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# Effect of machining on fracture toughness of corundum

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Different machining processes such as ultrasonic machining and grinding by a diamond wheel produce varying degrees of surface damage. The amount of surface damage appeared to be related to the type of machining process. However, the degree of surface damage could not be related to the surface roughness for different machining processes. The surface damage created by the machining process can be fully or partially recovered by heat treatment subsequent to machining. The degree of recovery by heat treatment seems to be dependent on the severity of the surface damage during the machining process. Observation of the surface microcracks and determination of the fracture toughness of the material after machining or heat treatment indicated recovery of some of the microcracks during the heat treatment.

## 1. Introduction

It has been well established that the surface condition of single-crystal alumina has a direct effect on its strength [1-3]. Machining operations, such as diamond wheel grinding, have been shown to affect the fracture strength of the material, primarily due to the introduction of flaws at or near the machined surfaces [1-4]. Surface flaws that result from conventional machining processes are typically scratches and cracks [1-3]. Sub-surface flaws may be produced by the same processes which include twinning and slip [4]. Such flaws are believed to be the consequence of the highly anisotropic structure of single-crystal alumina [4]. Owing to the anisotropy of the material, preferred planes of cleavage must be correctly oriented with respect to the cutting process so as to minimize the introduction of the aforementioned flaws during machining [4]. Additionally, it is believed that conventional machining methods result in residual surface stresses which also decrease the fracture strength of single-crystal alumina [2, 3]. The effect of such flaws on or near the surface of single-crystal alumina has been found to be decreased by various post-machining surface treatments [1–3]. The present study has the most interest in heat treatments which result in improvements in surface condition. Heuer and Roberts [2] demonstrated that heat treatment of single-crystal alumina at 1800° C in a hydrogen atmosphere increased the room-temperature strength of the material by approximately 20%. The observed increase in room-temperature strength was attributed to a favourable modification of the most critical surface flaws, which result from the machining process. It has also been further demonstrated that such heat-treatment procedures increase the fracture strength of single-crystal alumina by reducing residual surface stress caused by machining [3].

Based upon the preceeding discussion, it is therefore apparent that a synergy exists between machining methods used to form articles made of single-crystal alumina and heat treatment, as it relates to room-temperature fracture strength. The purpose of the present study was to examine the effect of various machining methods and a heat-treatment procedure of the fracture strength of single-crystal alumina. Three-point-bend specimens machined by methods which potentially would yield varying degrees of damage to the specimen surface were used. The machining methods employed included abrasive means such as diamond filing, grinding, and an erosion process based upon ultrasonic machining.

## 2. Experimental procedure

The material studied by this investigation is commercially available single-crystal alumina, synthetically grown by the Czochralski process. The material was supplied as discs having a diameter of 112 mm and a thickness of 2.3 mm. The specimens were ground from the discs parallel to the *R* plane using a resin-bonded diamond wheel (40 to 60 $\mu$m diamond particles in a 50% resin matrix by weight), at a feed rate of 0.5 cm sec$^{-1}$ using a water-soluble oil coolant. A notch was then formed using one of three techniques: (1) diamond filing (150 $\mu$m metal-bonded diamond particles); (2) diamond wheel grinding (40 to 60 $\mu$m diamond particles in a 50% resin matrix by weight); and (3) ultrasonic machining (40 to 60 $\mu$m boron carbide particles in a 50% by weight water slurry at a machining frequency of 20 kHz). The ultrasonic machining method is a more recent and potentially less harmful process based upon erosion. The basis of such a machining method is to accelerate particles in the slurry by tools which are coupled to an ultrasonic horn at a nominal frequency of 20 kHz. The tool used possesses the negative form of the part or cut to be made. The work piece is submersed in a slurry of

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TABLE I Summary of heat treatment used for fracture specimens

| |
|---|
| Atmosphere: |
| high-purity (99.999%), dry hydrogen |
| Molybedenum boats |
| Ramp: |
| pre-heat at 1000° C for 10 min |
| heat at 1920° C for 12 h |
| cool to room temperature |

boron carbide. The particles of boron carbide are accelerated by the energy supplied by an ultrasonic convertor, passed through a horn and directed by the tool. The impact of the particles chips away the work piece thus yielding a machined surface. A more complete description of the process is provided elesewhere [5–7].

