Journal of the European Ceramic Society 23 (2003) 1005–1011
www.elsevier.com/locate/jeurceramsoc

Machining behaviour of green gelcast ceramics

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Received 15 June 2001; received in revised form 8 July 2002; accepted 14 July 2002

Abstract

Green gelcast alumina samples containing binder and samples prepared in bisque fired conditions were subjected to three machining operations—drilling, grinding and milling. Forces were measured during grinding and milling. Drilling of binder-containing samples indicated rapid wear of HSS tools while carbide tools could be used without significant wear. Bisque fired samples required lower force for grinding. Tangential and normal forces during grinding increased rapidly with successive passes due to clogging of the wheel. Increase in forces was much more rapid for binder-containing samples and for higher depth of cut. The rise in grinding force with increase in binder content correlated with the observed increase in Vickers hardness number of the green samples. During milling the tangential force increased with slight wearing of the tool. Material removal during grinding was in the form of large binder-powder aggregates for binder-containing samples, in smaller powder particle clusters for bisque fired samples. During milling of binder-containing samples, the material came out in the form of long chips.

Keywords: Al_2O_3; Finishing; Machining; Shaping; Suspensions

1. Introduction

Besides the need for ceramic components with greater complexity in shapes, the driving force for machining of ceramics in the green (unfired) state has been its significantly lower energy requirements, lesser tool wear and high material removal rates. Due to the above reasons, green machining of ceramics has been practiced on a commercial scale through several different operations including drilling, grinding, milling, single point turning on a lathe and others, in contrast, grinding is almost the only used operation for the machining of sintered ceramics.

Grinding has been used as a machining operation in the fabrication of ceramic sensors and spark plugs but it is more of a finishing operation, which involves little material removal. For large material removal, milling or even single point machining on lathe machines become the preferred machining operations.

Research in the field of machining of green engineering ceramics is still extremely limited[1] and is in a stage of infancy as far as the machining of gelcast ceramics is concerned. From the available literature and preliminary studies conducted, the following important material and machine parameters are known to influence the machining behaviour of green ceramic compacts—the binder content, the nature of the binder, the particle size and distribution of powders, the nature of agglomerates, the solids loading of the slurry, the density and strength of the green compact and bisque fired parts, the tool speed during machining, the feed rate of machining, the depth of cut.

A study on pressed compacts predicted that green ceramic compacts were better machined if they had low pressed strength as compared to high pressed strength, in which case edge retention was found to be a problem.[2,3] The mechanism of material fracture during machining changed form interagglomerate fracture to a mix and then to predominantly transagglomerate fracture with increase in compaction pressure.

Even though the gelcast ceramic samples have low binder content (3–5 wt.%) they typically had strengths near 3 MPa which is higher than for the samples prepared by other forming methods.[4] Nunn et al. have shown that the gelcast samples could be easily machined using carbide tools with negligible wear while the tool steels wore out rapidly. In the study on green machining of gelcast samples they also found that samples with

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0955-2219/03/$ - see front matter
PII: S0955-2219(02)00265-0

lower strength binder could be machined to better surface finish. Material removal during machining of all gelcast ceramics occurred in the form of turnings or shavings while a minimum amount of dust was generated.[4]

Another study on machining of gelcast compacts on a lathe machine demonstrated that compacts containing large bubbles—of the order of 100′s of microns—could not be machined to a good surface finish. The bubbles in the samples encouraged random fractures at the surface being machined or sometimes fracture originated at the sites where the sample was gripped during machining.[5]

In the present study three material removal operations—drilling, milling and grinding were studied (Fig. 1). The objective of the study was to evaluate the suitability of HSS tools in drilling and to study the grinding and milling behaviour of green gelcast ceramics including measurement of forces during the operations. Future studies will attempt to correlate the mechanical properties of the materials considered here with their machining behaviour.

