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INVESTIGATIONS ON THE PERFORMANCE OF ULTRASONIC DRILLING PROCESS WITH SPECIAL REFERENCE TO PRECISION MACHINING OF ADVANCED CERAMICS

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Abstract. Advanced ceramics are assuming an important role in modern industrial technology. The applications and advantages of using advanced ceramics are many. There are several reasons why we should go in for machining of advanced ceramics after their compacting and sintering. These are discussed in this paper. However, precision machining of advanced ceramics must be economical. Critical technological issues to be addressed in cost effective machining of ceramics include design of machine tools, tooling arrangements, improved yield and precision, relationship of part dimensions and finish specifications to functional performance, and on-line inspection. Considering the above Ultrasonic Drilling is an important process used for the precision machining of advanced ceramics. Extensive Studies on tool wear occurring in the ultrasonic machining of advanced ceramics have been carried out. In addition, production accuracy of holes drilled, surface finish obtained and surface integrity aspects in the machining of advanced ceramics have also been investigated. Some specific findings with reference to surface integrity are:

(a) There were no cracks or micro-cracks developed during or after ultrasonic machining of advanced ceramics.
(b) While machining Hexoloy Alpha Silicon Carbide a recast layer is formed as a result of ultrasonic machining. This is attributed to the viscous heating resulting from high energy impacts during ultrasonic machining. While machining all other types of ceramics no such formation of recast layer was observed, and
(c) There is no change in the micro-structure of the advanced ceramics as a result of ultrasonic machining.

1 INTRODUCTION

Today, advanced ceramics play an important role in modern industrial technology. There are two important sub-divisions of Advanced Ceramics; viz. Electronic Ceramics and Structural Ceramics.

Electronic Ceramics typically include resistors, capacitors, piezo electrics and semiconductors, optical fibres and other electronic devices. The recent applications of electronic ceramics include their use as superconductors. Beryllia doped Silicon Carbide ceramics have high thermal conductivity and strength and hence is particularly suitable for use in the higher integration circuits of super computers.

Structural Ceramics typically include High Alumina, Silicon Nitride, Silicon Carbide, Boron Carbide Carbide, SiALON, Zirconium Boride, Cubic Boron Nitride, Steatite and Super-plastic Ceramics such as Alumina-Yttria stabilized Tetragonal Zirconia.

Typeset by $\mathcal{A}\mathcal{M}\mathcal{S}$-TEX

The applications of structural ceramics are amazingly diverse and include turbine blades, turbine rotors, cutting tools and forming dies, Wear parts, bearings, seals, pump and valve components (valve plates, valve rods), engine components, heat exchangers, nuclear fuels, nose cones, missiles, pollution emission control devices, gas and humidity sensors, thermal barrier bearings, bio-medical ceramics (artificial teeth, hip joints), etc.

Unlike traditional ceramics, advanced ceramics have to be processed in clean conditions from pure raw materials such as Alumina, Zirconia, Silicon Nitride, Silicon Carbide, Tungsten Carbide, Boron Carbide, Boron Nitride etc. High quality ceramic powders are processed under precisely controlled operating conditions to produce Ceramic materials and components with exceptional properties.

Some of the Ceramics processing techniques include slip casting, tape casting, injection moulding, extrusion, plasma spraying, pressure sintering and Hot Isostatic Pressing (HIP). Since the quality of powders (i.e. purity and uniformity of particle size) determine the ultimate properties of the finished ceramic part, considerable research has been undertaken to develop new methods for powder preparation.

The Superplastic formation of Al_2O_3 -YTZ (Alumina-Yttria Stabilized Tetragonal Zirconia) ceramics is well established (Elongation up to 800% at 1550°C) Nich [1]. This has potential applications in aerospace and metal industries. Above a certain temperature, rapid diffusion occurs around the grains of submicron-ceramic powders, aided by the glassy phase formation. The grains become mobile sliding over one another under the application of pressure. Thus it is possible to shape ceramic parts by forging them like metal.

