Mechanical Properties, Reliability, and Failure in Ferroelectric Materials

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This short course will introduce the user of piezoelectric materials to issues that arise associated with mechanical properties, reliability, and failure.

Linear piezoelectricity describes the mechanical behavior as a perfectly linear stress-strain curve that can be shifted along the strain axis by application of an electric field. In reality, ferroelectric materials are heterogeneous and display stress-strain behavior that is non-linear and hysteretic. The source of the non-linearity and hysteresis is non 180-degree domain wall motion and phase transformations. This lecture will begin with a review of the types of domain wall motion and phase transformations in ferroelectric materials with perovskite structure, and the effects on mechanical properties. Examples will be presented that explain the observed stress-strain behavior in commonly available ferroelectric materials that include various compositions of lead zirconate titanate (PZT) and PMN-PT based single crystals and how this behavior is affected by electric field.

Ferroelectric materials are used in a broad range of applications from acoustic imaging to high power sonar, from micron scale actuation to macro-scale morphing. Reliability is not an issue for low cycle, low stress, and low electric field applications; but considerations of reliability in device design become increasingly important when the ferroelectric materials are used in high field applications. This part of the course will focus on mechanical reliability that is compromised by tensile stress. Tensile stress arises any time the ferroelectric material is clamped and the applied electric field drives it to contract. This can occur where a piezoelectric actuator is mounted against a rigid structure, or within the ferroelectric material in regions where the electric field is not homogeneous such as near the edges of electrodes. A number of examples will be presented that result in field inhomogeneities including interdigitated electrodes, partial electrodes in multilayers, and surfaces with patterned electrodes to control shape. A first approximation of stress concentrations can be obtained using a linear piezoelectric finite element analysis. The limitations of this approach will be discussed. More details can be obtained using material models with hysteresis, but these take programming and are not generally commercially available.

Mechanical failure ends the life of the device. In many cases mechanical failure can be avoided by properly pre-loading the ferroelectric material in compression, but there are times when this simply is not possible. Over the past several decades, researchers have attempted to use fracture mechanics to better understand failure in these materials. The results have met with mixed degrees of success. At this point the contributions of electric field to crack tip stress concentrations are fairly well understood, but avoiding fatigue and fracture still comes down to designing to avoid tensile stress. An overview of the fracture mechanics approach to understanding fracture will be presented. This will be followed by several approaches that have led to improved actuator reliability through the use of pre-stress.