2. Experimental

2.1. Sample preparation

An aqueous premix of water-soluble monomer, methacrylamide (MAM) and cross linker, methylene bis acryl amide (MBAM) in 6:1 ratio, was used to prepare the slurries.[6] Darvan 821 A (polyacrylic ammonium salt, M.W. = 6000), a commonly used ceramic dispersant (1.16 g per hundred gram of alumina) was added to the aqueous premix followed by addition of the alumina powder and antifoaming agent (*n*-octanol). All samples were prepared with 45 vol.% alumina loading in the slurries and the powder used had a mean particle size of 0.64 μm. The slurry was mixed/milled for 24 h using zirconia grinding media (diameter ∼2–3 mm) and then kept at rest (idle) for 30 min followed by vacuum deairing. The following amounts of the initiator and catalyst respectively—1 μl of ammonium per sulphate (APS) and 0.5 μl of tetra methyl ethylene di amine (TEMED) per gm of slurry were mixed into the slurry. The slurry was then poured into wax or plastic molds and allowed to gel at room temperature. The samples prepared for drilling study were cylindrical (30 mm diameter and 10 mm height) and those for grinding and milling were in the form of rectangular bars ($65\times13\times5$ mm).

As the grinding wheel performance is known to be affected with the loose material generated during the operation,[7] samples with three different contents—15, 22.5 and 30 wt.% of the binder (MAM-MBAM) in the premix and a set of samples bisque fired at 900 °C (no binder) were prepared to study the effect of binder content on grindability. The density of the samples containing 15, 22.5 and 30 wt.% binder was respectively 2.13, 2.17 and 2.2 g/cc and the density of bisque fired sample was 2.7 g/cc.

2.2. Hardness measurement

The hardness of green samples containing binder and of the bisque fired sample was measured through Vickers indentations using 10 mg force (Table 2). Prior to indenting, all samples were lightly coated with marker pen ink to make the indentations clearly visible. All indentations were symmetrical and had the perfect diamond pyramid shape.

2.3. Machining

2.3.1. Drilling

The drilling experiments were carried out on a standard fixed drilling machine to compare the performance of HSS and carbide drill bits in drilling green gelcast samples. For each experiment a new drill bit was used and change in weight and effectiveness of drilling and the quality of the drilled holes was monitored. HSS and WC drill bits (1 mm diameter) were used to drill 10 mm thick alumina gelcast samples.

2.3.2. Grinding and milling

For grinding and milling experiments the rectangular, samples were mounted on to steel mounts by use of epoxy resin. This was done to facilitate the placement of

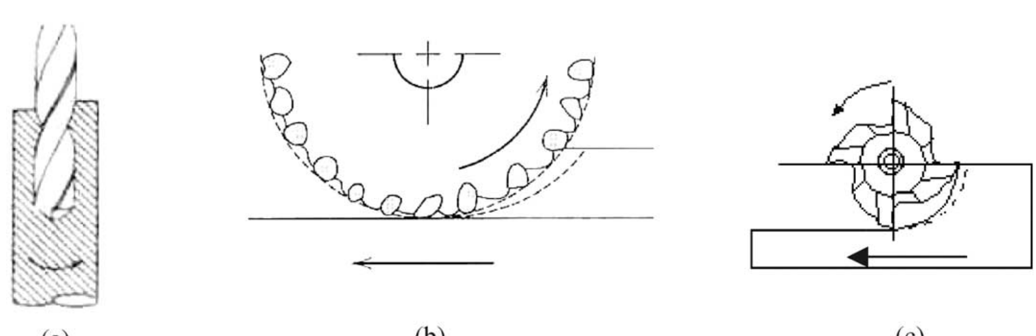

Fig. 1. Schematic of the three machining operations—(a) drilling (b) grinding (c) milling—used in the present study.

the samples in the machining fixtures. The samples on the steel mounts were mounted in a frame that was bolted to the Dynamometer (Kistler type 5011). This dynamometer was connected to a charge amplifier for displaying the forces in normal and tangential directions (Fig. 2). The grinding experiments were performed on a surface-grinding machine (Churchill Machine Tools Company Ltd., Manchester, UK) using a silicon carbide grinding wheel (GC 60-K5-VG, Carborundum Universal Ltd.). The milling was carried out on a vertical milling machine (Cincinnati Milling Machines Ltd., Birmingham, UK) using a high-speed steel (HSS) 5/8 inch end mill cutter.

