In situ observation of electric field induced crack propagation in BaTiO3 crystals along loading direction

Yingwei Li, Faxin Li[a)]

State Key Lab for Turbulence and Complex Systems, College of Engineering, Peking University, Beijing, 100871, China

Summary Electric field induced fracture in $BaTiO_3$ crystals is in-situ observed using polarized light microscopy. Domain evolution and crack propagation process is recorded by CCD during cyclic electric loading with the field direction parallel to the crack surface. It is found that near the crack tip, 90^o domain switching always occurs before crack propagation. The shear stress caused by the incompatible domain switching near the crack tip is thought to be the driving force for crack growth.

INTRODUCTION

Ferroelectric materials have been widely used as actuators, sensors, transducers, etc. in modern industry due to their peculiar electromechanical property. However, the fracture problem caused by electric field has limited its use in high reliable equipments. In order to improve the reliability of ferroelectric devices, it is essential to understand the crack growth behaviour in ferroelectric material under electric field loading. Since the pioneer work of Cao and Evans[1], electric field induced crack propagation has been intensively investigated by several research groups, experimentally[2,3] and theoretically[4]. Although the general mechanism for crack propagation in ferroelectrics is still under debate, it has been widely accepted that domain switching has considerable effect on crack propagation[3,4].

In order to clarify the crack growth mechanism induced by electric field, it is necessary to in situ observe the domain evolution and crack propagation process in ferroelectric materials. So far, very few works have been done in this aspect[5,6] and the applied electric field was either perpendicular or with an acute angle to the crack direction. What will be going if the applied electric field is parallel to the crack? With this question, we in-situ investigated a precracked $BaTiO_3$ crystal under cyclic applied electric loading with field direction parallel to the crack face. It is found that cyclic electric field can induce crack propagation along the loading direction. The mismatch shear strain caused by the 90^o domain wall motion is thought to be the driving force.

EXPERIMENTAL

A $5*4*1mm^3$ $BaTiO_3$ single crystal poled along the 4mm direction is used in this investigation. Both the $5*4mm^2$ faces were finely poled by diamond paste, with a roughness of about 10nm. The two opposite $4*1mm^2$ faces, perpendicular to the poling direction, was carefully spread with silver paint as electrode. At room temperature, the coercive electric field and saturated polarization is 100V/mm and $27pC/cm^2$, respectively. Firstly, Knoop indentation was used to generate a through crack along the 4mm direction near the edge of the specimen. Then, the specimen was immersed into a transparent tank filled with silicon oil to prevent electric arcing during loading. A high voltage power amplifier (Trek 30/20A) together with a function generator, are used to provide AC electric fields. A triangular wave form electric field, with the amplitude of 200V/mm and period of 5s, was used. Different from previous studies, the loading direction is parallel to the crack face. During loading, the domain structures and the crack configuration were observed using a polarized light microscope and recorded by a CCD.

RESULTS AND DISCUSSIONS

The domain structure evolution and crack propagation process during a cyclic electric loading is shown from Fig 1(a) to Fig 1(e). It can be seen that there are domain walls emerging from upper and lower surfaces of the crack and they are perpendicular to each other. While no domain walls were observed in the front of the crack tip. Deduced from the crystallographic symmetries and compatible condition of tetragonal BaTiO3 crystal[7], the domain walls observed in the specimen are 90^o a-a domains wall.

When a positive electric field is applied to the specimen, the 90^o domain walls near the crack tip tends to become thinner by domain wall movement, seen in Fig 1(b), and then disappeared gradually. Upon unloading, the disappeared domain near the crack tip comes out again, but its width was thinner than before, as shown in Fig 1(c). Meanwhile, the crack tip, marked by 'M', remains its original position during loading, indicating that a positive electric field can not drive the crack propagation.

When a negative electric field is applied, the 90^o domain near the crack tip becomes wider, which is shown in Fig 1(d). Furthermore, with the expanding of the domain wall, the crack propagates from 'M' to 'N', with an increment about 6μm. The increment of the crack length is equal to the growth of the domain width. During unloading, its width becomes thinner again, which is shown in Fig 1(e).

a) The correspondence author, Email: lifaxin@pku.edu.cn

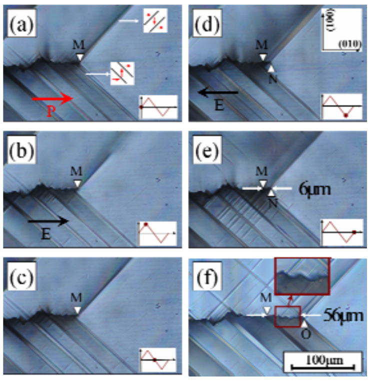

Fig 1. (a) to (e) are micrographs of domain evolution and crack propagation process during a cyclic loading, (f) is the micrographs of specimen after 10 cycles loading.

