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Anisotropic and Cyclic Mechanical Properties of Piezoelectrics—Compression Testing

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Abstract

The mechanical stressing of PZT produces irreversible deformation by the irreversible switching of 90° domains. This leads to highly anisotropic deformation behaviour for poled materials. The threshold stresses required to produce this switching are relatively small, < 10 MPa. The strains that can be achieved, $\sim 1\%$, are relatively large for ceramic materials. The domain switching is a thermally activated process, so that the deformation behaviour is strain rate dependent. The cyclic stressing of PZT produces significant incremental increases in the irreversible strain. This behaviour is the basis of electromechanical fatigue effects that cause the degradation of piezoelectric materials.

Keywords: compression and irreversible strain, PZT.

1 Introduction

Piezoelectric ceramics are already used widely for mechanical actuators, ultrasonic applications, resonators and load sensors. For most applications they do not require high strength, but more importantly they do require long term stability and reliability. The electrical and mechanical cycling of piezoelectrics, however, can cause irreversible microstructural damage in the form of microcracking and reversible damage in the form of irreversible ferroelectric domain reorientation. This leads to non-reproducibility and degradation of electromechanical properties and increased electrical and mechanical losses. It is well known, for instance, that the performance of piezoelectric displacement actuators degrade during long-term applications. The problem is becoming more important as components are increasingly being used in applications that subject them to relatively large cyclic electrical and mechanical loading.

On cooling through the Curie temperature a phase transformation takes place. This gives rise to a ferroelectric domain structure. The domain walls have mechanical twin like structure and relieve residual stress within the material. The preferential alignment of domains produced by the poling of the material to produce a piezoelectric consequently induces residual stresses. Mechanical stresses can reorientate 90° domains by producing twinning shears. This process may influence the fracture and fatigue behaviour of the materials, producing anisotropy and toughening effects. The irreversible reorientation of these domains may also be the origin of ageing and degradation effects. With a good understanding of the inter-relationship between domain behaviour and electromechanical behaviour it may be possible to develop techniques for controlling domain structure to achieve optimum poling and increased resistance to ageing and degradation. Another related problem is the structural integrity of ferroelectric/piezoelectric materials. The materials have relatively poor mechanical properties. The development of microstructural damage under cyclic and static loading may be very detrimental. It is, therefore, important to be able to predict the limits of application of piezoelectric materials under mechanical and electrical loading.

For many applications of piezoelectrics the direct stressing of components (electrically or mechanically induced) on their domain structure and ultimately on their ageing and degradation behaviour is more important. Relatively low stresses may produce reversible and irreversible domain reorientation. Relatively high stresses may be sufficient to produce irreversible microstructural damage in the form of microcracks. A good approach to investigating these behaviours is to study stress–strain hysteresis in

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compression, as used by others.[1,3] These tests provide mechanical loss data and specify the stress levels at which reversible and irreversible processes take place. In this paper we present data for cyclic compression stressing of a hard and soft PZT.

2 Materials and Method

Two commercial PZT (lead zirconate titanate) materials produced by Morgan Matroc, Transducer Division, Southampton were used in this study: 4D ('hard' with $d_{33}=315\times10^{-12}$C/N) and 5H ('soft' with $d_{33}=593\times10^{-12}$ C/N). The compression specimens were prepared with nominal dimensions of 4×2×2 mm, with the compression axis corresponding to the longest dimension. The specimens were prepared to a high degree of squareness and parrallelism ($<0{\cdot}01°$) of the compressed faces. This was achieved by sequential diamond polishing using polishing jigs with well machined insets. The specimens were then poled at 2·5 KV mm^{-1} at 100 °C.

The compression jig developed for the tests is shown in Fig. 1. It consists of a fixed upper platten of Si_3N_4 and a floppy bottom platten to allow for accommodation of any misalignment. The displacements/strains were measured using a purpose built capacitance device. The device had an annular active ring. This means that the displacements measured are effectively the average of the displacements in all angular directions around the specimen. The sensitivity of the device was about 0·1 μm. The quality of the specimens and the alignment of the testing jig is reflected in the linearity of the stress–strain curves at low stresses on initial loading.

