THERMAL-INDUCED FRACTURE OF ELECRTODED PIEZOELECTRIC COMPOSITES

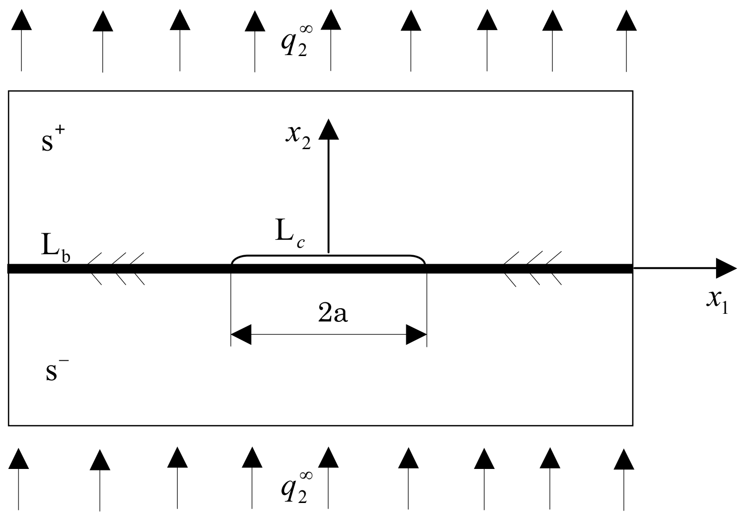
Cun-Fa Gao, Masayuki Ishihara, Naotake Noda

Dept.of Mech. Eng., Shizuoka University, 3-5-1, Johoku, Hamamatsu, Shizuoka 432-8561, JAPAN

Summary A thermally partially- insulated and electrically completely-permeable interface crack is studied based on the Stroh formalism. The crack is located between an internal electrode layer and one of two piezoelectric matrices subject to remote heat flux. It is found that the singular fields near the crack-tip are the same as those in a purely elastic bi-material system with an interface crack.

INTRTODUCTION

The multilayer piezo-ceramic actuators with metal electrodes have widely been used in engineering. Due to material mismatch between electrodes and ceramics, the electrode may partially debond from the matrix when the actuators work in high temperature environment. Some important results have been presented by Dos Santos e Lucato et al. [1] for the case where the electrode is located in a homogeneous material, and also by Deng and Meguid [2] for an electrode embodied between two dissimilar piezoelectric materials. On the fracture problems of electrode-matrix interface cracks, one may referee to the work of Ru [3]. The cited results did not take into account the thermal effort. With the rapidly increasing use of piezoelectric materials in high-temperature environment, it is also of both theoretical and practical importance to study the fracture problems of electrode-matrix interface cracks under thermal loading. This work studies an interface crack in a piezoelectric bi-material system, which consists of a soft internal electrode layer and two dissimilar piezoelectric semi-bodies s^+ and s^-, which are subject to remote heat flux q_2^∞, as shown in the figure. Singular fields near the crack will be analysed and then exact solution for the stress intensity factor will be presented based on the mixed-form Stroh formalism for thermo- piezoelectric materials.



MAIN ASSUNPTIONS

In this work we assume that (i) the traction-free crack is thermally partially-insulated and electrically completely-permeable; (ii) the electrode layer is so thin that its mechanical properties can be neglected, and (iii) the two half-infinite piezoelectric matrices coexist in the state of generalized 2D deformation under the remote heat flux.

ESSENTIAL EQUATIONS

Define a generalized stress vector $\hat{\boldsymbol{\phi}}_{,1} = (\sigma_{21}, \sigma_{22}, \sigma_{23}, -E_1)^T$, where σ_{ij} and E_1 are the components of stress and electric field, respectively. Then, we can finally give the expression of $\hat{\boldsymbol{\phi}}_{,1}$ along the x_1 axis as

$$\hat{\boldsymbol{\phi}}_{,1}^{+}(x_1) = \hat{\mathrm{h}}\mathrm{U}^{+}(x_1) + \bar{\hat{\mathrm{h}}}^{-1}\mathrm{U}^{-}(x_1) + \hat{\mathrm{m}}' q_{2\Delta}^{\infty} x_1 + \hat{\mathrm{m}}'' q_{2\Delta}^{\infty}\sqrt{x_1^2 - a^2}\ , \tag{1}$$

where $\hat{\mathrm{h}}$, $\hat{\mathrm{m}}'$ and $\hat{\mathrm{m}}''$ are constant matrix and vectors, respectively, $\mathrm{U}(z)$ is an unknown complex function and $q_{2\Delta}^{\infty} = q_2^{\infty}(\lambda_0 - 1)$, in which $0 \le \lambda_0 \le 1$ is a factor characterizing the heat conductivity of the crack surface.