The specimens were tested in both the machined and heat-treated conditions. The heat treatment used is summarized in Table I. The sequence used for the manufacture and heat treatment of specimens is contained in Table II. All specimens were subjected to a standard post-machining heat treatment (i.e. heat-treatment sequence S2) with the exception of one specimen group. This group was subjected to a sequence of pre- and post-machining heat treatment (i.e. heat-treatment sequence S3).

Fracture strength was measured using three-point bending. The specimens possessed a rectangular configuration with the following dimensions; 0.23 cm × 0.23 cm × 2.54 cm. The tests were conducted at 23° C and 50% r.h. The flaw dimension of the precracked specimen was measured after cleavage usisng a calibrated microscope. Calculation of the fracture toughness was accomplished using the equation

$$K_{IC} = \sigma(\pi a)^{1/2} f(a/w) \quad (1)$$

where

$$\sigma = \frac{3PS}{2B(w^2)} \quad (2)$$

$$f(a/w) = 1.11 - 2.12\,(a/w) + 7.71\,(a/w)^2 - 13.55\,(a/w)^3 + 14.25\,(a/w)^4 \quad (3)$$

$\sigma$ is the fracture stress in bending, $P$ the load, $S$ the span, $B$ the specimen thickness, $w$ the specimen height and $a$ the flaw dimension.

## 3. Results

The results of the fracture study are summarized in Tables III and IV. The values given in each table are the average of ten test specimens, unless stated otherwise. Interpretation of results is based upon heat treatment and method of forming the precrack.

TABLE II Specimen identification with respect to pre-test conditioning

| Specimen identification | |
|---|---|
| S1 | Machine specimens → Machine notch → Test → |
| S2 | Machine specimens → Machine notch → Heat treatment → Test → |
| S3 | Machine specimens → Heat treatment →Machine notch → Heat treatment → Test → |

TABLE III Summary of three-point-bend fracture stress test results. Tests conducted at 23° C, 50% r.h., span = 18.3 mm and cross-head speed = 0.025 mm min$^{-1}$.

| | $\sigma_f$ (MPa) $n$ = 10 |
|---|---|
| As-machined | 422 ± 110 |
| Heat treated | 450 ± 52 |

The observed fracture stress seemed to be fairly independent of heat treatment. Examination of Table III indicates that the average value of fracture stress for heat-treated specimens was approximately 7% greater than that observed for non-heat-treated specimens.

The standard deviation measured for the non-heat-treated specimens was approximately twice that measured for the heat-treated specimens. Such a result is in agreement with Heuer and Roberts [2], but is contradictory to that reported by Mallinder and Proctor [1] which may be related to differences in specimen configuration and machining.

Fracture toughness values obtained for conventionally machined specimens were generally in agreement with those reported by other investigators [4, 8–11]. Non-heat-treated ultrasonically machined specimens were also within this range. When the same specimens were heat treated by either heat-treatment sequence S2 or S3, the resultant fracture toughness was greater than those reported in the literature.

Table IV summarizes the values of the fracture toughness measured relative to heat treatment and method of forming specimen precrack. Specimens in which the precrack was formed by diamond filing exhibited an 18% increase when heat treated. When diamond wheel grinding was used to form the precrack, only a 4% increase in fracture toughness was observed. The values of fracture toughness measured for these two groups of specimens were within 0.5 MPa m$^{1/2}$ of each other. Heat treatment resulted in the greatest improvements for specimens in which the precrack was formed by ultrasonic machining. Utilization of the standard heat-treatment procedure (S2) yielded a 71% increase in fracture toughness. When the specimens were heat treated prior to forming the precrack by ultrasonic machining, the

TABLE IV Summary of three-point-bend fracture toughness test results. Tests conducted at 23° C, 50% r.h., span = 18.3 mm, and cross-head speed = 0.025 mm min$^{-1}$

| Method of precracking specimen* | Specimen identification | $K_{IC}$ (MPa m$^{1/2}$) $n$ = 10 |
|---|---|---|
| DF | S1 | 1.7 ± 0.3 |
| DF | S2 | 2.0 ± 1.0 |
| DWG | S1 | 2.3 ± 0.6† |
| DWG | S2 | 2.4 ± 0.1 |
| USM | S1 | 4.1 ± 0.7 |
| USM | S2 | 7.0 ± 2.3† |
| USM | S3 | 9.0 ± 0.9 |