3. Results and discussions

The primary concerns in this study on machining of green gelcast ceramic samples were the forces involved or the energy consumed, and the quality of surface produced. Forces—normal and tangential—were measured through the use of the appropriate set-up during grinding and milling operations while no such set-up was available for measuring forces during drilling. Although the same measurements were made during grinding and milling, a direct comparison has been avoided due to the fact that the two operations are used for different purposes.

The normal and tangential forces measured during machining in general are representative of the resistance to penetration and micro-fracture of the sample during machining of the surface. It is known that in general dense samples will offer greater resistance and thus require higher forces or greater energy consumption in machining. The machining parameters such as feed rate and depth of cut also have a strong influence on the forces during machining. Forces during machining in general increase with greater material removal rate as obtained by increasing feed rate and depth of cut.

3.1. Drilling

Using a HSS drill bit (1 mm diameter) a total of 12 holes were made in the alumina compacts and the loss of the weight of the tool was found to be negligible with no change in the diameter of the drill bit. However the tip of the drill bit was rounded off during this as indicated by increasing difficulty in drilling further holes. Any excess pressure to continue drilling further holes resulted in cracking and breakage of samples.

Similar drilling (1 mm diameter) was attempted using a WC drill bit and it was found that it could drill equal and even greater number of holes without any loss of material from tool or any loss in cutting efficiency.

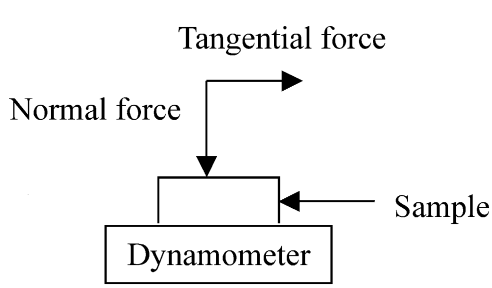

Fig. 2. Schematic of the forces measured during grinding and milling.

3.2. Grinding

Grinding was undertaken with the machining parameters listed in Table 1. The grinding wheel was dressed prior to use; by a diamond tipped dressing tool and this dressing was repeated prior to each set of the forces measurements for different samples.

The normal and tangential forces during grinding of the bisque fired samples were the lowest among all samples. Fig. 3 shows the tangential and normal forces recorded during grinding in the first five passes. Forces for only the first five passes were selected because as the material accumulation on the grinding wheel kept on increasing, the forces also kept on increasing rapidly causing over loading of the dynamometer amplifier especially in the case of the samples containing binder.

The forces increased with each subsequent cut apparently due to the powder getting lodged between the abrasive particles on the grinding wheel, thus clogging the wheel and reducing the cutting/grinding action. Other studies on machining of green ceramics have also reported similar clogging of the grinding wheel particularly during machining of components composed of submicron sized ceramic particles and binder(s).[8]

In the present study, with each successive pass the powder accumulated on the grinding wheel and the forces climbed up further. However, every time after a cleaning of the wheel was carried out using the bristles of a simple toothbrush the grinding forces returned to the original values of the first pass. This phenomenon was more pronounced in the case of the 50 μm cut as compared to the forces during a 25 μm cut. As grinding progressed, powder was also seen to be accumulating on the sample surface left behind after grinding. The powder accumulated on the surface could be removed simply by blowing air on the surface revealing the actual ground surface.

