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# Single Point Diamond Machining of Ferroelectric Materials

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***Abstract***

*One of the most important ferroelectric ceramic materials used in a wide range of applications is the lead zirconate titanate solid solution series (PZT). The ability to machine ferroelectrics in a ductile manner and by so doing reduce sub-surface damage, could eliminate the need for subsequent lapping and polishing and thus reduce production costs. Fracture mechanics techniques were used to investigate the localised elastic/plastic behaviour in these materials. The possibility of machining brittle materials using single point diamond turning in a 'ductile mode' has been investigated by many researchers in recent years and for this study poled and unpoled PZT ceramics were single point diamond turned under different machining conditions and ductile machining has been achieved. X-ray diffraction (XRD) indicates the degree of domain reorientation caused by machining, and it is suggested that the strain generated by re-orientation accounts for brittle damage. Appropriate poring can have a marked effect on the brittle/ductile machining response. © 1999 Elsevier Science Limited. All rights reserved*

*Keywords*: machining, X-ray methods, fracture, mechanical properties, PZT.

## 1 Introduction

Ferroelectric ceramics and single crystals have attained a considerable importance in an ever-widening range of applications. Their exceptional combination of properties includes strong piezoelectric, pyroelectric and electro-optic effects. One of the most important and widely-used groups is the lead zirconate titanate solid solution series (PZT). A wide range of products rely on the high-precision fabrication of piece-parts using ferroelectric ceramics, including: ultrasonic medical imaging transducers, ink jet printing heads, and optical modulation systems. The contemporary technology that has been used to machine these materials has been grinding and diamond sawing followed by lapping and polishing. Although much work has been reported on the machinability of brittle materials, little has been reported concerning ferroelectric ceramics. Subbarao *et al.*[1] reported the effects of grinding on the surface and sub-surface alterations of $BaTiO_3$ and attributed the texture to the effects of electric fields generated during machining. Mehta and Virkar[2] reported a limited investigation into the surface and sub-surface alterations formed during grinding. Cheng *et al.*[3] investigated the effects of lapping and polishing on poled and unpoled PZT ceramics and they considered the domain re-orientation to be due to a stress relieving mechanism. Beltrao, *et al.*[4] investigate the effects of single point diamond ruling on poled and unpoled hard and soft PZT ceramics. The extent of brittle damage adjacent to the grooves generated during ruling correlated with the results of domain re-orientation observed by XRD. This observation was explained as domain re-orientation producing enough mechanical strain in the surface to cause fracture. Ductile machining phenomena have been observed in brittle materials when subjected to laterally moving indenters. In such observations, instead of brittle damage, material was seen to pile up either side of the machined groove.[5] This phenomenon has also been described for single point diamond turning by Puttick *et al.*[6] and they observed that, for cuts below some critical value, together with appropriate machining conditions, glasses and other brittle materials can be machined in a ductile

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manner. Some experimental methods have been used to determine the critical ductile-brittle transition cut-depth in single point diamond turning experiments such as machining a wedge grooved surface, and more recently by the shoulder analysis technique.[7] Sintered PZT ceramics have been single point diamond machined by Nah[8] and he observed that the material composition was the most influential aspect in those tests. The current investigation is aimed at identifying the conditions in which such ductile behaviour can be expected in hard and soft PZT ceramics.

## 2 Material Preparation

Disk shaped samples (4 mm thick) were diamond sawn from cylinders of PC4D (hard) and PC5K (soft) PZT materials produced by Morgan Matroc Ltd. (Unilator Division). These were lapped and polished on a Logitech PM4 polishing unit fitted with a PP6 vacuum jig. The final flatness was observed interferometrically to be better than half a wavelength of HeNe laser light. Both PC4D and PC5K are MPB PZT ceramics. Surface preparation was a two-stage procedure. Initially, samples were lapped flat. The second finishing stage included polishing for 1 h with colloidal silica using a polyurethane pad. Samples of three different conditions of each composition were prepared. The conditions were (a) poled in-plane, (parallel to the surface), (b) poled perpendicular to the surface and, (c) unpoled. By observing the {002}/{200} XRD reflection doublet it could be seen that very little domain re-orientation had taken place in the near surface during final polishing.