Advantages of using advanced ceramics are many. Advanced Ceramic materials possess high strength at elevated temperatures, corrosion resistance, lighters in weight, tough, wear-resistant and give improved component performance.

2 VERIFICATION OF THE MECHANISM OF MATERIAL REMOVAL IN ULTRASONIC DRILLING

The mechanism of material removal in Ultrasonic Drilling process can be studied by the Surface Integrity approach in addition to the other approaches. According to Field and Khales [2] Surface integrity is the sum of enhanced surface and sub-surface conditions or properties of the work material left after machining.

In ultrasonic drilling, the cavitation or hammering action of the abrasives is the energy principally responsible for material removal. The work material is removed as tiny particles. This is confirmed by SEM (Scanning Electron Microscope) analysis (Figure 1). Ultrasonic machining technique is very useful in producing complex hole configurations in hard and impact brittle materials such as advanced ceramics and in the machining of blind holes, etc. Though stock removal rates by ultrasonic machining are low compared to conventional machining of ceramics like diamond machining and diamond grinding, the technique competes on the basis of shapes producible and ability to machine materials that cannot be machined by either normal or other non-conventional processes.

In the beginning when the process was developed it was believed that in ultrasonic machining, the material removal was only by brittle fracture. Therefore, it was thought that only brittle materials could be machined by this process. However, it has since been observed by an analysis of the samples of the slurry containing the debris of the process that chips are formed by plastic deformation indicating that ductile fracture can also take place in ultrasonic drilling, Pentland and Ektermanis [3]. Thus the range of materials that can be machined by ultrasonic drilling is not restricted to the hard and brittle materials

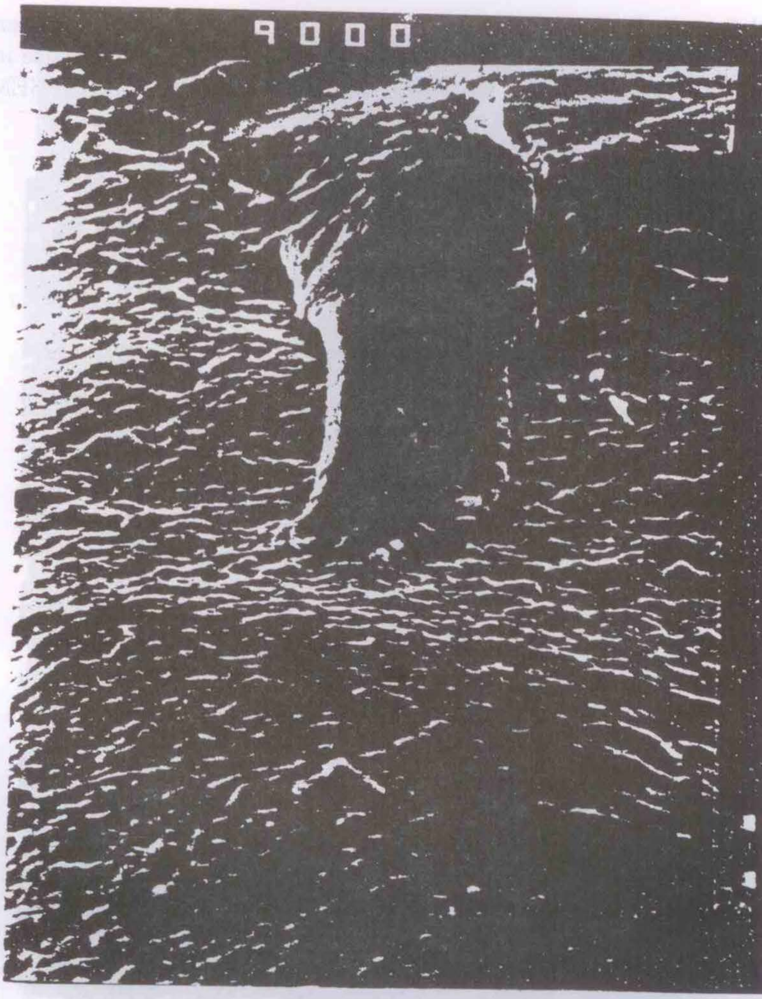

Fig. 1 SEM analysis: work material is removed in the form of tiny particles (Magnification: X300)

only though the soft and ductile materials can be cut more easily and economically by conventional machining methods. However, ultrasonic machining of ductile materials is always associated with higher tool wear, Adithan [4].