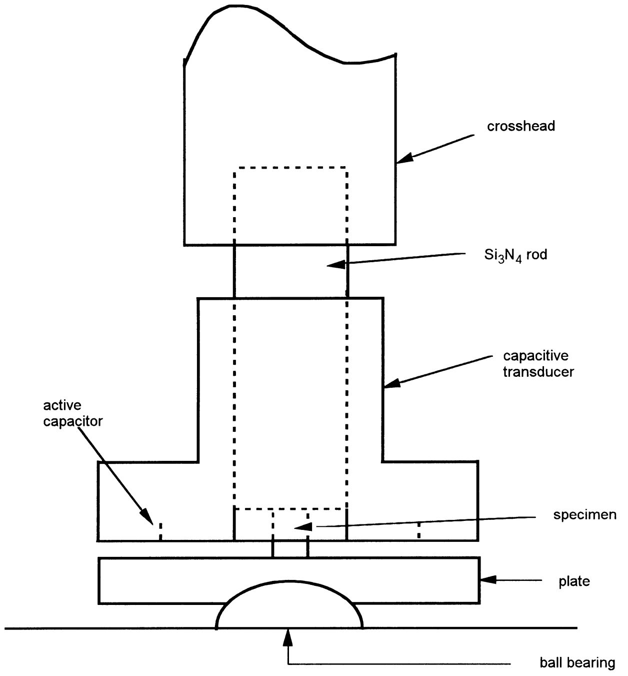
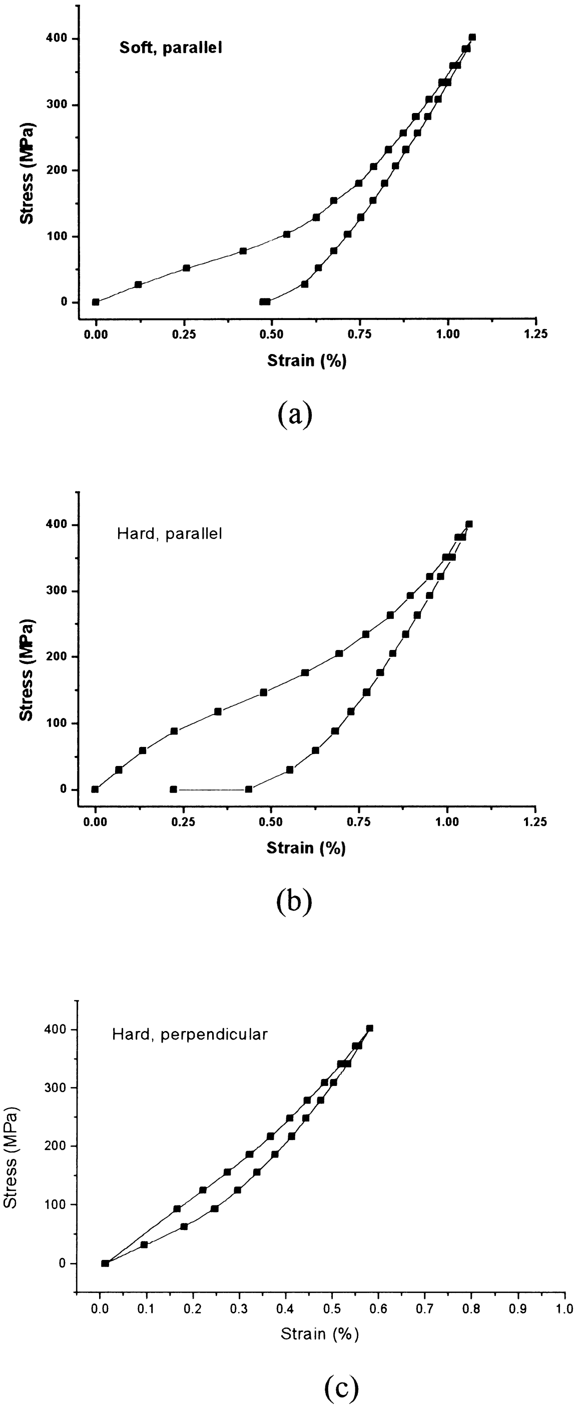


Fig. 1. Compression jig.

3 Results and Discussions

3.1 Stress–strain curves

Figure 2(a) and (b) show the stress–strain curves for the soft and hard materials stressed to 400 MPa



(a)

(b)

(c)

Fig. 2. Compression stress–strain data for: (a) soft material parallel to poling axis; (b) hard material parallel to poling; and (c) hard material perpendicular to poling. The tests were performed in load control.

and then unloaded parallel to the poling axis. The threshold stresses required to produce domain reorentation are relatively small, less than 10 MPa. The maximum strains achieved are similar, about 1%, and relatively large for ceramic materials. The materials show a hardening behaviour at the higher stresses because of the exhaustion of the available 90° domains that could be switched and the high degree of difficulty of switching those that were available. On unloading the recoverable strain, which is produced by domains switching back, is greater for the hard material than for the soft material. It is achieved with a considerable component of relaxation, taking about 3 min to achieve >90% of the achievable recovery. The explanation for this is probably that higher internal stresses are generated in the harder material, assisting the recovery. The irreversible strains are produced by domains that remain permanently reoriented, producing depoling and degradation of the piezoelectric properties. If no microcracks are produced, it should in principle be possible to reverse this damage by repoling.

Figure 2(c) shows the stress–strain behaviour of the hard material compressed perpendicular to the poling axis. The maximum strain is about 0·5%, which is half of that achieved parallel to poling. This strain is fully recovered on unloading, with no irreversible strain produced.

3.2 Irreversible strain under cyclic loading

Figure 3(a) shows the effect of cyclic loading at constant displacement amplitude (zero to 1% at a rate of 1% per minute for the first cycle) on the hard material. Every cycle produces an increment in the cumulative irreversible strain. The progressive increase of the load and the narrowing of the hysteresis loop is indicative of the material hardening. This is because the number of available domains to switch is decreasing and those remaining are more difficult to switch because of their microstructural configuration and the presence of opposing internal stresses. The observed behaviour is similar to what you would expect for a plastically deformed metal.

