Research Article

Exact Solutions for Interaction of Parallel Screw Dislocations with a Wedge Crack in One-Dimensional Hexagonal Quasicrystal with Piezoelectric Effects

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The purpose of this paper is to consider the interaction between many parallel dislocations and a wedge-shaped crack and their collective response to the external applied generalized stress in one-dimensional hexagonal piezoelectric quasicrystal, employing the complex variable function theory and the conformal transformation method; the problem for the crack is reduced to the solution of singular integral equations, which can be further reduced to solving Riemann–Hilbert boundary value problems. The analytical solutions of the generalized stress field are obtained. The dislocations are subjected to the phonon field line force, phason field line force, and line charge at the core. The positions of the dislocations are arbitrary, but the dislocation distribution is additive. The dislocation is not only subjected to the external stress and the internal stress generated by the crack, but also to the force exerted on it by other dislocations. The closed-form solutions are obtained for field intensity factors and the image force on a screw dislocation in the presence of a wedge-shaped crack and a collection of other dislocations. Numerical examples are provided to show the effects of wedge angle, dislocation position, dislocation distribution containing symmetric configurations and dislocation quantities on the field intensity factors, energy release rate, and image force acting on the dislocation. The principal new physical results obtained here are (1) the phonon stress, phason stress, and electric displacement singularity occur at the crack tip and dislocations cores, (2) the increasing number of dislocations always accelerates the crack propagation, (3) the effect of wedge angle on crack propagation is related to the distribution of dislocations, and (4) the results of the image force on the dislocation indicate that the dislocations can either be attracted or rejected and reach stable positions eventually.

1. Introduction

As a new structure of solid, quasicrystal (QC) was discovered by Shechtman et al. [1] in 1984. QC is a new solid structure with long-range orientation order and without translational symmetry which differs from crystals. The elastic problem of QC is related not only to the phonon field which describes lattice vibration, but also to the phason field which is about the quasiperiodic arrangement of atoms. As soon as the quasicrystal was discovered, it attracted wide attention because of its special symmetry and good performance. In the early discovery of the quasicrystal, the defects in the quasicrystal were observed [2]. Due to the unique properties of

quasicrystal materials, many achievements have been made in the study of quasicrystal elasticity and fracture mechanics [3–9]. To name a few recent researches, Lou et al. [10] proposed a model of a thin elastic inclusion embedded in an infinite 1D hexagonal quasicrystal. Wang and Schiavone [11] investigated the elastic field near the tip of an anticrack in a homogeneous decagonal quasicrystal material subjected to plane strain deformations. Zhao et al. [12] studied the frictional contact problem and the adhesive contact problem in three-dimensional (3D) icosahedral quasicrystal. Li et al. [13] have given analytical solutions for arbitrarily shaped planar cracks in a two-dimensional (2D) hexagonal QC media.

Quasicrystal is sensitive to force, electricity, magnetism, heat, and light, and these physical properties have been extensively studied. It is well known that QCs with piezoelectric effects have better performance in smart composite structures. Therefore, the study of quasicrystal materials considering the piezoelectric effect is of great significance. A lot of work on QC with piezoelectric effects has been published in the open literature. Li et al. [14] obtained three-dimensional general solutions to static problems of a 1D hexagonal piezoelectric QC. Yu et al. [15] considered an antiplane crack problem by the semi-inverse method in a 1D hexagonal piezoelectric QC. Yu et al. [16] also discussed the complex variable method for an antiplane elliptical cavity. Yang et al. [17] presented the fracture behavior of two asymmetrical limited permeable cracks emanating from an elliptical hole in a one-dimensional hexagonal quasicrystal with piezoelectric effects. Yang et al. [18] derived the closed-form solution for a multilayered two-dimensional decagonal QC plate. Guo et al. [19] analyzed an elliptical inclusion embedded in an infinite 1D hexagonal piezoelectric QC matrix. Li et al. [20] have given the exact solution for a layered piezoelectric quasicrystal nanoplate with nonlocal effect in cylindrical bending. Zhang et al. [21] addressed the static bending deformation of a functionally graded multilayered 1D hexagonal piezoelectric QC simply supported nanoplate. Zhou and Li [22] dealt with the problem of two collinear cracks in a one-dimensional hexagonal piezoelectric QC strip under mode III far-field loading, while they analyzed the electroelastic problem related to two collinear cracks of equal length and normal to the boundaries of a 1D hexagonal piezoelectric quasicrystal layer with the aid of a singular integral equation in ref. [23]. Besides, Zhou and Li [24] examined the electroelastic behavior induced by a penny-shaped dielectric crack of a 1D hexagonal piezoelectric quasicrystal plate of finite thickness, and they considered a Yoffe-type moving crack in a 1D hexagonal piezoelectric quasicrystal by using the Fourier transform technique in ref. [25]. Li and Liu [26] derived the electroelastic field of a straight dislocation in an icosahedral piezoelectric QC. Li et al. [27] displayed the interaction between a screw dislocation and an elliptical hole with two asymmetrical cracks in a 1D hexagonal quasicrystal with piezoelectric effects. Hu et al. [28] studied an antiplane interface crack between dissimilar 1D hexagonal piezoelectric QC.