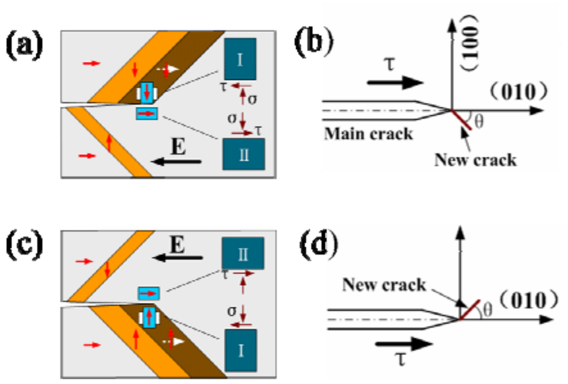

Fig 2. Crack growth mechanism during cyclic electric loading

Fig 1(f) shows the micrographs of the domain structure and crack configuration after 10 cycles's loading. It can be seen that the crack tip moves from 'M' to 'O', with the increment about 56μm. The crack is not perfect straight but shows zigzag shape, which can be seen clearly from the inset amplified photograph.

The coexistence of domains with different polarization direction is harmonized by domain walls for ferroelectrics materials. Under electric loading, ferroelectric domains are inclined to keep themselves parallel to the loading direction by domain nucleation and domain wall motion[8]. Take BTO crystals for instance, the domains are coordinated with each other by 90^o or 180^o domain walls. When positive electric field is applied to the specimen, the domains perpendicular to the electric field become thinner by a-a domain wall motion. Because the domain wall can spread across the specimen uniformly, so the stress concentration is limited and there is no crack growth during positive electric loading.

However, the switched unit cell can not be compatible with adjacent unswitched cells below the crack when the 90^o domain walls move to the crack tip under negative electric field. The switched unit cell will contract along the previous polarization direction and elongate along the current polarization. The unswitched unit cell below the crack subject shear stressing from the switched unit cell along (010) direction, and compression stress along the (-100) direction, which is shown in Fig 2 (a). Compression stress provides no contribution to the crack propagation, but the shear stress may drive crack propagation when it exceeds a threshold value.

According to the maximum hoop stress fracture criterion by Sih[9], crack will not propagate along the original crack direction under a shear stress, but will deviate a negative angle of 'θ' from the major crack, as shown in Fig 2(b). What's more, the driving force may come from the domain wall movement below the crack face, which is shown in Fig 2(c). In this case, the crack will deviate a positive angle from its original direction, as shown in Fig 2(d). In this way, the crack will propagate steadily in a zigzag manner along the main crack under cyclic electric loading.

CONCLUSIONS

In summary, cyclic electric field induced crack growth in a prepoled BaTiO3 crystal is in-situ observed by polarized light microscopy. Results show that the incompatible 90^o domain wall movement near the crack tip induced by negative electric field can drive crack propagation along the loading direction. This observation provides direct evidence that the misfit domain switching may cause fracture in ferroelectrics. The zigzag shaped crack pattern is attributed to the alternating 90 degree domain switching above and below the crack face.

References

[1] Cao H, Evans AG. J. Am. Ceram. Soc. 77, 1782, 1994
[2] Fang DN, Liu B, Sun CT, J. Am. Ceram. Soc. 87, 840, 2004
[3] Westram I, Oates WS, Lupascu DC, Rödel J, Lynch CS. Acta. Mater. 55, 301, 2007
[4] Yang W, Zhu T, J. Mech. Phys. Solids. 47, 81, 1999
[5] Fang F, Yang W, Zhang FC, Luo HS, J. Am. Ceram. Soc. 88, 9, 2491, 2005
[6] Jiang YJ, Fang DN, Scripta. Mater. 57, 735, 2007
[7] Shu YC, Bhattacha K, Philos. Mag. 81, 2021, 2001
[8] Little EA, Phys. Rev. 98, 4, 1955
[9] Sih GC, Int. J. Fracture. 10, 305, 1974