For green samples containing binder the forces recorded were higher and the grinding wheel clogged faster than it did in the case of the bisque fired sample. Fig. 3(a) and (b) show the forces during grinding of samples with 22.5 and 30 wt.% binder in premix. In the case of samples containing binder the removed swarf clogged the wheel and at the same time the binder burnt due to the frictional heat especially for the larger 50 μm depth of cut causing a brownish appearance of the ground surface.

Table 1
Machining parameters used for grinding and milling

	Grinding	Milling
Tool material	Silicon carbide	High speed steel (HSS)
Tool specifications	GC-60-K5-VG, Carborundum Universal Ltd.	Straight shank, end mill cutter
Tool dimensions	OD 125 mm, ID 31.75 mm, Thickness 13 mm	5/8 inch Outer diameter
Machine used	Surface grinding machine (Churchill machine tools)	Vertical milling machine (Cincinnati milling machines Ltd., Birmingham, UK)
Feed rate	18 ft/min	10 ft/min
RPM of tool	2390	178
Depth of cut	0.025 and 0.05 mm	1 mm (1000 μm)
Dynamometer used	Kistler instruments. Type 5011	Kistler instruments. Type 5011

The burning of the binder could also be detected from its typical smell.

The greater forces during grinding of samples containing binder were possibly due to the higher green strength of the samples and more effective clogging of the grinding wheel. The higher green strength of the samples containing larger amount of binder was evident from the relatively lesser deformation induced by indentation of the green samples at 10 mg force (Table 2). The indentation diagonal for the bisque fired sample was 180 μm while it was only 110 μm for sample containing 30 wt.% binder.

For 50 μm depth of cut, it was found that the grinding forces in the case of the sample with 30 wt.% binder (in premix) were higher by 4 times (tangential) and 6 times (normal) than those for bisque fired samples. The depth of cut had a direct bearing on the amount of deposition of swarf on the grinding wheel and the forces required. This effect of depth of cut was most clearly evident for samples with 30 wt.% binder (in premix)—for a 50 μm depth of cut the forces were found to be 120 N (normal) and 64 N (tangential) just after five passes while for the

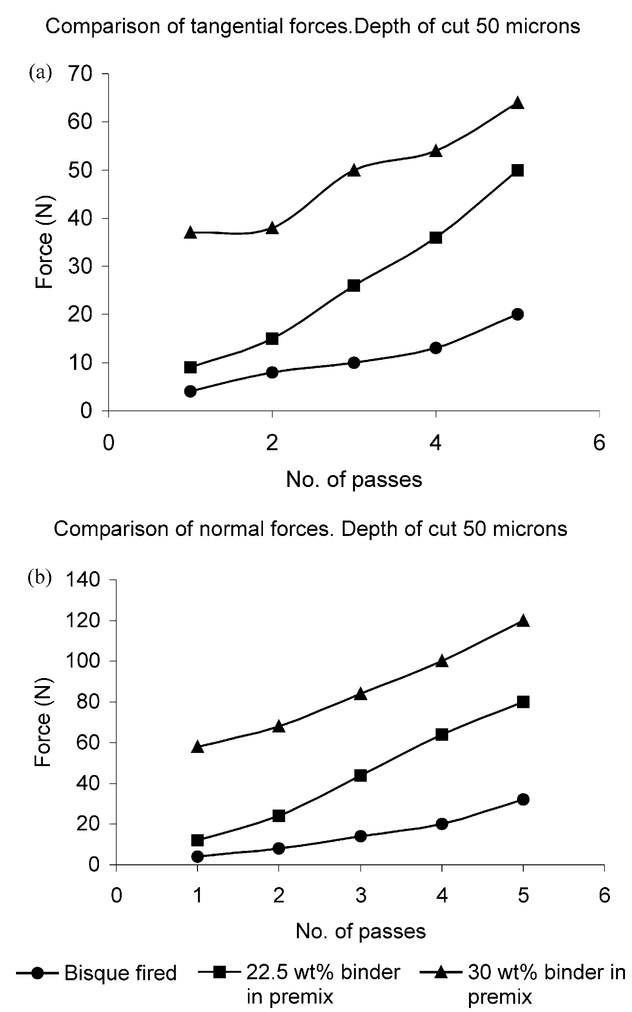

Fig. 3. Tangential and normal forces during grinding of green and bisque fired gelcast samples.