Engineering materials always contain some defects, such as dislocations, inclusions, and cracks. The existence of these defects often seriously affects the safety and reliability of materials. There is not only one defect in the material, but usually different types of defects also exist at the same time, and the interaction between multiple defects has a very important impact on the mechanical properties and physical properties of the material. Dislocation activity is the cause of plastic deformation at the crack tip, which determines the crack propagation behavior, so the interaction between crack and dislocation has attracted more and more attention. Concerning the wedge-shaped crack which is an important geometric form of structures interacting with a single dislocation, Ohr et al. [29]

performed the elastic analysis of the interaction between a wedge crack and a screw dislocation. Zhang et al. [30] obtained an analytical solution of the interaction of edge dislocation with the wedge crack by using the elastic technique of Muskhelishvili. Chen et al. [31] derived the closed solution of the electroelastic field for a screw dislocation situated near the tip two-bonded wedge-shaped dissimilar piezoelectric materials. Furthermore, they deduced the electroelastic stress field in the interaction of a piezoelectric screw dislocation with a wedge-shaped bimaterial interface in ref. [32]. Li and Zhao [33] coped with the problem of the interaction of a screw dislocation with the interface and wedge-shaped cracks in a one-dimensional hexagonal piezoelectric QC biomaterial using the conformal mapping method in conjunction with the image principle. Jiang and Liu [34] investigated the interaction between a screw dislocation and a wedge-shaped crack in the 1D hexagonal piezoelectric QC based on the conformal mapping method and the perturbation technique.

The research studies mentioned above were mainly focused on the single screw dislocation interacting with the various types of cracks. In engineering practice, structures with pairs of dislocations are very common. Dislocation emission and dislocation pile-up at the crack tip will result in crack blunting, inhibiting the growth of the crack and then improving the fracture toughness of the material. Concerning multiple dislocations interacting with cracks, the dislocation is not only subjected to the external stress and the internal stress generated by the crack, but also to the force exerted on it by other dislocations. Lin and Thomson [35] earlier investigated the elastic interaction between pairs of dislocations and a cleavage crack under external loads. Later, Juang and Lee [36] examined the interaction of the two-dislocation model and a surface crack by using the dislocation-modelling technique and the complex variable method. More recently, Liu and Yang [37] made a detailed analysis of the stress field of infinitely many parallel screw dislocations near a semi-infinite crack tip without applied loads, and dislocations considered here are located at particular points to make the total stress finite. Lv and Liu [38] addressed the analytical solution of the generalized stress field for parallel screw dislocations near a semi-infinite crack in magnetic-electric-mechanical coupling fields. However, for the piezoelectric QC, these problems become more complicated than the conventional material due to the introduction of the phason field and the electric field. To the best of the authors' knowledge, the study on the interaction between the wedge-shaped crack and multiple dislocations in a 1D hexagonal QC with piezoelectric effect has not been reported yet. In this paper, through the singular integral technique, we consider the antiplane problem of the interaction between many parallel screw dislocations and a wedge-shaped crack under remote uniform loadings, and the dislocations are subjected to the phonon field line force, phason field line force, and line charge at the core. The positions of the dislocations are arbitrary. The advantage of the present

model is demonstrated when dealing with many dislocations because the dislocation distribution is additive. The expressions for the generalized stress field, field intensity factors, energy release rate, and image force are derived in a closed form. The exact solutions are presented and compared with those already obtained by other authors. Numerical examples are presented for various parameters of the problem.

2. Basic Equations

The quasicrystal piezoelectric material considered here is transversely isotropic with a hexagonal symmetry, which has an isotropic basal plane of $x_1 - x_2$ plane and an electric field poling direction and quasiperiodic direction of the x_3 axis. When the defects penetrate along the x_3 axis, the quasicrystal piezoelectric boundary value problem is treated as in the case of out-of-plane phonon field displacement $u_3(x_1, x_2)$, out-of-plane phason field displacement $w_3(x_1, x_2)$, and in-plane electric field $\varphi(x_1, x_2)$. The basic equations can be written as follows [39].

In this case, the constitutive relations become

$$\begin{aligned}\sigma_{3k} &= C_{44}u_{3,k} + R_3w_{3,k} - e_{15}\varphi_{,k}, \\ H_{3k} &= R_3u_{3,k} + K_2w_{3,k} - d_{15}\varphi_{,k}, \\ D_k &= e_{15}u_{3,k} + d_{15}w_{3,k} + \lambda_{11}\varphi_{,k}, \\ (k &= 1, 2).\end{aligned}\quad (1)$$

Generalized strain-displacement relations are given by

$$\begin{aligned}\varepsilon_{ij} &= \frac{(u_{i,j} + u_{j,i})}{2}, \\ \omega_{ij} &= w_{i,j}, \\ E_i &= -\phi_{,i}, \\ (i &= 1, 2, 3).\end{aligned}\quad (2)$$

Equilibrium equations are

$$\begin{aligned}\sigma_{ij,i} &= 0, \\ H_{ij,i} &= 0, \\ D_{i,i} &= 0,\end{aligned}\quad (3)$$

where a comma represents differentiation with respect to x_i ($i = 1, 2, 3$); the repeated indices denote that summation σ_{3k} and ε_{3k} are the phonon field stress and strain; H_{3k} and ω_{3k} are the phason field stress and strain; D_k and E_k are the electric displacement and the electric field; C_{44} , K_2 , and R_3 are the phonon field elastic, phason field elastic, and phonon-phason field coupling coefficients; e_{15} and d_{15} are the piezoelectric constants; λ_{11} is the dielectric constant.