Riddie and Roch [5], Bulat [6]. and Willard [7] reported that the cavitation bubbles formed during ultrasonic oscillations produce an intensity of pressure more than 1000 kgf/cm^2 on the workpiece surface when the bubbles collapse. This pressure rise is responsible for certain material removal. The theory developed by Shaw [8] has a number of limitation, e. g. it does not correctly predict the effect of variation of amplitude of tool vibration, static load i. e. feed force and frequency of vibrations on the MRR (Material Removal Rate). When static load is increased, the material removal rate decreases, because the abrasive grains get crushed under increases up to a certain limit, thereafter, material removal rate high static loads and also the vibrations get damped. This has been confirmed by Adithan [4], Saha, Bhattacharya and Mishra [9]. Abrasives after their use in the ultrasonic drilling process were collected, dried and photo-micrographed on the SEM and their size was found reduced as shown in Figures 2 and 3.

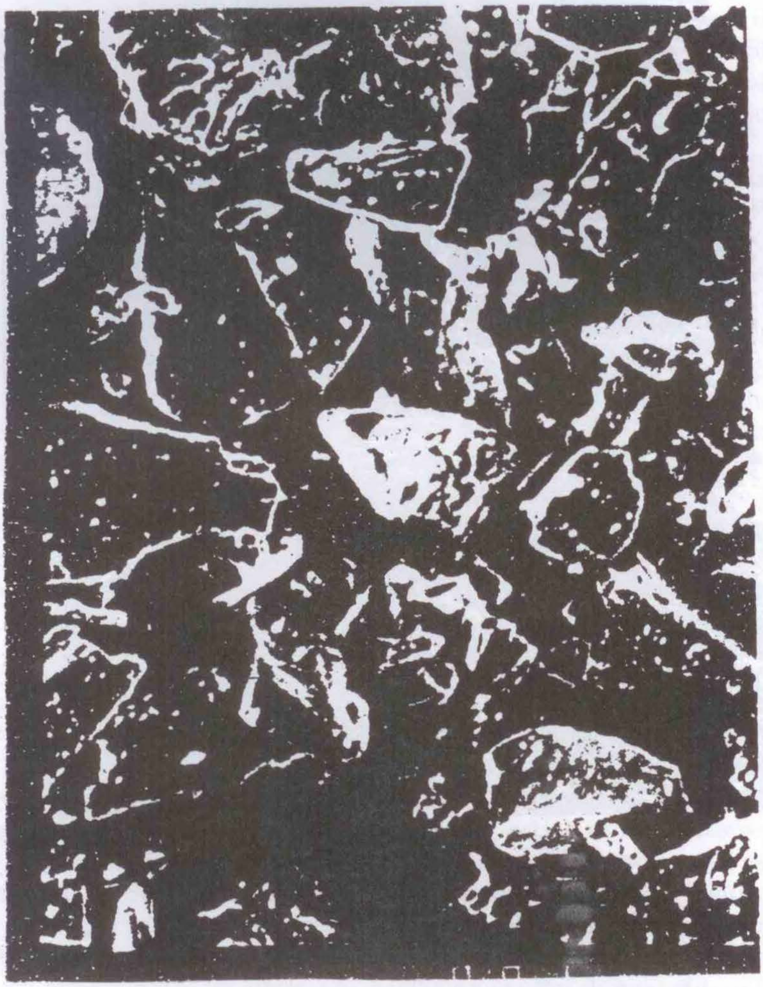

Fig. 2 Fresh Silicon carbide abrasives (Mesh No. 180) (Magnification: X300)

3 NEED FOR MACHINING OF ADVANCED CERAMICS

There are many reasons why we shall go in for machining of advanced ceramics after their compacting and sintering:

(a) During the sintering process shrinkage of the ceramics cannot be entirely avoided, hence to achieve closer tolerances and dimensional accuracies of parts.