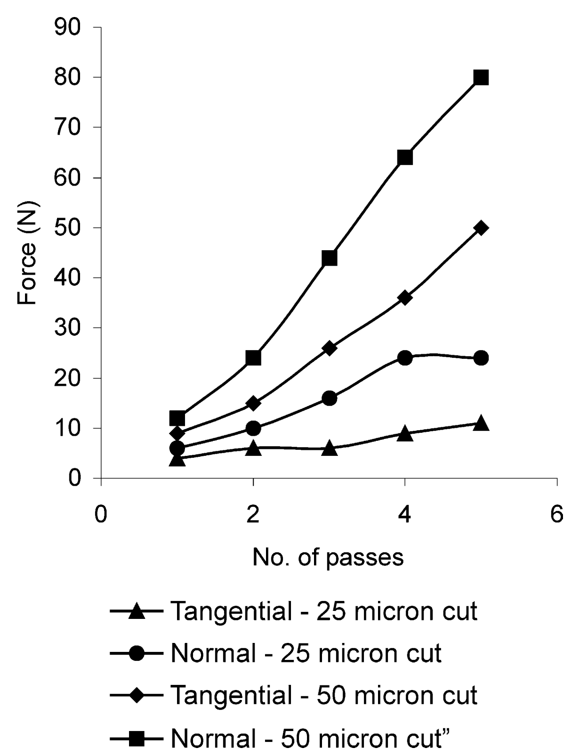

Fig. 4. Comparison of forces for 25 and 50 μm depths of cut during grinding of a gelcast sample containing 22.5 wt.% binder in premix.

25 µm depth of cut the forces got up to only 80 N (normal) and 42 N (tangential) even after 15 passes. Fig. 4 shows the comparison of forces recorded for grinding operations on the sample with 22.5 wt.% binder for 25 and 50 µm depth of cut. The ratio of tangential to normal forces was found to be 1:1.5 approximately in case of bisque fired samples and 1:2 in case of samples with binder, which is again due to the relative ease of clogging of the wheel during grinding of the samples containing binder.

The average roughness (Ra) of the samples was measured using telesurf (Taylor Hobson, Surftronic 3P). The roughness readings were taken in the direction perpendicular to the direction of traverse of the tool. Ten readings were taken on each sample at 1 mm interval and then averaged to obtain the readings for comparison. The average roughness (Ra) for 25 µm depth of cut was found to be minimum for the sample with 22.5-wt.% binder in the premix (0.35 µm). Next was the sample with 30-wt.% binder in the premix (0.48 µm) and the roughness was highest for the bisque fired sample (0.74 µm).

The roughness was lower in the case of the samples with binder because the surface had the powder pressed and locked in the binder which was smeared across the surface by the action of the grinding wheel, whereas in case of the bisque fired sample the powder or powder particle clusters were loose and contributed to rubbing action as the wheel moved relative to the surface thus contributing to greater surface roughness. Fig. 5 shows the scanning electron microscope pictures of ground surfaces of 22.5 wt.% binder containing and bisque fired samples and Fig. 6 shows the swarf obtained during grinding of the sample with 30 wt.% binder in the premix and the bisque fired sample. It is evident from the pictures of the swarf that during the grinding of binder containing sample, material is removed in the form of bigger clusters of particles bound together with the binder while the material is removed as powder or small particle aggregates from the bisque fired sample.