Substituting equations (1) and (2) to (3), the governing equation becomes

$$C\nabla^2 \mathbf{u} = 0, \quad (4)$$

in which

$$\begin{aligned}\mathbf{u} &= [u_3 \ w_3 \ \varphi]^T, \\ \nabla^2 &= \frac{\partial^2}{\partial x_1^2} + \frac{\partial^2}{\partial x_2^2}, \\ \mathbf{C} &= \begin{bmatrix} C_{44} & R_3 & e_{15} \\ R_3 & K_2 & d_{15} \\ e_{15} & d_{15} & -\lambda_{11} \end{bmatrix}.\end{aligned}\quad (5)$$

In general,

$$\det \mathbf{C} = -C_{44}d_{15}^2 - K_2e_{15}^2 + 2R_3d_{15}e_{15} - C_{44}K_2\lambda_{11} + R_3^2\lambda_{11} \neq 0. \quad (6)$$

Equation (4) can be written as

$$\nabla^2 \mathbf{u} = 0. \quad (7)$$

3. Description of the Problem and Its Solutions

3.1. The Electroelastic field of Parallel Screw Dislocations. The physical problem is shown in Figure 1. There are n parallel screw dislocations located at $z_i(r_i, \theta_i)$ ($i = 1, 2, \dots, n$) with the Burgers vectors $(0, 0, b_3^{(i)}, b_\perp^{(i)}, b_\phi^{(i)})$ in the vicinity of a wedge-shaped crack in the 1D hexagonal QC piezoelectric material which is under the far-field uniform loading $(\sigma_{32}^\infty, H_{32}^\infty, E_2^\infty)$. The dislocations are subjected to the phonon field line force p , phason field line force q , and line charge v at the core. The wedge-shaped crack is infinitely long along the negative real axis, and α denotes the wedge angle.

As shown in Figure 1, we have the following crack boundary conditions:

$$\begin{aligned}\sqrt{x_1^2 + x_2^2} &\longrightarrow \infty: \sigma_{32} = \sigma_{32}^\infty, \\ H_{32} &= H_{32}^\infty, E_2 = E_2^\infty, \\ (x, y) \in \theta &= \pm \left(\pi - \frac{\alpha}{2} \right): \sigma_{32} = 0, \\ H_{32} &= 0, \\ E_2 &= 0.\end{aligned}\quad (8)$$

Proposing a conformal transformation function

$$\begin{aligned}z &= m(\zeta) = \zeta^{1/\lambda}, \\ \lambda &= \frac{2\pi}{2\pi - \alpha},\end{aligned}\quad (9)$$

which maps the wedge-shaped crack in the z plane to a semi-infinite crack along the negative real axis in the ζ plane (see Figure 2). The problem turns into the interaction of parallel screw dislocations with a semi-infinite crack.

FIGURE 1: The interaction between a wedge-shaped crack and many parallel screw dislocations.

FIGURE 2: Conformal transformation.

In the ζ plane, we first consider the analytical solution of the elastic field of a screw dislocation. Assuming that one of the dislocations is situated at the point ζ_d with the Burgers vector $(0, 0, 0, b_3, b_\perp, b_\varphi)$, $\mathbf{u}$ can be expressed by the imaginary part of an arbitrary analytic function $\mathbf{f}(\zeta)$ following the theory of a complex variable function, and $\zeta = \xi_1 + i\xi_2$ and

$$\mathbf{u} = \text{Im}[\mathbf{f}(\zeta)]. \quad (10)$$

It is reasonable to assume that the potential function is composed of two parts; that is,

$$\mathbf{f}(\zeta) = \mathbf{f}_0(\zeta) + \mathbf{f}_1(\zeta), \quad (11)$$

where $\mathbf{f}_0(\zeta)$ is the complex potential for the dislocation in an infinite medium and $\mathbf{f}_1(\zeta)$ is the additional term which assumes that the stress boundary conditions on the cleavage surfaces are satisfied. Based on the force conditions of the dislocation, $\mathbf{f}_0(\zeta)$ can be chosen as

$$\mathbf{f}_0(\zeta) = \mathbf{A} \ln(\zeta - \zeta_d), \quad (12)$$

with

$$\mathbf{A} = [A_1 + iA_2, B_1 + iB_2, C_1 + iC_2]^T. \quad (13)$$

Then,

$$\begin{aligned} \text{Im} \left[\oint_{\zeta_d} \mathbf{f}'_0(\zeta) d\zeta \right] &= \text{Im} \left[\oint_{\zeta_d} \frac{\mathbf{A}}{\zeta - \zeta_d} d\zeta \right] = \text{Im} [2\pi i \mathbf{A}] \\ &= [b_3, b_\perp, b_\varphi]^T, \\ \text{Im} \left[\oint_{\zeta_d} -i \mathbf{C} \mathbf{f}'_0(\zeta) d\zeta \right] &= \text{Im} \left[\oint_{\zeta_d} \frac{-i \mathbf{C} \mathbf{A}}{\zeta - \zeta_d} d\zeta \right] = \text{Im} [2\pi \mathbf{C} \mathbf{A}] \\ &= [-p, -q, v]^T. \end{aligned} \quad (14)$$