Taking the fourth row of (1) gives

$$-E_1(x_1) = \sum_{j=1}^{4} \hat{h}_{4j} U_j^{+}(x_1) + \sum_{j=1}^{4} \bar{\hat{h}}_{4j} U_j^{-}(x_1) + \hat{m}_4' q_{2\Delta}^{\infty} x_1 + \hat{m}_4'' q_{2\Delta}^{\infty}\sqrt{x_1^2 - a^2}\ . \tag{2}$$

Using the condition $E_1(x_1) = 0$ along the x_1 axis we can express $U_4(z)$ by using $U_1(z), U_2(z)$ and $U_3(z)$ through use of (2). Then, substituting the obtained $U_4(z)$ into the first three rows of (1) we can get the expression of stress components, which contains only three unknown functions $U_1(z), U_2(z)$ and $U_3(z)$ that is

$$\boldsymbol{\sigma}_2 = \Lambda \mathrm{U}_3^{+} + \bar{\Lambda}\mathrm{U}_3^{-} + \lambda' q_{2\Delta}^{\infty} x_1 + \lambda'' q_{2\Delta}^{\infty}\sqrt{x_1^2 - a^2} \tag{3}$$

where Λ, λ' and λ'' are new constant matrix and vectors, respectively, $\boldsymbol{\sigma}_2 = (\sigma_{21}, \sigma_{22}, \sigma_{23})^T$ and $\mathrm{U}_3 = (U_1, U_2, U_3)^T$. Using the traction-free condition $\boldsymbol{\sigma}_2 = 0$ on the crack faces, together with single-valued conditions of displacements and electric potential, we can give the solution of $\mathrm{U}_3(z)$ from (3). With this solution, all other solutions will finally be determined.

MAIN RESULTS

Main results include the expression of stress intensity factor vector as

$$\mathrm{k}_{\sigma} = \sqrt{\pi a}\,[\Lambda \mathrm{Q}]\mathrm{diag}\left((2a)^{-i\varepsilon_{\alpha}}\right)[\Lambda \mathrm{Q}]^{-1}\,\mathrm{k}_0(\lambda) a q_{2\Delta}^{\infty}, \tag{4}$$

with $\mathrm{k}_0(\lambda) = \left\langle\left\langle 1 + 2i\varepsilon_{\alpha} + \varepsilon_{\alpha}^2 - 4\varepsilon_{\alpha}^2 / a\right\rangle\right\rangle(\lambda' + \lambda'') - \lambda''/2$, where Q is a known matrix and the positive and real constant ε depends on the material properties and characterizes the oscillatory singularities. For special cases of a homogeneous material we have $\mathrm{k}_{\sigma} = \sqrt{\pi a}\,\lambda' a q_{2\Delta}^{\infty}$.

CONCLUSIONS

Main conclusions are:

(i) The structure of singular fields near the electrode-matrix interfacial crack is the same as that in a purely elastic bi-material system with interface cracks, that is, the crack-tip singularities of electrode-matrix interface cracks can uniquely be characterized by an inverse square root singularity and a pair of oscillatory singularities.

(ii) The intensities of singular fields depend on the heat conductivity of the crack surface.

REFERENCES

[1] Dos Santos e Lucato, S.L., Lupascu, D.C., Kamlah, M., Rödel, J., Lynch, C.S.: Constraint-induced crack initiation at electrode edges in piezoelectric ceramics. Acta Mater. **49**: 2751-2759, 2001.

[2] Deng, D., Meguid, S.A.: Analysis of conducting rigid inclusion at the interface of two dissimilar piezoelectric materials. J. Appl. Mech. **65**: 76-84, 1998.

[3] Ru, C.Q.: Electrode-ceramic interfacial cracks in piezoelectric multilayer materials. J. Appl. Mech.**67**, 255-261, 2000.