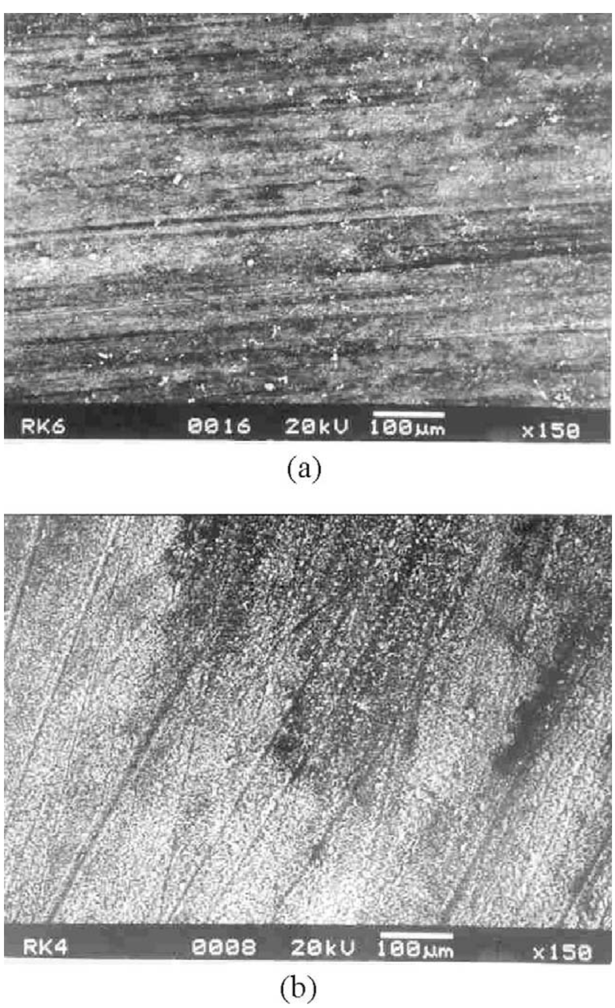

Fig. 5. SE micrograph of ground surface of (a) sample with 22.5 wt.% binder (in premix), (b) bisque fired sample.

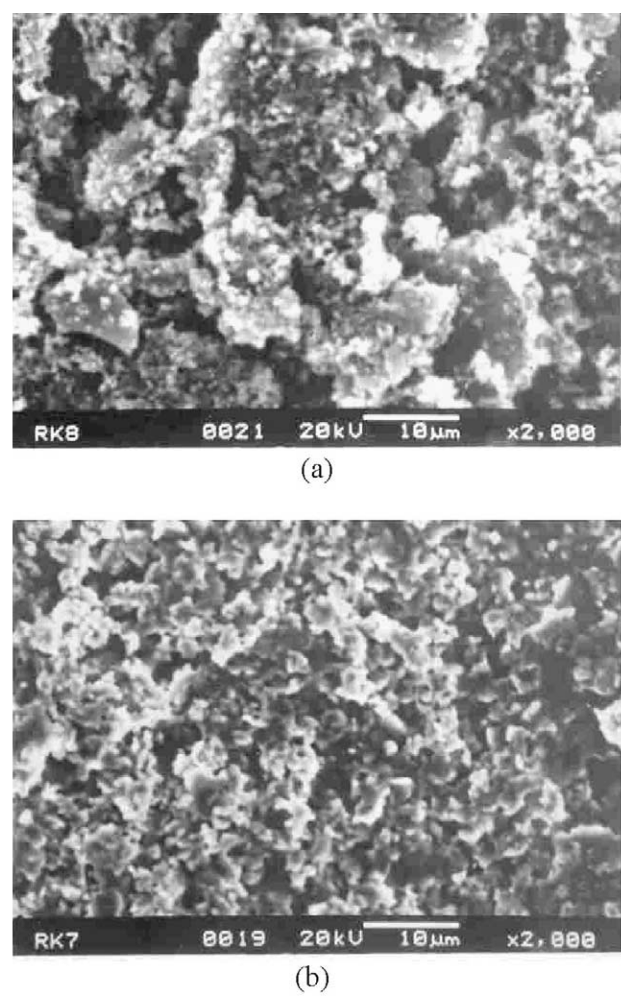

Fig. 6. Swarf from grinding of (a) sample with 30 wt.% binder, (b) bisque fired sample.