Figure 3(b) shows data for a similar test, but performed at four times the rate (0–1% at 4% min^{-1}). In the faster rate tests the maximum irreversible strain produced is smaller than for the slower tests, as you would expect for a thermally activated process such as domain reorientation, and is achieved by smaller increments of irreversible strain per cycle. The degree of hardening is presumably less also because the material is less depoled and more 90° domains are therefore available to accommodate the deformation.

Figure 4 shows the evolution of cumulative strain in constant stress amplitude experiments for

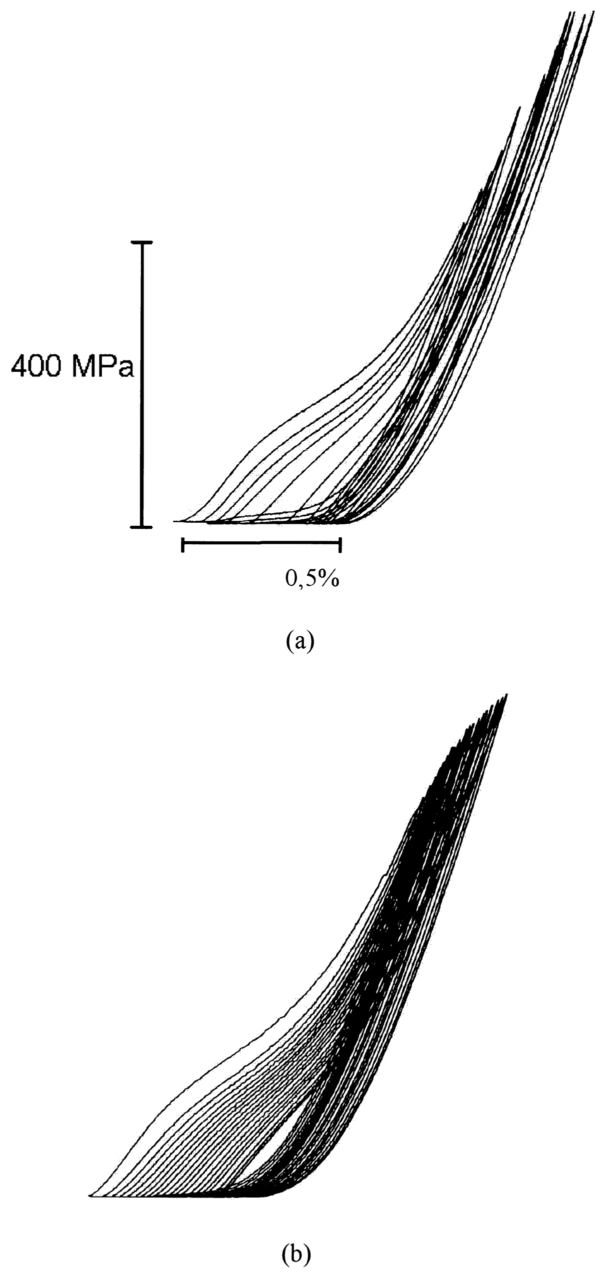


Fig. 3. Constant strain amplitude cyclic compression stress–strain data for hard material: (a) 1% strain amplitude at 1% per min, and (b) 1% strain amplitude at 4% strain per min.

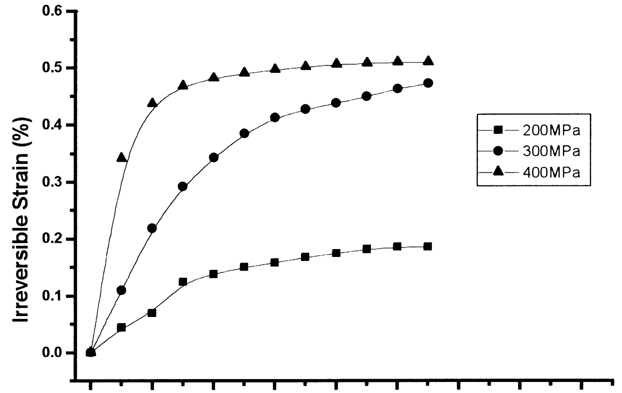


Fig. 4. Cumulative irreversible strain in constant stress amplitude cyclic compressive tests.

three stresses, 200, 300 and 400 MPa. Again, it shows that cyclic loading initially produces a significant increment in the cumulative irreversible strain on each cycle before eventually saturating.

4 Conclusions

The mechanical stressing of PZT produces irreversible deformation by the irreversible switching of 90° domains. This leads to highly anisotropic deformation behaviour for poled materials. The cyclic stressing of PZT produces significant incremental increases in the irreversible strain, These cyclic effects are much more significant for hard materials. This behaviour is the basis of electromechanical fatigue effects which produces the degradation of piezoelectric properties.

Acknowledgements

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