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The Effect of Grinding Conditions on Lead Zirconate Titanate Machinability

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Abstract

In many of the existing and newly emerging applications for ferroelectrics there is a need to machine them to high precision, with control over the surface and near surface properties. This is particularly the case regarding microdevices. With such devices, cracking and ferroelastic domain reorientation can result in significant degradation in device performance due to grain pullout, strength degradation and depoling of the near surface region. It is vital that the parameters controlling machinability are determined and their effects characterised. From such information, optimum machining conditions may then be selected. The effects of fixed abrasive dicing conditions have been studied in four lead zirconate titanate compositions suitable for piezoelectric actuator applications. The severity of brittle surface damage has been investigated by image analysis. The thicknesses of the depoled regions have been measured by their effects on the piezoelectric coupling factors of array elements of various widths. It has been established that machinability is particularly sensitive to wheel grit size, feed rate and material composition.

Keywords: machining, surfaces, piezoelectric properties, PZT, actuators.

1 Introduction

Piezoelectric ceramics based on the perovskite solid solution series $Pb(Zr_xTi_{1-x})O_3$ (PZT) are used in an ever widening range of sensors and actuators with applications as diverse as medical ultrasound transducers and ink jet printer heads. Many of the properties desirable in an actuator, such as high coupling, peak at the rhombohedral tetragonal morphotropic phase boundary (MPB) at $x \approx 0{\cdot}52$. Unfortunately, many mechanical properties important to machinability are poor at this composition, making device fabrication difficult. The ferroelectric domain reorientation occurring during poling is normally achieved with a high electric field. However, mechanical stress can also cause ferroelastic domain reorientation. Mehta and Virkar[1] reported this effect at stresses of only 50 MPa; considerably lower than PZT's yield strength[2] and comparable with its tensile fracture strength.[3] Joyomura *et al.*[4] estimated a depoled region of 0·1 to 2 μm wide in lapped Ba- and Sr-modified lead titanate and lead zirconate ceramics. Cheng *et al.*[5] investigated the lapping and polishing of poled and unpoled soft PZT. The degree of texture generated in unpoled PZT abraded by 45 μm diamond and 600 grit SiC was comparable with that of unpolished poled material. In a lapping and polishing study, Goat *et al.*[6] found soft PZT underwent more near surface domain reorientation and fracture than hard PZT. Both the hard and soft PZT contained similar rhombohedral and tetragonal volume fractions. While these proportions were stable in hard compositions, there was considerable rhombohedral to tetragonal transformation in the soft PZT; this did not appear to exacerbate fracture in the soft composition. Increasing brittle fracture would appear to result from ferroelastic domain reorientation in the rhombohedral phase.[7] Whatmore and Goat[8] found that during machining, a predominantly rhombohedral PZT composition becomes more tetragonal; the opposite occurs in tetragonal PZT. The degree of machining stress induced phase transformation increased as the MPB was neared, particularly from the rhombohedral side. Such phase transformation must also destroy polarization in the near surface. In simple planar piezoelectric devices most of the degradation caused by sawing or grinding can be removed by polishing, but for

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complex geometries, such as 1–3 composites for ultrasound applications, this is not always viable. Continuing device miniaturisation means that the volume fraction of PZT rendered piezoelectrically inactive increases, reducing device performance. It is unfortunate that the soft compositions used in actuators and sensors are those most prone to such damage. Cheng *et al.*[5] considered domain reorientation to be a stress relieving mechanism. Whatmore and Goat[8] took this viewpoint further, proposing a model for the ductile absorption of machining energy by domain wall motion and phase transformation.

2 Experimental Method

Two types of damage were investigated in four commercial PZTs commonly used for piezoelectric devices. The types of damage are:

1. Surface crystallite loss. Surface roughness is increased giving poor machining tolerance and less potentially active piezoelectric.
2. Ferroelastic/thermal depolarisation adjacent to the kerf. This causes a loss in piezoelectric performance, and the stresses created by crystallographic reorganisation can encourage damage of types 1 and 2.

