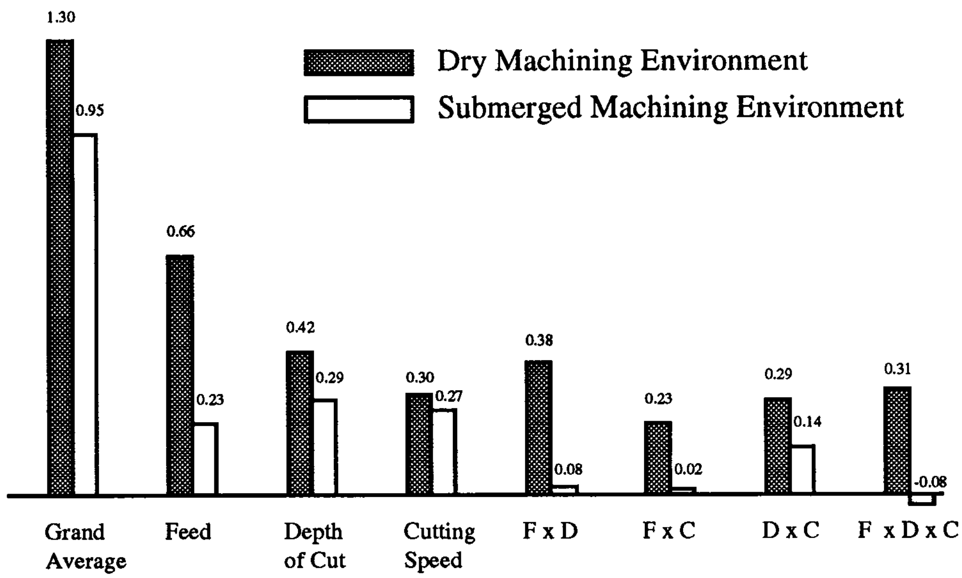


FIGURE 6 COMPARISON OF ESTIMATED EFFECTS BETWEEN THE DRY AND SUBMERGED MACHINING ENVIRONMENTS

in section 3 are shown in Figs. 7a and 7b for the dry and submersion environments, respectively. As specified earlier, the density values listed in Table 1 represent the crack densities evaluated at a distance of 1.7σ below the central plane. Arranging by a descendent order, the density values for the 8 machined surfaces under the dry machining environment are listed as follows:

Density: 7.0%→6.0%→5.5%→4.0%→3.5%→3.0%→3.0%→2.5%

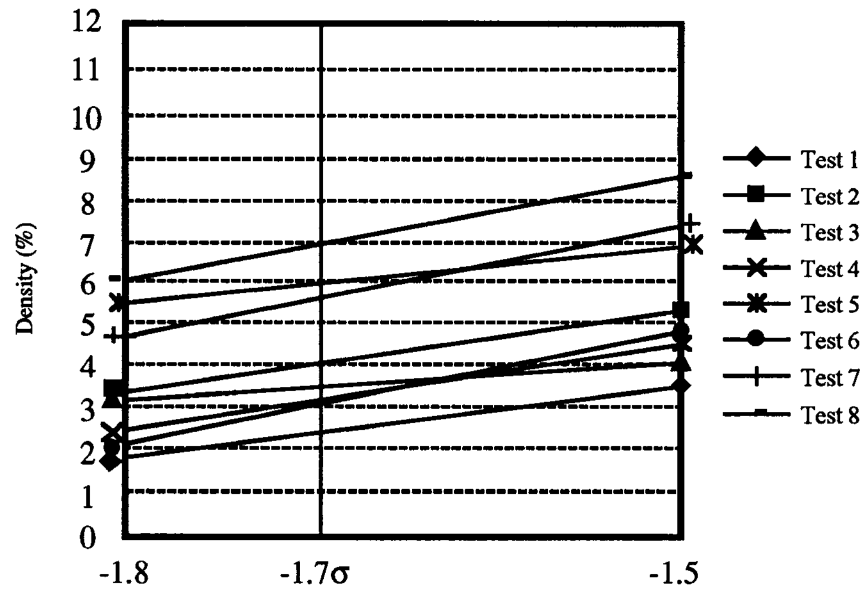
Test No. (8) (5) (7) (2) (3) (6)(4) (1)