*DF = diamond filing; DWG = diamond wheel grinding; USM = ultrasonic milling.
†$n$ = 13

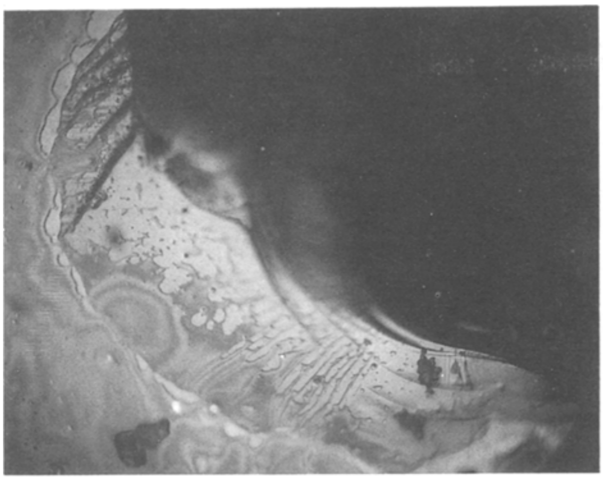

*Figure 1* Presence of microcracks on the edge of a notch ground by diamond wheel, as seen perpendicular to the direction of grinding. × 280.

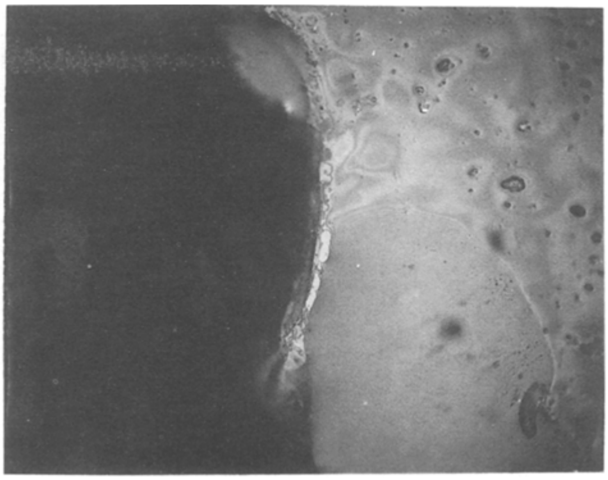

*Figure 2* Edge of a notch as seen perpendicular to the length of the notch, machined ultrasonically. No observable microcracks are present. × 280.

fracture toughness was improved by 120% when compared to non-heat-treated specimens. It therefore appears that the benefits possible with heat treatment, in terms of improved fracture toughness, are somewhat dependent upon how the precrack was machined into the specimen.

Comparison of fracture toughness on the basis of machining method used to form the precrack, indicates that specimens which were ultrasonically machined exhibited the greatest improvement in fracture toughness when compared to specimens which were machined by either filing or grinding. Specimens that were precracked by diamond filing exhibited average mean fracture toughness values of 1.9 and 2.2 MPa $m^{1/2}$ for as-machined and heat treated (i.e. heat-treated sequence S2) specimens, respectively. Heat-treatment produced a slight improvement in fracture toughness of the specimens machined by diamond wheel grinding having the mean values of 2.3 and 2.4 MPa $m^{1/2}$. Non-heat-treatment specimens in which the precrack was formed by ultrasonic machining exhibited a fracture toughness of 4.1 MPa $m^{1/2}$. Heat treatment of the ultrasonically machined specimens yielded a mean fracture toughness of 7.0 MPa $m^{1/2}$. When such specimens were heat treated prior to machining, then followed with the standard post-machining and heat treatment (i.e. heat-treatment sequence S3), the fracture toughness was found to be further improved, yielding a mean value of 9.0 MPa $m^{1/2}$.

## 4. Discussion

In the following discussion, it is assumed that the specimens used were free from micro or macro porosities induced during the manufacturing of single-crystal alumina. Although generally during the growth of single crystals, internal flaws frequently occur, variation in their net effect on the fracture stress values is considered indiscernible. Similar fracture stress values are indicated in Table III, which supports this assumption for specimens that have been machined by different processes. Hence, variation in fracture stress and fracture toughness of single-crystal alumina specimens can only be attributed to the superficial flaws introduced during processing by various cutting methods. Futhermore, the improvements in fracture toughness due to the heat treatment are believed to be related to the improvements in the quality of the surface or the immediate sub-surface of the material.