All cutting tests were carried out on a Loadpoint Microace Series 3 precision saw. Four PZTs were evaluated: Motorola HD3203, Sumitomo 9C and H5D and GEC Marconi H7. To investigate surface crystallite loss and loss of piezoelectric activity, PZT wafers were bonded to glass substrates, and lapped to a thickness of 450 μm. Three 55·56 mm diameter metal bonded diamond wheels were used; 2–4, 4–6 and 8–12 μm grit size with 500 μm exposure. Cutting tests were carried out at 20 000 and 40 000 rpm, at feed rates of 0·2, 1, 5 and 25 mms^{-1}. Coolant was directed at the cutting zone at 1500 mlmin^{-1}. A one dimensional array of slots 430 μm deep was formed. Surface finish was examined with scanning electron microscopy and surface crystallite loss quantified by image analysis. To find the width of the piezoelectrically inactive region groups of cuts were made under the same cutting conditions to produce PZT elements of widths between 125 and 40 μm wide. If the width of the piezoelectrically inactive zone remains constant under the same cutting conditions, there will be less piezoelectric activity the thinner the piezoelectric element becomes. It can be shown that the piezoelectric coupling factor of the PZT strips will be given by k_{3s}^0, where $k_{3s} = k_{3s}^0 - 2k_{3s}^0 w_0/w$. Here, w_o is the thickness of the piezoelectrically inactive region, w the thickness of the strip and k_{3s}^0 is the coupling factor for $w_o = 0$ (Note that k_{3s} is not the same as k_{33} as the former is for a long thin strip while the latter is for a rod poled along its length[a]. w_o can thus be determined from the variation in k_{3s} with w. The calculation of k_{3s} was based upon the PZT elements' resonant and antiresonant frequencies.[9]

3 Results and Discussion

All four PZT compositions behaved similarly regarding the effect of machining conditions on surface finish. There was particular sensitivity to and interaction between diamond grit size and feed rate (Fig. 1). A 2–4 μm diamond wheel is only beneficial at a low feed. A 4–6 μm wheel offered reasonable performance over the whole feed rate range. Other sensitive parameters were PZT formulation, batch and coolant flow rate. Coolant temperature and blade rotational speed both had a slight effect on surface finish.

As expected, a straight line relationship was found between k_{3s} and $1/w$, (Fig. 2). The width of the piezoelectrically inactive zone was particularly sensitive to PZT formulation, (Table 1). On the basis of the results collected to date, there is little sensitivity to wheel grit size, but some advantage in a higher feed rate.

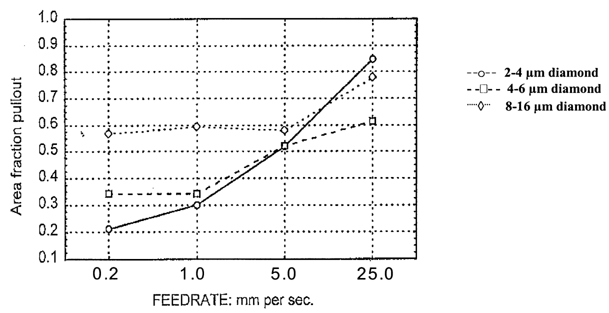

Fig. 1. The effect of grit size and feed rate on surface finish.

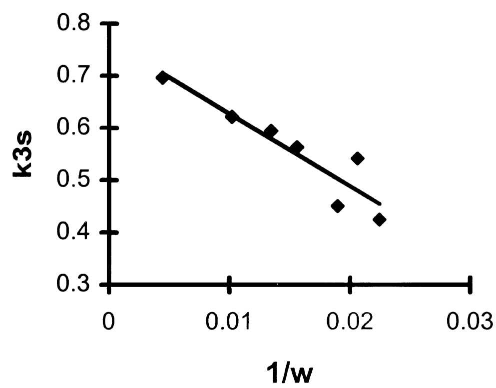

Fig. 2. The effect of standup width on piezoelectric coupling factor in Sumitomo 9C.

Table 1. The inactive zone widths of the four piezoelectric materials

Material	$w_o \mu m$	*Blade grit* (μm)	*Feed Rate* (mms^{-1})
Motorola HD3203	3·3	4–6	5
Motorola HD3203	5·2	2–4	1
GEC Marconi H7	1·6	2–4	1
Sumitomo H5D	6·7	2–4	1
Sumitomo, 9C	10·8	4–6	1
Sumitomo 9C	9·1	2–4	1

4 Conclusions

Both types of damage were sensitive to machining conditions and PZT formulation. There appears to be some correlation between how soft a formulation is, and the width of its inactive zone. The width of the inactive zone of three of the ceramics is in the order of decreasing dielectric constant K_3: 9C (7000), H5D (4380) and HD3203 (3300). This indicates that softer materials give thicker damage layers, all other things being equal. In the case of the H7 material ($K_3 = 4000$), there was evidence that the material gave a relatively poor surface finish due to high grain pull out at the material surface. This may be the reason for the relatively thin piezoelectrically inactive region (3 μm) in comparison with the others. The loss of surface material effectively carrying away the inactive layer.

Acknowledgements

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