From equations (10)–(14), we have

$$\begin{cases} A_1 = \frac{b_3}{2\pi}, \\ A_2 = \frac{(K_2 \lambda_{11} + d_{15}^2)p - (R_3 \lambda_{11} + e_{15} d_{15})q - (K_2 e_{15} - R_3 d_{15})v}{2\pi \det \mathbf{C}}, \\ B_1 = \frac{b_\perp}{2\pi}, \\ B_2 = \frac{-(\lambda_{11} R_3 + e_{15} d_{15})p + (\lambda_{11} C_{44} + e_{15}^2)q - (C_{44} d_{15} - R_3 e_{15})v}{2\pi \det \mathbf{C}}, \\ C_1 = \frac{b_\varphi}{2\pi}, \\ C_2 = \frac{(e_{15} K_2 - R_3 d_{15})p + (C_{44} d_{15} - R_3 e_{15})q + (C_{44} K_2 - R_3^2)v}{2\pi \det \mathbf{C}}. \end{cases} \quad (15)$$

Introducing the generalized strains $\mathbf{Z}_2 = [\varepsilon_{32}, \omega_{32}, -E_2]$ and $\mathbf{Z}_1 = [\varepsilon_{32}, \omega_{32}, -E_2]$ and the generalized stresses $\Sigma_2 = [\sigma_{32}, H_{32}, D_2]^T$ and $\Sigma_1 = [\sigma_{31}, H_{31}, D_1]^T$, the generalized strain field and the stress field can be written as

$$\mathbf{Z}_2 + i\mathbf{Z}_1 = \mathbf{f}'_0(\zeta) = \frac{\mathbf{A}}{\zeta - \zeta_d}, \quad (16)$$

$$\Sigma_2 + i\Sigma_1 = \mathbf{C} \mathbf{f}'_0(\zeta) = \frac{\mathbf{C} \mathbf{A}}{\zeta - \zeta_d}. \quad (17)$$

According to equation (17), the generalized stress stimulated by dislocation ζ_i which is working on ζ_1 is

$$\mathbf{F}_{i1} = \frac{\mathbf{C} \mathbf{A}}{\zeta_1 - \zeta_i}. \quad (18)$$

Now, we study the electroelastic solution of parallel screw dislocations. Taking the form of the corresponding matrix as $\mathbf{A}_{(i)}$, the generalized stress generated by dislocation ζ_i exerted on the arbitrary point ζ is

$$\mathbf{F}_0(\zeta) = \sum_{i=1}^n \frac{\mathbf{C} \mathbf{A}_{(i)}}{\zeta - \zeta_i}. \quad (19)$$

3.2. The Interaction of n Parallel Screw Dislocations with Crack. It can be seen from the above discussion that the distribution force induced by dislocations on a semi-infinite crack sur-

face is

$$\mathbf{F}_0(\zeta) = \sum_{i=1}^n \frac{\mathbf{C}\mathbf{A}_{(i)}}{\zeta - \zeta_i} + \frac{\mathbf{C}\bar{\mathbf{A}}_{(i)}}{\zeta - \bar{\zeta}_i}, \quad -\infty < \xi_1 < 0, \xi_2 = 0. \quad (20)$$

Here, the condition of the free crack surface is considered; that is,

$$\text{Re}[\mathbf{f}'(\zeta)]^T = 0, \quad -\infty < \xi_1 < 0, \xi_2 = 0, \quad (21)$$

where Re denotes the real part of an analytical function vector.

The physical meaning of the boundary condition equation (21) is that the additional distribution force $\mathbf{F}_1$ represents the cancelling force exerted on the boundary equal to the negative of $\mathbf{F}_0$. With the aid of equation (20), the boundary condition equation (21) leads to a system of the Riemann–Hilbert problem as

$$\mathbf{F}_1^+(\xi_1) + \mathbf{F}_1^-(\xi_1) = -\mathbf{F}_0(\xi_1). \quad (22)$$

Using the standard methods given by Muskhelishvili [40], the general solution of equation (21) arrives at

$$\mathbf{F}_1(\zeta) = -\frac{X(\zeta)}{2\pi i} \int_{-\infty}^0 \frac{\mathbf{F}_0(\xi_1)}{X^+(\xi_1)(\xi_1 - \zeta)} d\xi_1 + \mathbf{P}(\zeta)X(\zeta), \quad (23)$$

where

$$X(\zeta) = \zeta^{-(1/2)}, \quad (24)$$

and we have considered the single-valued condition of generalized displacements, i.e., $P(\zeta) = 0$.