(b) Side holes, slots and grooves are required to be incorporated as secondary operations since these configurations are difficult to obtain during compacting and moulding.

Fig. 3 Silicon carbide abrasives after their usage in ultrasonic machining (Rounding of corners of abrasives can be obserbed) (Magnification: X300)

(c) The manufacturing process has to accommodate limitless diversity of through holes, blind holes, odd shapes and contours for production of complex and intricate ceramic parts.

(d) For slicing into small pieces and thin wafers.

Considering the above ultrasonic drilling is an important process used for the precision machining of advanced ceramics. However, precision machining of advanced ceramics must be economical. Technical issues to be addressed in cost effective machining of ceramics include design of machine tools, tooling arrangements, improved yield and precision, relationship of part dimensions and finish specifications to functional performance and on-line inspection, Deckman [10].

Ultrasonic machining process is also used for manufacturing high quality electrodes required for EDM. In the case of intricate and complex shapes. Another interesting application area is the cutting of thermoplastic or combined natural-thermoplastic issues. Clean cuts are obtained because the ultrasonic vibrations melt the material and at the same time "weld" the particular cut fibres together. This techniques can be applied in direct combination with the operation of weaving looms. Another recent application is the cutting of Kevlar Composites and rubber.

4 TOOL WEAR IN MACHINING OF ADVANCED CERAMICS

Holes drilling and slitting operations were carried out on three types of ceramics viz. Steatite (MgO SiO_2), High Alumina (Al_2O_3) and Hexoloy Alpha Silicon Carbide (SiC).

With Steatite machining only the longitudinal wear was present and the lateral wear was almost negligible. The final wear profile was obtained after a number of holes were drilled as tool wear was small.

When High Alumina was machined both longitudinal and lateral wear values were appreciable and these were measured and plotted. The ultimate wear profile was obtained immediately after a few holes were drilled as tool wear was a considerable amount. Through the progressive wear of the tool the ultimate wear profile was being pushed up parallely. This tool profile was maintained during subsequent drillings.

When holes were drilled in Silicon Carbide work material both longitudinal and lateral tools wear values were very high as compared to machining of other ceramic work materials.

Thus it has been established that longitudinal tools wear propagation curve when Silicon Carbide material is machined is similar to the flank wear growth with respect to time in turning or wear curve in conventional drilling or grinding operations. The propagation of tool wears with respect to cutting time follows a mathematical model of the form:

$$\text{Longitudinal tool wear (in mm)} \propto Ct^n \qquad (1)$$

where C is a constant

t is cutting time in minutes

n is an exponent

The value of the constant C and the exponent n can be obtained as mean square values from individual test results. The analytical expression in the form of Equation (1) is the best approximation of the wear progress which holds good up to the point which indicates the start of tool breakdown. It is found that the magnitude of the parameters C and n depends on tool and work material combination, static load, cross section of the tool, tool material and amplitude of vibrations. (For the conditions cited in the experimental work, Table 1, the value of $C = 0.005$ and $n = 1.25$.)

The higher the static load the higher is the tool tip pressure or stress. At higher static loads the tool tip pressure is greater for tools of smaller cross-sectional area. Generally tools wear increases with static load.

Stainless steel tools suffer less lateral wear when compared with most of the other tool materials. This is due to the high resistance provided by stainless steel tool material against cavitation erosion.

Tools wear rate is proportional to the wear that has already taken place. Further wear of the tool and wear rate depends on this wear as well as initial irregularities present on the tool.

Table 1.

Work Materials	:	Silicon Carbide, High Alumina & Steatite
Work material thickness	:	2 mm
Abrasive slurry	:	Silicon carbide + Water (1:4 by weight)
Grit No.	:	280 (Mean grit size = 50 microns)
Depth of Holes Drilled	:	2.00 mm
Tool material	:	Stainless Steel
Tool size	:	4mm dia., Solid Tool, Cross sectional Area: 12.56 Sq. mm
Static load	:	3.25 kg.