As a test of the ability to cut a sharp edge by grinding, a 0.6 mm deep step was cut on the green samples. All the samples showed a good ability for edge retention, however amongst all the samples the bisque fired sample showed the best edge. Fig. 7 shows the edge formed by grinding process.

3.3. Milling

Milling was performed on samples with machining parameters listed in Table 1. The removal of the material during milling was in form of long chips (Fig. 8). The action of the tool was to fracture and scoop the material from the surface. The tool left some distinct marks on the surface of the sample in the direction of the tool traverse. The forces recorded on a sample with 15-wt.% binders content in the premix are shown in Fig. 9.

The normal forces were lower than the tangential forces as is expected in case of the milling. The normal forces were more or less constant with each pass but the tangential forces were increasing steadily. This was possibly due to the wear of the edge of the tool thus reducing the cutting ability of the tool and hence the increase in the forces.

The average of surface roughness for the milled sample was measured to be 1.78 μm. The surface roughness value is comparable to that reported by Scheller et al.[1] for Si_3N_4 polymer bonded ceramic samples machined using a vertical milling machine with 3.81 mm depth of cut. Although further experiments with different tool RPM, feed rates and depth of cut were not performed, it is believed that the surface finish could be improved further by studying the effect of these parameters and choosing the optimum values.

When viewed under SEM at a high magnification the surface after milling appeared to be a combination of regions pressed under the tool action and loosely

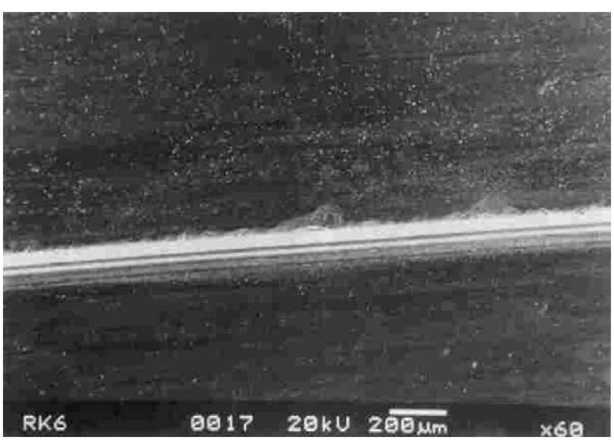

Fig. 7. Edge machined by grinding a sample containing 22.5 wt.% binder.

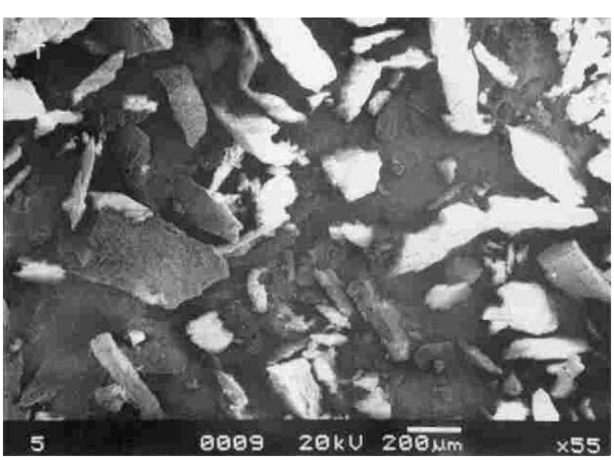

Fig. 8. Chips obtained during milling of sample containing 15 wt.% binder (in premix).