The solution of equation (20) together with equations (23) and (24) gives

$$\mathbf{F}_1(\zeta) = -\sum_{i=1}^n \frac{\mathbf{C}}{2\sqrt{\zeta}} \left(\frac{\mathbf{A}_{(i)}}{\sqrt{\zeta} + \sqrt{\zeta_i}} + \frac{\bar{\mathbf{A}}_{(i)}}{\sqrt{\zeta} + \sqrt{\bar{\zeta}_i}} \right). \quad (25)$$

Considering the stress field of the crack due to the far-field uniform loadings ($\sigma_{32}^\infty, H_{32}^\infty, E_2^\infty$), equation (20) combined with equation (25) yields

$$\mathbf{F}_{\text{total}}(\zeta) = \sum_{i=1}^n \frac{\mathbf{C}}{2\sqrt{\zeta}} \left(\frac{\mathbf{A}_{(i)}}{\sqrt{\zeta} - \sqrt{\zeta_i}} + \frac{\bar{\mathbf{A}}_{(i)}}{\sqrt{\zeta} - \sqrt{\bar{\zeta}_i}} \right) + \frac{\mathbf{C}\mathbf{B}}{\sqrt{\zeta}}, \quad (26)$$

in which $\mathbf{B} = [A_3, B_3, C_3]^T$ and

$$\begin{aligned} A_3 &= \frac{\sigma_{32}^\infty - R_3\omega_{32}^\infty + e_{15}E_2^\infty}{C_{44}}, \\ B_3 &= \omega_{32}^\infty, \\ C_3 &= -E_2^\infty. \end{aligned} \quad (27)$$

Therefore, the analytic solution of electroelastic interaction of many parallel screw dislocations with the crack is

$$\begin{aligned} \mathbf{F}_{\text{total}}(z) &= \frac{\mathbf{F}_{\text{total}}(\zeta)}{m'(\zeta)} = \sum_{i=1}^n \frac{\lambda \mathbf{C}}{2z^{1-(\lambda/2)}} \left(\frac{\mathbf{A}_{(i)}}{z^{\lambda/2} - z_i^{\lambda/2}} + \frac{\bar{\mathbf{A}}_{(i)}}{z^{\lambda/2} - \bar{z}_i^{\lambda/2}} \right) \\ &\quad + \frac{\lambda \mathbf{C}\mathbf{B}}{z^{1-(\lambda/2)}}. \end{aligned} \quad (28)$$

If $\lambda = 1$ and $i = 1$, equation (28) reduces to the result in ref. [41] under some restrictions.

4. Field Intensity Factors and Energy Release Rate

4.1. Field Intensity Factors. In the z plane, according to ref. [31], the phonon field stress, the phason field stress, and the electric displacement intensity factor at the wedge-shaped crack tip are defined as

$$\mathbf{K} = \begin{bmatrix} K_{\sigma_{32}} + iK_{\sigma_{31}} \\ K_{H_{32}} + iK_{H_{31}} \\ K_{D_2} + iK_{D_1} \end{bmatrix} = \lim_{z \rightarrow 0} (2\pi z)^{1-(\lambda/2)} \mathbf{F}_{\text{total}}. \quad (29)$$

Actually, only $\varepsilon_{32}, \omega_{32}, E_2, \sigma_{32}, H_{32}$, and D_2 are singular at the crack tip. Substituting equation (28) to (29) and setting $z_i = r_i e^{i\theta_i}$, we obtain

$$K_{\sigma_{32}} = \frac{\lambda}{(2\pi r_i)^{\lambda/2}} \sum_{i=1}^n \left[p \sin \frac{\lambda}{2} \theta_i - (C_{44}b_3 + R_3b_\perp + e_{15}b_\varphi) \cos \frac{\lambda}{2} \theta_i \right] + \lambda (2\pi)^{1-(\lambda/2)} \sigma_{32}^\infty, \quad (30)$$

$$\begin{aligned} K_{H_{32}} &= \frac{\lambda}{(2\pi r_i)^{\lambda/2}} \sum_{i=1}^n \left[q \sin \frac{\lambda}{2} \theta_i - (R_3b_3 + K_2b_\perp + d_{15}b_\varphi) \cos \frac{\lambda}{2} \theta_i \right] \\ &\quad - \lambda (2\pi)^{1-(\lambda/2)} \left(d_{15}E_2^\infty - K_2\omega_{32}^\infty - \frac{R_3(e_{15}E_2^\infty - R_3\omega_{32}^\infty + \sigma_{32}^\infty)}{C_{44}} \right), \end{aligned} \quad (31)$$

$$\begin{aligned} K_{D_2} &= -\frac{\lambda}{(2\pi r_i)^{\lambda/2}} \sum_{i=1}^n \left[v \sin \frac{\lambda}{2} \theta_i + (e_{15}b_3 + d_{15}b_\perp - \lambda_{11}b_\varphi) \cos \frac{\lambda}{2} \theta_i \right] \\ &\quad + \lambda (2\pi)^{1-(\lambda/2)} \left(\lambda_{11}E_2^\infty + d_{15}\omega_{32}^\infty + \frac{e_{15}(e_{15}E_2^\infty - R_3\omega_{32}^\infty + \sigma_{32}^\infty)}{C_{44}} \right). \end{aligned} \quad (32)$$

Equations (30)–(32) agree with Chen's results [31] if there is only one dislocation and the phason field and the applied generalized stress are not considered. If the applied loading is $(\sigma_{32}^{\infty}, H_{32}^{\infty}, E_2^{\infty})$ and the matrix only contains one dislocation whose core are not under the line force, the above equations can reduce to Li's results [3]. On the basis of the above restrictions, if the phason field is neglected, the solutions agree with those in ref. [34]. Moreover, equations (30)–(32) suggest that $K_{\sigma_{32}}$ is independent of q and v , $K_{H_{32}}$ is independent of p and v , and K_{D_2} is independent of p and q , if all $b_3, b_{\perp}, b_{\phi}, p, q$, and v are supposed to be positive.