Work material	Machining time (min.)	Longitudinal Tool Wear (mm)	Relative Tool Wear (%)	Machining Rate (mm^3/min)	Relative Machining (%)
Steatite	2.00	0.05	1%(BASE)	12.560	100(BASE)
Silicon Carbide	20.00	0.26	5.2	1.256	10.0
High Alumina	8.00	0.15	3.0	3.140	25.0

It is also found that the tools wear rate depends on the static load applied during ultrasonic drilling. Tools wear rate increases as static load increases up to a certain limit and then it decreases.

It has been established that higher machining rates result in almost a constant machining ration (Machining ratio = Material removal rate / Tool wears rate) and higher tools wear rates. For Silicon Carbide work material with a Stainless steel tool a machining ratio of 25 to 35 can be easily achieved, whereas for High Alumina and Steatite work materials with Stainless Steel tools the machining material with Stainless Steel tools the machining ratio obtained was only 3 and 10 respectively.

5 INFLUENCE OF TOOL WEAR ON MACHINING RATE

It is found that machining ratio increases with the hardness of the tool on account of the fact that harder tools deliver higher impact blows to the abrasives. Tool wear is also less with harder tools. Hence we obtain higher machining ratios for a given work material with harder tools. The plots (Figure 4) show lower machining ratios for Silicon Carbide and High Alumina work materials as compared to Steatite work material.

Thus for a given tool wear, the total length of holes drilled or the number of holes

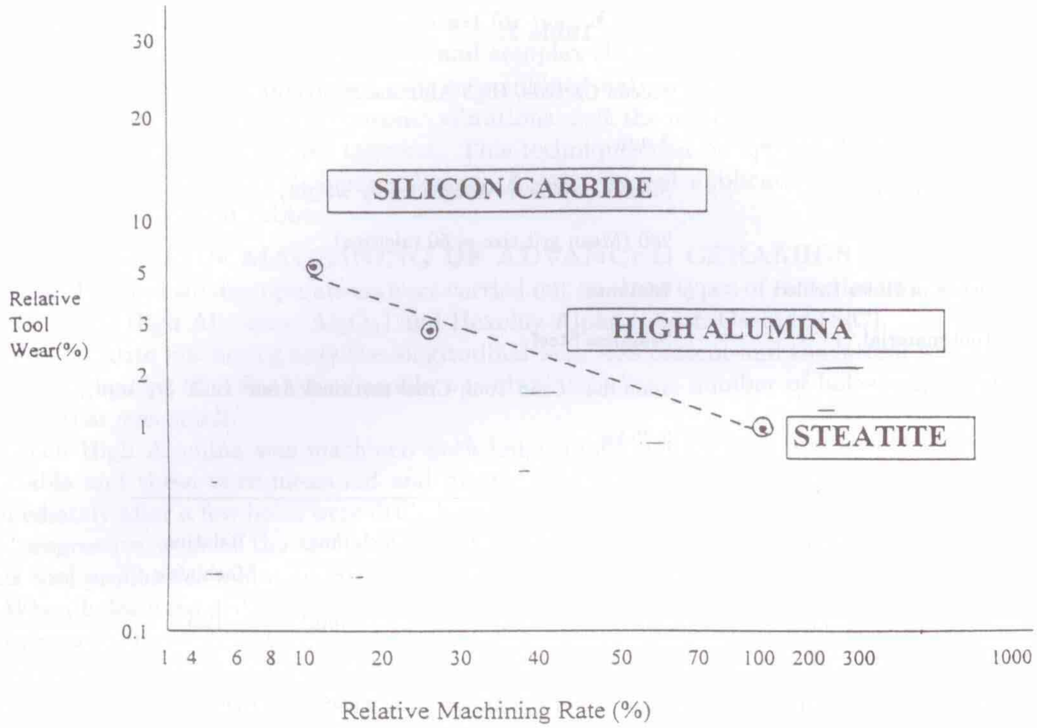

Fig. 4 Relative tool wear (%) vs. relative machining rate (%) (based on observations in Table 1)

drilled using the same tool without any appreciable loss of machining rate can be predicted accurately.