Stock removal of hard and brittle materials involves an impact between a harder particle which is present in the cutting media and the material which is being cut (in this case, single-crystal alumina). This process leads to continuous chipping and removal of material from the chipped surface. Each particle impact produces a host of microcracks around the point of impact. Fig. 1 illustrates the presence of such cracks as seen on the plane perpendicular to the direction of the cut in a specimen that was ground using a diamond wheel. Highly stressed areas around the cutting edge are also apparent. The extent of these microcracks depends on the size of the chip, which in turn is a function of the severity of the impact. Fig. 2 shows the cutting edge of a surface when produced by ultrasonic machining. It is obvious that relatively very little surface damage and no visible microcracks at this magnification have been introduced.

Although surface roughness of the ultrasonically machined specimens may be greater than those ground by diamond wheel, Fig. 3, the actual surface damage appears the be substantially smaller. Rougher surfaces are generally attributed to a more severe stock-removal process and surface damage. However, Heuer and Roberts [2] also concluded that the apparent surface roughness did not correlate with the strength of the material because the roughness was not representative of the superficial flaws. Table IV presents the fracture toughness values for the specimens in the as-machined condition (S1). It can be seen that ultrasonic machining provided fracture toughness values that are greater than those of diamond file or diamond wheel grinding by 141% and 78%, respectively. Considering that, in general, fractures initiate from a surface flaw (possibly microcracks on the surface), various values obtained for different cutting processes are believed to be due to the severity of the damage to the surface caused during processing.

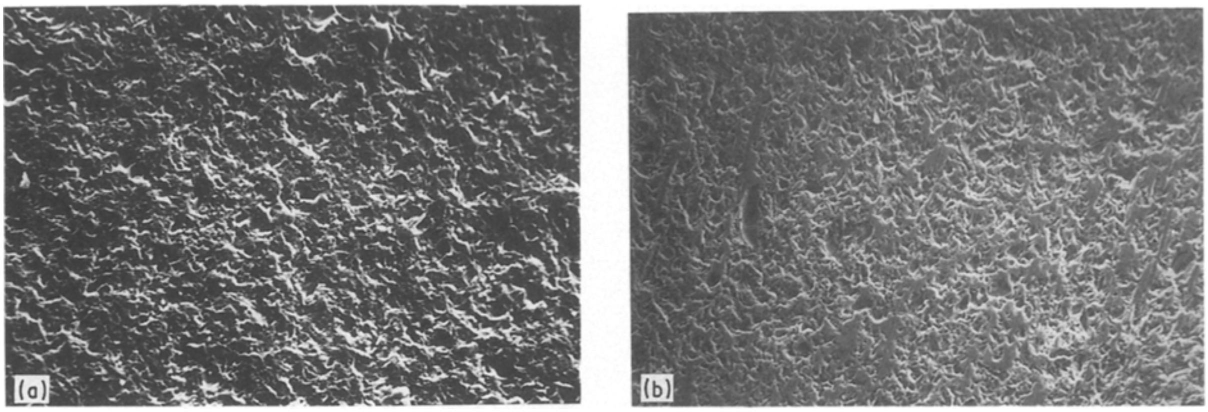


*Figure 3* Qualitative comparison of the surface roughness of: (a) ultrasonically machined surface; (b) ground surface using a diamond wheel.

Studies of fracture toughness of single-crystal alumina have demonstrated that heat treatment in the range between 1000 and 1800° C have resulted in improved room-temperature fracture toughness [2, 3]. Heat treatment results in the recovery of surface damage by: stress relieving of the highly stressed areas close to the cutting edge; elimination of dislocations resulting from plastic deformation near the cutting surface; topographical rounding of asperities; and healing of cracks [12]. It is well understood that elevated temperatures enhance the diffusion process in the direction at which the surface and bulk energies are decreased. Lower heat-treatment temperatures predominantly result in stress relieving and possible dislocation removal.