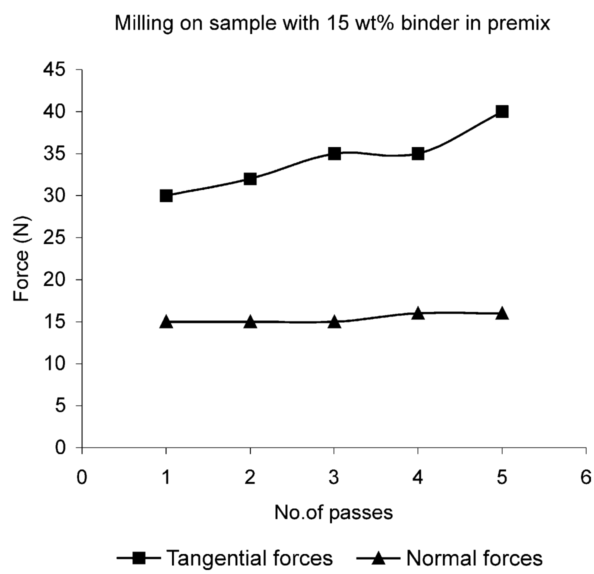

Fig. 9. Forces measured during milling of a green gelcast sample containing 15 wt.% binder in premix.

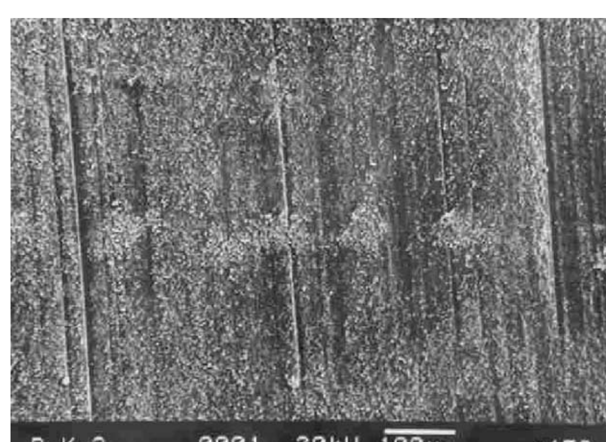

Fig. 10. SE micrograph of surface obtained after milling.

Table 2
Vickers hardness of gelcast alumina green and bisque fired samples

Alumina samples	VHN
15 wt.% binder	0.57
22.5 wt.% binder	1.06
30 wt.% binder	1.55
15 wt.% sample bisque fired at 900 °C for 2 h	0.57

packed particles due to cutting action. Fig. 10 shows the sample surface after milling operation.

4. Summary

The drilling study brought out that the HSS drill bits are not suitable for drilling the green samples produced by gelcasting, however this task could be performed easily using WC (tungsten carbide) drill bits or WC tipped drill bits without any significant loss in cutting efficiency.

During grinding of the green ceramic samples it was observed that the grinding wheel got clogged due to packing of the ceramic particles in between the abrasive particles. This clogging of the wheel occurred faster and became severe in presence of binder. The extent of clogging increased with increase in the binder content in the green compacts thus reducing the grinding efficiency as seen from the rapid increase in the measured forces. Removal of powder packed in between the abrasive particles on the wheel after machining the binder containing samples was difficult even with mechanical action using a brush while the wheels clogged from machining the bisque fired samples could be cleaned relatively easily.

Milling could be performed on the gelcast compacts with reasonably low forces. The edge retention by milling could be a problem due to the brittle nature of the compacts, however a reasonable surface finish can be obtained by milling. Though a HSS tool was used for this study, considering the tool wear during drilling and the wear pattern of the milling tool it is believed that WC tool would be a better tool choice even for milling. WC tool is expected to maintain its edge for a longer machining time and may influence the edge retention also.

Acknowledgements

The authors gratefully acknowledge the help received from Prof. A. B. Chattopadhyay, Prof. S. Paul and Mr S. Ghosh of the Mechanical Engineering Department, IIT Kharagpur, in conducting some of the machining experiments. The financial support from CSIR (Project No. ø3(0917)/øø/EMR-II) and DST (Project No. SR/FTP/ET-72/2øøø) is thankfully acknowledged.

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