When a number of holes are successively drilled in advanced ceramics, such as Silicon Carbide, High Alumina and Steatite work material using the same tool three distinct phases of cutting action of tool were observed:

(i) As soon as the first hole is drilled, there is a considerable reduction in the machining rate. This is due to the onset of initial tool wear;

(ii) A gradual working up of the tool occurs which keeps the machining rate almost at a constant level; and

(iii) Further drillings result in an appreciable decrease in the machining rate.

Thus it is concluded that when the holes are successively drilled using the same tool, the reduction in the machining rate depends upon the extent of tool wear that has already occurred on the tool.

6 PRODUCTION ACCURACY OF HOLES DRILLED IN ADVANCED CERAMICS

Oversize of the holes produced mainly depends on the grain size of the abrasives used in the slurry and the work material. An oversize equal to two times the mean grit diameter of the abrasives used can be predicted under optimum machining conditions.

Out-of-roundness of the hole is due to the formation of longitudinal ridges on the side surface of the hole in the workpiece. The reasons are as explained below:

> Cavitation and slurry flow initially produce grooves on the tool and these grooves are reflected on the workpiece as a sort of ridges. Grooves on the tool surface are also caused by bending or flexural vibrations of the tool which causes the abrasive particles to move up and down the tool resulting in grooves. Such grooves were observed on the tools after their use in ultrasonic drilling in the present investigations also. These flexural vibrations of the tool are also responsible to some extent for oversize holes produced in ultrasonic drilling.

It is found that actual value of oversize obtained varies from 4 to 5 times mean grit diameter of the abrasives used for machining. Theoretical value of oversize = 2 times mean grit diameter of abrasives used. The actual oversize values are more than the theoretical values for the following reasons.

There are always some lateral or side vibrations. These are due to the Poisson-ratio effect for transverse vibration's amplitude. The transverse vibrations occur at the same frequency as the longitudinal vibrations. Thus lateral or side vibrations cannot be entirely avoided. Also during the assembly of the feed mechanism of the USD machine, though all precautions are taken by proper mounting and clamping of the acoustic head viz. the trunk and the transducer to the supporting plates and the machine frame at a nodal plane, due to certain design limitations, transmission of lateral or side vibrations cannot be entirely suppressed. Some side vibrations are also due to eccentric brazing or incorrect setting of the tool tip to the shank. These side vibrations also result in increasing the oversize of the holes produced. It is also observed that the actual value of oversize of the holes obtained by various investigators is much more than what they predicted, Adithan and Venkatesh [11].

The following are the findings in respect of production accuracy of holes obtained in the present investigations:

(a) ORR (Out-or-Roundness) of the hole produced at the exit face is always greater than that produced at the entry face of the hole.
(b) The diameter of the hole at the entry side is always larger than that at the exit side, and for a given thickness of the workpiece, the difference in the diameters at the entry and at the exit gives the taper for conicity) of the holes produced.
(c) For an analysis of the oversize of the holes produced, it is necessary that the tool wear dimensions (Lateral wear values) are taken into consideration.

Tools of different diameters were used to study the influence of diameter on the oversize of the holes produced. It is found that while silver brazing was done for small diameter tools some eccentricity always occurs while brazing of the tools on the shank. This eccentricity leads to increased side vibrations. With large size tools this problem was reduced considerably. It was found that in some cases oversize in respect of small holes was comparatively more than that with large sized holes.

There is an indirect relationship between low machining rates and large oversize. From the experiments it is established that oversize produced in drilling Silicon Carbide work material is more than that with High Alumina and Steatite work materials. In respect of Steatite work materials. In respect of Steatite work material oversize was less than that obtained with High Alumina.