## 3 Quasi-static Indentation and Ruling

The crack system obtained in quasi-static indentation was used to investigate the behaviour of PC4D and PC5K ceramics in this study. Vickers indentation experiments were performed on a micro-hardness tester. The analysis of the results showed that the values of PC4D hardness and fracture toughness were consistently higher than for PC5K. Poling direction had an important effect on the fracture toughness results. Threshold loads and cracks were also calculated and the results were found to agree with the Hagan[9] model for brittle materials. Yield stresses were calculated, considering the stresses parallel and perpendicular to the polar axis, based on the model proposed by Studman, Moore and Jones.[10,11] Complementary to quasi-static indentation, the process of single point diamond ruling was used for this study.[12] A hatchet-shaped tool was used for the ruling tests. Samples were tested in the three poling conditions and three ruling speeds (from 22 to 63 mm sec$^{-1}$) were used for a range of loads (from 0·2 to 1·1 N). XRD analysis using Co$K_\alpha$ radiation was undertaken before and after ruling and the degrees of domain re-orientation were compared. From the tests it was observed that the ductile/brittle threshold depth of cut was dependent upon material mechanical properties and the poling orientation. PC4D exhibits a more ductile response when compared with PC5K over a range of loads and speeds. Using the model proposed by Bifano[13] it was possible to predict the critical depths of cut for ductile grinding.[11] These results show good agreement with the ruling results for PC4D and PC5K poled parallel to the surface and provide a basis for other machining processes to be interpreted.

## 4 Single Point Diamond Machining

Three unpoled samples of each composition were prepared and machined using a diamond tip on an air-bearing precision facing lathe. The diamond tip had a nose radius of 1.143 mm and a negative rake angle of 10°, and no cutting fluid was used. The cuts were made using a fast tool servo to rapidly remove the tool from the surface during the cut producing a transition shoulder region to observe the ductile brittle transition. In order to evaluate the sensitivity of the most important machining parameters, a Taguchi design experiment loads employed, using two variables, feed rates and depths of cut, with three levels chosen based on those used by Nah,[8] although those materials had a higher level of porosity and therefore a lower mechanical strength than PC4D and PC5K.[11] Some regions were also machined as wedges varying in depth of cut from 0 to 400 nm, in order to obtain shallower depths of cut. Before and after machining, the surface roughnesses in three points of each region were measured using a Wyko Topo 3D phase shift (Linnik) interferometer, which provides a 250 $\mu$m$^2$ assessment area. After the first assessment, another set of tests was carried out to investigate the effect of the negative rake angles, cutting speed and cutting fluid using different PZT compositions and poling conditions.[11]

## 5 XRD Analysis

Before and after the turning tests the {200}{002} doublet was examined using Cu$K_\alpha$ radiation. A Siemens 5005 diffractometer operating under PC control was used for XRD in small areas (3×2 mm). The high lead content of PZT results in

90% of the Cu$K_\alpha$ radiation intensity being absorbed within the first $3{\cdot}2\,\mu$m of the surface. The {002}/{200} ratio was examined both before and after turning and the changes in domain reorientation were measured and quantified using Traces and Galactic Peak Solve Software.[11]

## 6 Results and Discussion

The average values of the roughness $R_a$ found in the polished regions of the three samples, were 7·19 nm for PC4D and 15·3 nm for PC5K. The best surface roughness average result for PC4D was 5·02 nm, and the best surface roughness average result for PC5K was 11·4 nm. None of the surface roughness average $R_a$ results found in the hard material were better than that for the polished region. On the other hand, the best surface roughness result found in the soft material was 9·69 nm in the second turned region, where the cutting conditions were $0{\cdot}1\,\mu$m for depth of cut and $0{\cdot}1\,\mu\text{m rev}^{-1}$ for feed rate. PC4D showed a more constant behaviour than the soft material in terms of surface roughness degradation. It is possible to use deeper cuts and faster feed rates to achieve the same surface quality. Nevertheless, Fig. 1 shows ductile machining of PC5K ceramic from the bulk material. Using the shoulders produced in the unpoled ceramics and the equation proposed by Blake[7] the critical depths of cut calculated are shown in Table 1.

It was observed in the range of parameters analysed, that an increase in feed rate and depth will increase the brittle damaged area with more grain pull-out regions, reducing the internal strain on the bulk material. However, although no improvement has been observed in the surface roughness with the use of more negative rake angles, the texture level decreased with a tool of high negative rake angle of 25°. Dry cuts show superior surface roughness and less domain switching, and no

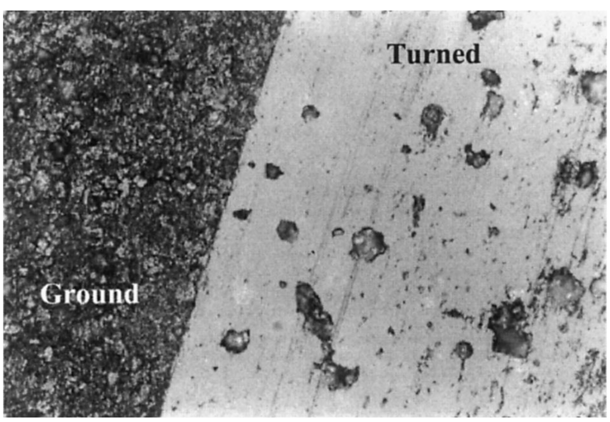


**Fig. 1.** Optical microscope photograph of PC5K turned from the ground sample (the image is 360 microns wide).

**Table 1.** Critical depth of cut using shoulder technique

| | *PC5K* | *PC4D* |
|---|---|---|
| Critical depth of cut ($\mu$m) | 0·043 | 0·170 |