It is not surprised that the highest density value of surface cracking is associated with the machining condition where the three machining parameters were set at the high levels, and the lowest density value at the three low levels. However, observations obtained from the data under the submerged machining do not follow the pattern observed under the dry machining environment. The measured density values for the 8 machined surfaces under the submerged machining environment are listed as follows:

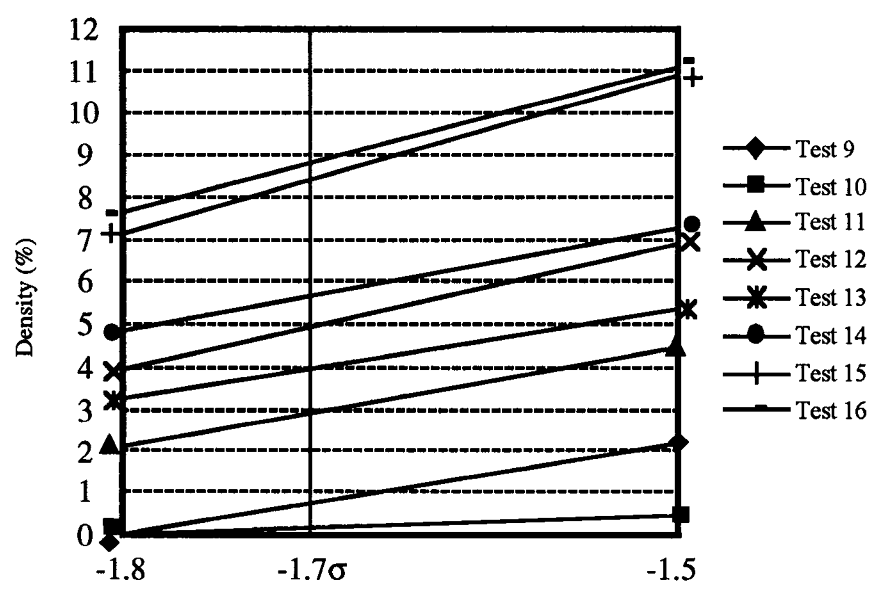
Density: 8.8%→8.5%→5.5%→5.0%→4.0%→3.5%→0.3%→0.1%

Test No. (16) (15) (14) (12) (13) (11) (9) (10)

These results show that, under the submerged machining, the density value of surface cracking decreases significantly at certain machining conditions only, such as Tests 9 and 10 where the crack density values have decreased from 2.5% and 4.0% to 0.3% and 0.1%, respectively. Note that the machining conditions for tests 2 and 10, which are set at low depth of cut and low cutting speed. Figures 5a and 5b present a comparison of the crack density formed during machining between tests 2 and 10. In Fig. 5a, the fractures are characterized by individual intergranular fractures with discontinuous propagation. In Fig. 5b, the fractures are characterized by individual intergranular



(a) Evaluated Densities of Surface Cracking (dry machining environment)



(b) Evaluated Densities of Surface Cracking (submerged machining environment)

FIGURE 7 DENSITIES OF SURFACE CRACKING AT LEVELS BELOW THE CENTRAL PLANE fractures with continuous propagation caused by striations. Under certain circumstances during service, these fractures are ready to grow and to gradually form cleavages. Therefore, depth of cut and cutting speed are the two key factors to control surface cracking during machining. It is important to note that a smooth surface after machining could have a relatively high surface cracking, such as the one obtained from Test 11 with R_a equal to 0.47 μm and the density of surface cracking equal to 3.5%. Therefore, combining the findings from assessing the finish quality and surface cracking, a balance has to be made between maintaining a smooth surface and a low density of surface cracking when setting machining parameters.

5. CONCLUSIONS

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 summarized as follows:

(1) Submerged machining demonstrates a better performance in terms of surface finish and 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 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.

(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.

ACKNOWLEDGMENTS

This research is part of the collaboration with the Dental School at UMDNJ. Special thanks are due Dr. E. D. Rekow for her firm support. The authors also acknowledge the support of the University of Maryland Research Board, the Department of Mechanical Engineering, and the Institute for Systems Research at the University of Maryland under Engineering Research Centers Program: NSFD CDF 8803012. The valuable assistance from Mr. Myron E. Taylor, Director of the Central Facility for Microanalysis, and Mr. D. T. Le is deeply appreciated.

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