7 SURFACE INTEGRITY INVESTIGATIONS IN THE MACHINING OF ADVANCED CERAMICS

7.1 Work Material: Hexoloy Alpha Silicon Carbide ($\mathcal{L}$ SiC)

Several holes of diameters ranging from 1.5 mm to 7.5 mm were drilled in plates of Hexoloy Silicon Carbide of different thickness. These holes were cleaned with Acetone and later on Gold plated for 1 micron thickness for Surface integrity studies using Scanning Electron Microscope. The following were the investigations w. r. t. surface integrity.

(a) While machining holes in Silicon carbide work material, no cracks or microcracks developed during or after ultrasonic machining.

(b) A recast layer is formed as a result of ultrasonic machining of Hexoloy Alpha Silicon Carbide work material (Figure 5) This is due to the viscous heating resulting from high energy impacts during Ultrasonic drilling. High energy impacts cause considerable increase in the workpiece temperature resulting in the formation of a recast layer.

(c) No definite material structure was formed during or after the ultrasonic machining of Hexoloy Alpha Silicon Carbide material. In other words, there is no change in the microstructure of the work material as a result of ultrasonic machining.

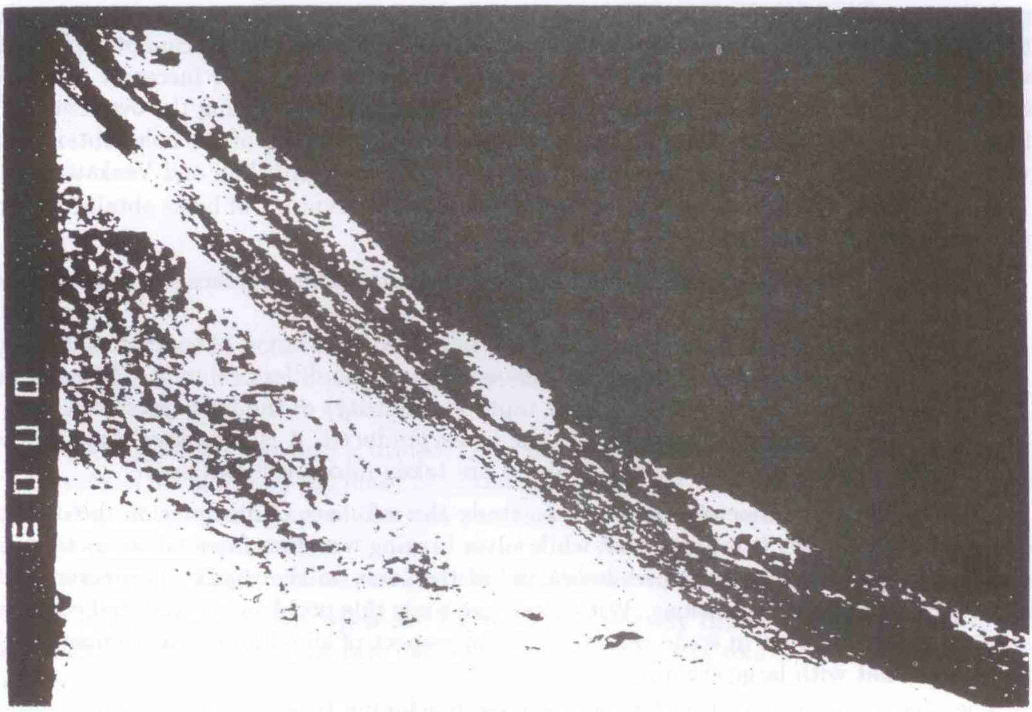

Fig. 5 SEM showing formation of recast layer while machining Hexoloy Alpha Silicon Carbide work material.

7.2 Work Material: High Alumina (Al_2O_3)

Holes drilling and slitting operations were carried out ranging from 1.5 mm dia. to 7.00 mm dia. in plates and workpieces of different thickness. SEM studies reveal the following:

(a) While machining holes in High Alumina work materials, no cracks or microcracks developed.

(b) There is no formation of a recast layer during or after the ultrasonic machining of High Alumina work material.

(c) There is no definite change in the microstructure of this work material also. However, Figure 6 shows the original microvoids present which were/are left during compacting and sintering process. (These microvoids may lead to microcracking at some stage of working of these materials.)