4.2. Energy Release Rate. The energy release rate can be calculated as [42]

$$G = \frac{1}{4} \mathbf{K}^T \mathbf{H} \mathbf{K}, \quad (33)$$

where $\mathbf{H} = 2\mathbf{C}^{-1}$.

Thus, the energy release rate for the interaction of the wedge-shaped crack with screw dislocations is derived as

$$\begin{aligned} G = & \frac{1}{2\det\mathbf{C}} \left[(-d_{15}^2 - K_2\lambda_{11})K_{\sigma_{32}}^2 + (-e_{15}^2 - C_{44}\lambda_{11})K_{H_{32}}^2 \right. \\ & + (C_{44}K_2 - R_3^2)K_{D_2}^2 + 2(d_{15}e_{15} + R_3\lambda_{11})K_{\sigma_{32}}K_{H_{32}} \\ & \left. + 2(-C_{44}d_{15} + e_{15}R_3)K_{H_{32}}K_{D_2} + 2(-e_{15}K_2 + d_{15}R_3)K_{\sigma_{32}}K_{D_2} \right]. \end{aligned} \quad (34)$$

5. Image Force

The image force is expressed as [43]

$$\begin{cases} F_1 = b_3\sigma_{32}^T + b_{\perp}H_{32}^T + b_{\phi}D_2^T + p\varepsilon_{31}^T + q\omega_{31}^T + vE_1^T, \\ F_2 = -b_3\sigma_{31}^T - b_{\perp}H_{31}^T - b_{\phi}D_1^T + p\varepsilon_{32}^T + q\omega_{32}^T + vE_2^T, \end{cases} \quad (35)$$

where stresses and strains with superscript “T” are the perturbation stresses and strains at the dislocation point.

Therefore, the image force exerted on the dislocation at z_d (z_d is excluded from z_i) in the presence of a wedge-shaped crack and a collection of other dislocations at z_i can be expressed as

$$\begin{aligned} \bar{f}_d = F_1 - iF_2 = & \frac{\mathbf{b}\mathbf{C}}{m'(\zeta_d)} \left[-\frac{\mathbf{A}}{4\zeta_d} + \frac{\bar{\mathbf{A}}}{2\sqrt{\zeta_d}(\sqrt{\zeta_d} - \sqrt{\bar{\zeta}_d})} \right] \\ & + \frac{i\mathbf{b}'}{m'(\zeta_d)} \left[-\frac{\mathbf{A}}{4\zeta_d} + \frac{\bar{\mathbf{A}}}{2\sqrt{\zeta_d}(\sqrt{\zeta_d} - \sqrt{\bar{\zeta}_d})} \right] + \\ & \sum_i \left\{ \frac{\mathbf{b}\mathbf{C}}{m'(\zeta_d)} \left[\frac{\mathbf{A}_{(i)}}{2\sqrt{\zeta_d}(\sqrt{\zeta_d} - \sqrt{\zeta_i})} + \frac{\bar{\mathbf{A}}_{(i)}}{2\sqrt{\zeta_d}(\sqrt{\zeta_d} - \sqrt{\bar{\zeta}_i})} \right] \right. \\ & \left. + \frac{i\mathbf{b}'}{m'(\zeta_d)} \left[\frac{\mathbf{A}_{(i)}}{2\sqrt{\zeta_d}(\sqrt{\zeta_d} - \sqrt{\zeta_i})} + \frac{\bar{\mathbf{A}}_{(i)}}{2\sqrt{\zeta_d}(\sqrt{\zeta_d} - \sqrt{\bar{\zeta}_i})} \right] \right\} \\ & + \frac{\mathbf{b}\mathbf{C}\mathbf{B} + i\mathbf{b}'\mathbf{B}}{m'(\zeta_d)\sqrt{\zeta_d}}, \end{aligned} \quad (36)$$

TABLE 1: Material constants in the 1D hexagonal piezoelectric quasicrystal.

$C_{44} (\text{Nm}^{-2})$	$R_3 (\text{Nm}^{-2})$	$K_2 (\text{Nm}^{-2})$	$e_{15} (\text{Cm}^{-2})$	$d_{15} (\text{Cm}^{-2})$	$\lambda_{11} (\text{C}^2 \text{N}^{-1} \text{m}^{-2})$
5×10^{10}	1.20×10^9	0.30×10^9	-0.138	-0.16	82.6×10^{-12}

FIGURE 3: Contours of phonon field stress components are induced by dislocations situated at $(0, 1)$ and $(0, -1)$, (a) σ_{32} and (b) σ_{31} , and at $(1, 0)$ and $(2, 0)$, (c) σ_{32} and (d) σ_{31} .

where

$$\begin{aligned} \mathbf{b} &= (b_3, b_\perp, b_\varphi), \\ \mathbf{b}' &= (p, q, v). \end{aligned} \quad (37)$$

Noting that the above solution can be reduced to Lin and Thomson [35] in the case of $\lambda = 1$ and the material is pure

elastic. Furthermore, equation (36) is comprised of three terms. The first term containing the quadratic of (b, b') coming from the image dislocation. The second term containing (b, b') and $(b^{(i)}, b'^{(i)})$ which are the interaction forces from the other dislocations acting on the dislocation z_d . The last one containing (b, b') which is induced by the applied generalized stress.