As the temperature is increased, diffusional activities also increase, thus yielding improvements in surface roughness and healing of superficial microcracks [12, 13]. High-temperature heat treatment is not expected to result in modifications in the crystal structure of single-crystal alumina (such as grain growth or introduction of microcracks due to the anisotropic expansion rate of the individual grains). Increasing heat-treatment temperature to the point where the predominant atomic mobility is bulk diffusion, may result in the recovery of microcracks that have extended well below the surface [11, 12]. Fig. 4 illustrates evidence of the healing of some of the microcracks that have been introduced by diamond wheel grinding, following the heat treatment at 1920° C for 6 h. It appears that the degree of recovery of the microcracks is dependent upon the crack size and the amount of the plastic deformation around that crack.

Table IV represents the values of fracture toughness obtained after the heat treatment of the precracked specimens. It can be seen that fracture toughness in all the specimens has been improved. The specimens with the highest initial fracture toughness (smallest surface damage) showed the greatest increase in fracture toughness following the heat treatment, while the specimens with small initial fracture toughness (more severe surface damage) showed small recovery.

Table IV presents the degree of recovery for various specimens. A significant aspect of the heat treatment was observed for the specimens that have been processed under condition S3. Although the behaviour of this set of specimens is not completely understood, it is believed that the heat treatment prior to precracking helps to eliminate the existing superficial microcracks, preventing their further propagation by subsequent machining, which in turn results in substantially higher fracture toughness values.

## 5. Conclusions

1. The ultrasonic machining method of cutting single-crystal alumina appears to have produced the

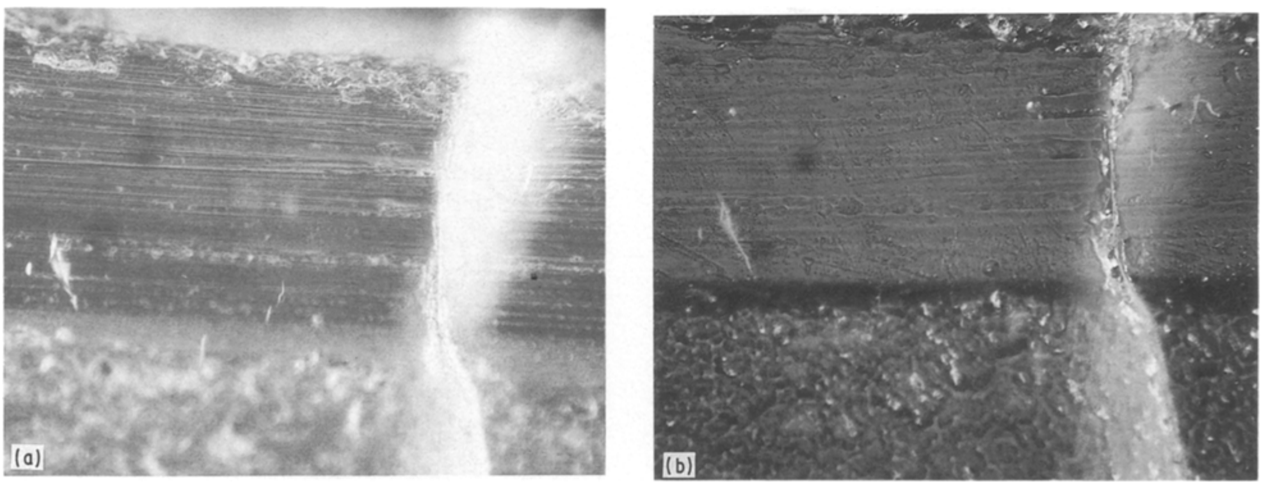


*Figure 4* Micro and macro cracks produced by diamond wheel grinding, are generally perpendicular to the direction of cutting, before (a) and after (b) heat treatment. × 35.

smallest surface damage to the material among all the processes tried.

2. Heat treatment of all the machined specimens improved surface quality and, hence, fracture toughness of the specimens.

3. The degree of fracture toughness improvement due to heat treatment depends on the amount of surface damage induced by the cutting process.

4. The greater the fracture toughness of the as-machined specimens, the greater is the increase in fracture toughness due to heat treatment.

5. Use of a diamond file with -100 mesh diamond particles produced the most severe damage to the surface, to the point that heat treatment could not appreciably recover the damage.

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