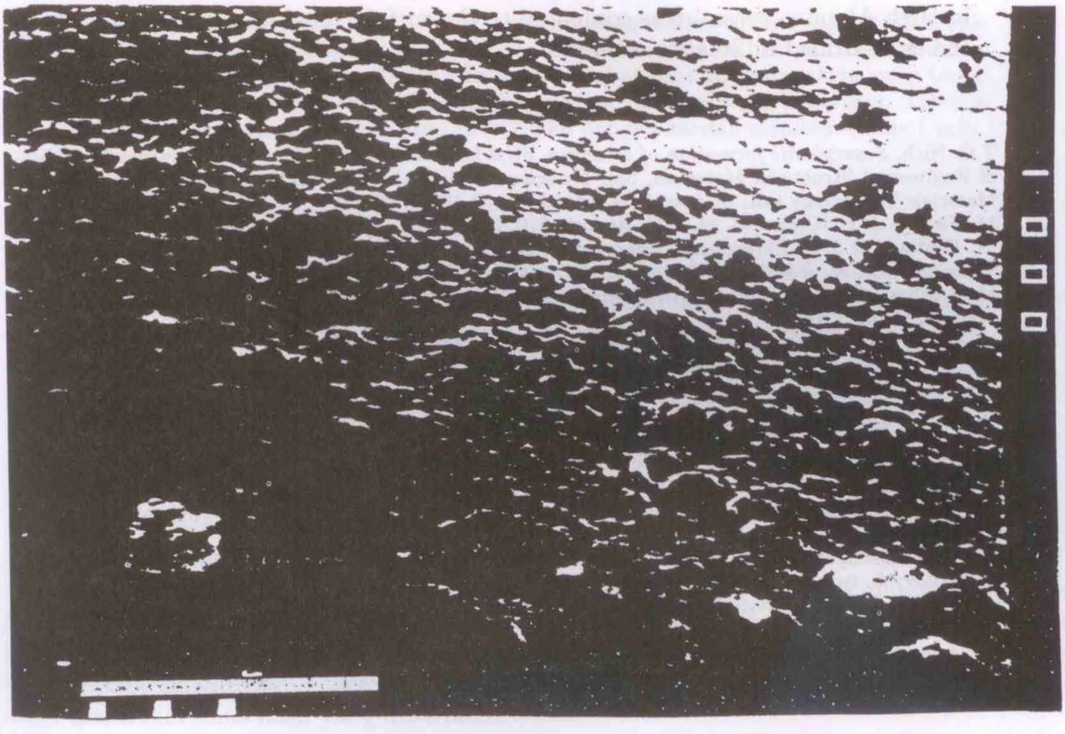

Fig. 6 SEM showing the microstructure (X300) at the inside of the wall of the hole drilled.
Tool material: Stainless Steel
Work Material : High Alumina Ceramic.

7.3 Work Material: Steatite ($MgO.SiO_2$)

Ultrasonic cutting, slitting and drilling of holes of various shapes (rectangular and square) were done on steatite work material. Hole size ranged from 1.5 mm to 7.0 mm in diameter. SEM studies reveal the following:

(a) While machining holes during slitting operations no cracks or microcracks developed.

(b) No Recast layer is formed as a result of ultrasonic machining.

(c) No definite alteration in the work material structure.

8 RESULTS OF SURFACE ROUGHNESS INVESTIGATIONS

(a) Surface roughness value increases with the increase in material removal rate.
(b) The finer the abrasives used in the slurry, the less is the surface roughness produced.
(c) Surface roughness values were less at entry of the hole when compared with the surface roughness values obtained at the exit of the hole.
(d) Surface roughness values were less, both at entry and at exit of the holes machined in Hexoloy Alpha Silicon Carbide work material when compared with the surface roughness values obtained on the hole drilling in High Alumina and Steatite work materials.
(e) Surface roughness values were less, both at entry and at exit of the holes machined in High Alumina ceramics as compared to the surface roughness values obtained on the holes drilled in Steatite ceramics.

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