FIGURE 4: Contours of phason field stress components are induced by dislocations situated at (0, 1) and (0, -1), (a) $H_{32}/10^{-2}$ and (b) $H_{31}/10^{-2}$, and at (1, 0) and (2, 0), (c) $H_{32}/10^{-2}$ and (d) $H_{31}/10^{-2}$.

When all the dislocations are located at the real axis, the solution can be simplified as

$$\begin{aligned} \bar{f}_d = & -\frac{\mathbf{bCA}}{4m'(\xi_d)\xi_d} - \frac{i\mathbf{b}'\mathbf{A}}{4m'(\xi_d)\xi_d} \\ & + \sum_i \left\{ \frac{\mathbf{bCA}_{(i)}}{m'(\xi_d)\sqrt{\xi_d}(\sqrt{\xi_d} - \sqrt{\xi_i})} + \frac{i\mathbf{b}'\mathbf{A}_{(i)}}{m'(\xi_d)\sqrt{\xi_d}(\sqrt{\xi_d} - \sqrt{\xi_i})} \right\} \\ & + \frac{\mathbf{bCB} + i\mathbf{b}'\mathbf{B}}{m'(\xi_d)\sqrt{\xi_d}} \end{aligned} \quad (38)$$

i.e.,

$$\begin{aligned} \bar{f}_d = & -\frac{\mathbf{bCA}}{4x_d} - \frac{i\mathbf{b}'\mathbf{A}}{4x_d} + \sum_i \frac{\mathbf{bCA}_{(i)}}{x_d^{1-(\lambda/2)}(x_d^{\lambda/2} - x_i^{\lambda/2})} \\ & + \frac{i\mathbf{b}'\mathbf{A}_{(i)}}{x_d^{1-(\lambda/2)}(x_d^{\lambda/2} - x_i^{\lambda/2})} + \frac{\mathbf{bCB} + i\mathbf{b}'\mathbf{B}}{x_d^{1-(\lambda/2)}}. \end{aligned} \quad (39)$$

6. Numerical Example

Although the field intensity factors, energy release rate, and the image force acting on the dislocation are expressed

FIGURE 5: Contours of electric displacement components are induced by dislocations situated at $(0, 1)$ and $(0, -1)$, (a) $D_2/10^{-11}$ and (b) $D_1/10^{-11}$, and at $(1, 0)$ and $(2, 0)$, (c) $D_2/10^{-12}$ and (d) $D_1/10^{-12}$.

explicitly in the previous sections, it is not straightforward that how the dislocation location, dislocation distribution, the wedge angle, and the number of dislocations affect them. The numerical examples are therefore performed in this section. The material constants we choose are listed in Table 1 [14].

The Burgers vectors, line forces, and line charge at the dislocation core are

$$\begin{aligned}
 b_3 &= b_{\perp} = 1.0 \times 10^{-9} \text{ m}, \\
 b_{\varphi} &= 1.0 \times 10^{-9} \text{ V}, \\
 p &= q = 10 \text{ N/m}, \\
 \nu &= 1.0 \times 10^{-3} \text{ C/m}.
 \end{aligned} \tag{40}$$

FIGURE 6: (a) K_1^* varies with r_d/b_3 . (b) K_1^* varies with θ_d . FIGURE 7: (a) K_2^* varies with r_d/b_3 . (b) K_2^* varies with θ_d .

The critical energy release rate is taken as $G_r = 5 \text{ N/m}$ and the wedge angle in the following numerical discussions is $\pi/6$. For the sake of discussion, the magnitude of all Burgers vectors is regarded as 10^{-9} and all the dislocation have the same value of (p, q, v) .

Figures 3–5, respectively, show the phonon field stress, phason field stress, and electric displacement component contours due to the dislocations. When the dislocations are located at the points $(0, 1)$ and $(0, -1)$, one may note that as

the lines of σ_{32} , H_{32} , and D_2 get closer to the crack surface, they become parallel to the surface and the generalized stress becomes smaller. The phonon field stress σ_{32} vanishes when it reaches the crack surface, as well as the phason field stress H_{32} and electric displacement D_2 , so that the boundary condition is satisfied. The lines of σ_{31} , H_{31} , and D_1 are antisymmetric about the straight line $x_2 = 0$, but the lines of σ_{32} , H_{32} , and D_2 are symmetric about the straight line $x_2 = 0$. These results also reveal that the phonon field stress,

FIGURE 8: (a) $K_3^*/10^{-5}$ varies with r_d/b_3 . (b) $K_3^*/10^{-6}$ varies with θ_d .

FIGURE 9: (a) K_1^* varies with r_d/b_3 of different α . (b) Field intensity factors vary with λ .

phason field stress, and the electric displacement field show square root singularity at the crack tip while having one order singularity at the location of dislocation. The phason field stress contours have the same trend as the phason field stress contours but is opposite to the electric field. In addition, the magnitude of the electric displacement is less than the magnitude of the phason field stress, but the magnitude of the phason field stress is less than the magnitude of the phonon field stress.