influence was noted when using higher or lower cutting speeds. The advantages of poling the PZT samples parallel to the surface after machining were not as noticeable during these tests as they were during the ruling and quasi-static indentation tests. This is thought to be due to the constant changes in cutting relative to poling direction which occur when turning. The influence of domain switching was not so strong as for the quasi-static indentation and ruling tests. The reason for this observation is that domain switching is probably time-dependent and the cutting process occurs at a faster speed during turning. Furthermore the generation of heat due to friction between tool tip and bulk material in turning tests maybe have an annealing effect in these materials. The diamond wear rate was investigated during the tests and the diamond edge is seen to be highly worn after 6 km of machining which is considered to be a poor result considering the small feed rate of 0.1 $\mu$m/rev$^{-1}$ used.

## 7 Concluding Remarks

Ductile mode machining was achieved in both soft and hard PZT compositions when single point diamond turned. The hard material compositions showed a more stable behaviour than the soft material and they were easier to machine in a ductile mode. XRD tests indicate that negative rake angles of −25° had a beneficial effect on the textural effects, reducing domain switching. Increases in feed rates and depths of cut reduced the domain switching due to the release of the surface strain through brittle damage and grain ejection. Although the cutting forces were very small, the cutting areas were also small which increased the pressures on the tools over the surface. In order to overcome the problem of the wear rate of the diamond tool, a multi-point diamond machining process (e.g. grinding) is required. Diamond wear rate is also high when machining these materials, which, together with the high levels of domain switching, suggest that the single point diamond turning process should be used only for special applications when machining PZT ceramics.

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## References

1. Subbarao, E. C., McQuarrie, M. C. and Buessen, W. R., Domain effects in polycrystalline barium titanate. *J. Appl. Phys.*, 1957, **28**, 1194–1200.
2. Mehta, K. and Virkar, A. V., Fracture mechanisms in ferroelectric–ferroelastic lead zirconate titanate (Zr:Ti = 0.54:0.46) ceramics. *J. Am. Ceram. Soc.*, 1990, **73**, 567–574.
3. Cheng, S., Lloyd, I. K. and Kahn, M., Modification of surface texture by grinding and polishing lead zirconate titanate ceramics. *J. Am. Ceram. Soc.*, 1992, **75**, 2293–2296.
4. Beltrão, P. A., Gee, A. E., Corbett, J., Whatmore, R. W., Goat, C. A. and Impey, S. A., Diamond machining of ferroelectric materials. In *Progress in Precision Engineering and Nanotechnology*, ed. Kunzmann, H., Wäldele, F., Wilkening, G., Corbett, J., McKeown, P., Weck. M. and Hümmer J. PTB Brauschweig und Berlin Presse, Braunschweig, Germany, 1997, pp. 578–581.
5. Taylor, E. W., A hardness table for some well-known types of optical glasses. *J. Sci. Inst.*, 1949, **26**, 314–316.
6. Puttick, K. E., Rudman, M. R., Smith, K. J., Franks, A. and Lindsey, K., Single point diamond machining of glasses. *Proc. Roy. Soc. Lond. A*, 1989, **426**, 19–30.
7. Blake, P. N., Ductile-regime diamond turning of germanium and silicon, Ph.D. thesis, North Carolina State University, Raleigh, NC, 1988.
8. Nah, Y. T., Ultraprecision machining of PZT (ceramic) materials. M.Sc. thesis, Cranfield University, Cranfield, UK, 1995.
9. Hagan, J. T., Micromechanics of crack nucleation during indentations. *J. Mat. Sci.*, 1979, **4**, 2975–2980.
10. Studman, C. J., Moore, M. A. and Jones, S. E., On the correlation of indentation experiments. *J Phys. D.: Appl. Phys.*, 1977, **10**, 949–956.
11. Beltrão P. A., Analysis of the potential for ductile mode machining of ferroelectric materials. Ph.D., thesis, Cranfield University, Cranfield, UK, 1998.
12. Hirst, W. and Howse, M. G. J. W., The indentation of materials by wedges. *Proc. Roy. Soc. Lond. A*, 1969, **311**, 429–444.
13. Bifano, T. G., Ductile regime grinding of brittle materials. Ph.D. thesis, North Carolina State University, Raleigh, NC, 1988.