Supposing there are already two dislocations located at $x_1 = 1000 \times b_3$ and $x_2 = 2000 \times b_3$, respectively, the relationship between the field intensity factors and the positions of the other dislocation is exhibited in Figures 6–8 without remote uniform loading. Let us define the normalized phonon field intensity factor, phason field intensity factor, and electric displacement intensity factor as $K_1^* = K_{\sigma_{32}}/C_{44}\sqrt{b_3}$, $K_2^* = K_{H_{32}}/C_{44}\sqrt{b_3}$, and $K_3^* = K_{D_2}/C_{44}\sqrt{b_3}$, respectively. It can be seen that the value

FIGURE 10: (a) G/G_r varies with r_d/b_3 . (b) $(G/G_r)/10^{-5}$ varies with θ_d .

FIGURE 11: (a) Energy release rate varies with λ when all the dislocations are located at the real axis. (b) Energy release rate varies with λ when all the dislocations are located at the imaginary axis symmetrically.

of K_1^* and K_3^* is always negative, but the value of K_2^* is always positive. We find that the effects of the dislocation position on the three intensity factors are different. Figures 6(a) and Figure 6(b) show that the shielding effect in the phonon field quickly decreases with the value of the normalized distance r_d/b_3 increasing, while decreases with the value of θ_d increasing. From Figures 7(a) and Figure 7(b), it is interesting to note that K_2^* increases with the increasing θ_d , while decreases with the increasing r_d/b_3 . When the dislocation is located at the real axis, the stress intensity factor is positive.

Figures 8(a) and Figure 8(b) indicate that the shielding effect on the electric field decreases as r_d/b_3 increases, while it decreases as θ_d decreases. Taking the stress intensity factor of the phonon field as an example, Figure 9(a) illustrates that K_1^* increases with α , and the larger the wedge angle is, the stronger the shielding effect will become. The variations in the three field intensity factors with the wedge angle are plotted in Figure 9(b). When the two dislocations are located at $x_1 = 1$ and $x_2 = 2$, it can be found that the phonon field stress intensity factor increases as the wedge angle increases,

FIGURE 12: (a) The force acting on the dislocation x_d varies with the distance from the dislocation x_d to the crack tip when the other dislocations are located at (1, 0) and (2, 0). (b) The force acting on the dislocation x_d varies with λ when the other dislocations are located at (1, 0) and (2, 0).

but λ has little effect on the phason field stress intensity factor and the electric displacement intensity factor since the material constants related to the phason field are far greater than those related to the phason field and the electric field.

Similarity, there exist two dislocations located at $x_1 = 1000 \times b_3$ and $x_2 = 2000 \times b_3$, respectively. In this case, Figures 10(a) and 10(b) more clearly show the retarding effects, respectively, of r_d/b_3 and θ_d on the energy release rate without far-field loading. The normalized energy release rate G/G_r increases as $d\theta$ decreases. In contrast, G/G_r increases as r_d/b_3 increases. Figure 10(a) implies that r_d/b_3 contributes none to the energy release rate when its value increases to a certain extent. Figure 10(b) illustrates that r_d/b_3 does not affect the energy rate when all the dislocations are situated at the real axis. Figures 11(a) and Figure 11(b) depict the effect of the wedge angle on the energy release rate when the dislocations are in different positions. The energy release rate is positive whether the dislocations are located at the real axis or symmetrically distributed at the imaginary axis, which means the wedge angle accelerates the crack propagation. G increases as the number of dislocations increases. Also, G increases with the increasing λ when all the dislocations are located at the real axis, while it increases first and then decreases when the dislocations are situated at the imaginary axis symmetrically.

Making all dislocations located at the real axis, and $x_1 = 1$ and $x_2 = 2$, in the absence of the remote applied generalized stress, Figure 12(a) shows that $\bar{f}_d$ is always negative when the dislocation x_d is between the crack tip and dislocation x_1 , which means dislocation x_d is always attracted. When the dislocation x_d from x_2 moves to x_1 , it is first rejected and then attracted, and the attractive force is gradually increased and the repulsive force is gradually reduced. When the dislocation x_d is farther away from x_2 , it is always rejected and the repulsive force is reduced. Figure 12(b) implies that the force on the dislocation is always positive and the magnitude decreases when increasing the wedge angle.

7. Conclusions

In this paper, the fracture mechanic model of the two-dimensional crack and parallel dislocations is established. The interaction between parallel screw dislocations and a wedge-shaped crack in a one-dimensional hexagonal quasicrystal with piezoelectric effects is studied, and the closed-form solutions of the electroelastic field, field intensity factors, energy release rate, and generalized Peach-Koehler force are obtained. The analytical solutions can reduce to the results from the existing literature. The disadvantage of the present solution is that the dislocations are considered to distribute uniformly in the numerical examples which do not reflect the microstructure of the material. The solutions are limited in numbers of dislocations, and only the same sign dislocations are considered here. From the numerical illustrations, some important results are summarized in the following outline:

- (1) The trend of contours of the phason field stress is similar to the phason field stress but is different from the electric displacement.
- (2) The stress concentration occurs at the crack tip and dislocations cores. The effects of the location of dislocations on the three field intensity factors are different, and the wedge angle always increases the shielding effect.
- (3) The increasing number of dislocations always accelerates the crack propagation. The wedge angle accelerates the crack growth when dislocations are located at the real axis, but it first promotes crack growth and then demotes crack propagation when dislocations are located at the imaginary axis symmetrically.
- (4) The image force acting on the dislocation in the presence of a crack and other dislocations decreases when increasing the wedge angle. The dislocation is

either attracted or rejected in the process of moving from left to right along the real axis.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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