Prediction of parameters of microscale coating-metal interface phase based on finite element method

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Abstract. The coating-metal transition interface can form a stable gradient interface phase composite. In this paper, a finite element model of gradient interface phase is established based on Tyson Polygon Method (TPM), and the microstructure equivalent parameters of interface material of the element are obtained by means of average method. By analyzing the functional relationship between the equivalent elastic parameters of the gradient interface element and the metal volume ratio, the functional expression of the microstructure parameter distribution of the interface phase is obtained. The results show that the equivalent elastic modulus and equivalent shear modulus of the interface satisfy the distribution of exponential function, linear function and power function in the local scope. The change rule of equivalent Poisson's ratio with metal phase volume fraction in local scope can be expressed by logistic function. It is found that the global parameter distribution of interface phase is different from that of local material. The equivalent elastic modulus and equivalent shear modulus of the global interface satisfy the double exponential function distribution, while the distribution law of the equivalent Poisson's ratio can be piecewise expressed by the logistic function and the exponential function.

1. Introduction

Corrosion is one of the most important failure modes of metal structure in ships and marine engineering etc, and anti-corrosion coating is a widely used method to preventing corrosion. When spraying anti-corrosive coating, interfacial phase materials with different properties of metal and coating materials are often formed [1-3], as shown in figure 1(b) [4]. Although the thickness of interface phase is very small, its structure and properties largely determine the interface strength.

(a)  (b)

Figure 1. (a) Anti-corrosion counterweight pipe and (b) SEM figure of anti-corrosive coating.
Structure and performance parameters of the interface phase have been widely concerned. The third-phase material between coating and metal has regular characteristics, and many studies about microscale parameters have been conducted. Sun et al [5] studied the influence of interfacial phase parameters on the uniaxial tensile behavior of ceramic matrix composites, and discussed the effects of interfacial phase component volume fraction, elastic modulus and Poisson's ratio on tensile behavior. However, the microscale elastic constant of the interface phase is heavily dependent on the experimental value. Li et al [6] established the composite material microscopic representative cellular model, four kinds of Voronoi cells with mathematical and statistical significance were established by using TPM. Leslie [7] calculates effective elastic material constants of composite materials by standard mechanics method and homogenization method, and discusses the influence of reinforcement arrangement on material performance parameters. Wakashima [8] proposed to establish the stress-strain relationship between the macroscopic gradient interface and the microscopic cellular model by applying the classical laminated plate theory. Li et al [9] studied the load-deformation behavior of the typical sub-laminated plate and derived the effective elastic constant from the properties of its constituent layers. The explicit expression of effective elastic constant of thick plate is given. Some scholars assume that the parameters change according to specific functions, such as exponential function [10,11] or power function [12,13]. At the same time, in order to consider the arbitrary variation form of material parameters, Wang put forward the laminated plate model [14], and Gao put forward a new layered model [15] based on the fact that any continuous curve can be approximated by a series of broken lines. Experiments have confirmed that the mechanical properties of the interface change regularly with the increase of the volume fraction of a phase [16]. In addition, the above studies based on theoretical analysis often assume that the mechanical parameters of the interface conform to a certain function distribution without further study. In this paper, the functional relations of equivalent parameters of gradient interface are predicted by studying the microscale parameters properties of interface materials by the numerical fitting method.

2. Interface layer model and finite element realization

2.1. Interface layer model

![Figure 2. Schematic diagram of coating - metal interface phase structure.](image)

In the coating - metal gradient interface phase, it is assumed that the volume fraction of the metal phase changes uniformly along the thickness direction, as shown in figure 2. In this paper, the \( k \)th thick layer of interface phase material is selected randomly to predict the changes of local interface phase material parameters. Since the model size established in this paper is very small, it is assumed
that the thin layer \( i \) within the thick layer is an ideal single layer without thickness, and the stress and displacement are continuous at and on the upper and lower surfaces of the thin layer. In this paper, based on the homogenization theory, by calculating the equivalent material parameters of each thin layer, the relationship between the interface phase equivalent parameters and the volume fraction of the metal phase is established. On this basis, the mechanical properties of the global interface phase are analyzed.

2.2. Thin layer microscopic model

The geometrical structure distribution of coating metal interface materials is random and discrete. The representative volume element (RVE) is established by using TPM [17] and the basic idea of this method is to construct a Tyson polygon containing only one discrete point data by connecting the vertical bisecting lines of the two adjacent points. The points in the Tyson polygon are closest to the corresponding discrete points, and the points on the side of the Tyson polygon are equal to the discrete points on both sides. The unit cell established by this method can fully explain the microstructure and profit strain field distribution of composite materials.

Metal particles can be virtually of any shape. However, in order to simplify the calculation, we choose the cube shape inclusion as the particle shape and the coating was used as the matrix to seamlessly fill the cube particles. Suppose the metal particles are arranged in a simple cubic way as one of the spatial arrangements of metal crystals. By using the Tyson polygon method, as shown in figure 3(a), combining the translation and symmetry properties of the unicellular geometric structure, we establish the 1/8 interface layer single-layer unit as shown in figure 3(b).

![Figure 3](image)

**Figure 3.** (a) Schematic diagram of division unit by Tyson polygonal method and (b) Schematic diagram of single-layer cell of 1/8 interface phase.

2.3. Periodic boundary conditions and its finite element realization

2.3.1. Periodic boundary conditions. In the direction perpendicular to the interface layer, the material properties vary with the different components of the two-phase mixture, and show a certain regularity. However, in each single layer, the micro structure presents a good periodicity. In the finite element calculation, the stress and strain distribution at the material microscopic level can be obtained by establishing single layer cell model of the interface and applying certain boundary conditions. Reasonable boundary conditions are the key to ensure accurate calculation. Xia *et al.* [18] proposed uniform periodic boundary conditions for a cellular model with relatively parallel boundary surfaces. For materials with periodic microscopic cell structure, the expression of periodic displacement field is as follows:
\[ u_i = -\hat{\varepsilon}_{ik} x_k + u_i^* \]  

Where: \( \hat{\varepsilon}_{ik} \) is the average strain of the unit cell; \( x_k \) is the coordinates of any point in the unit cell; \( u_i^* \) is the correction of periodic displacement.

Xia et al. [18] used the symmetry property of cells to establish the relative displacement relationship between parallel planes, and obtained the expression of general periodic boundary conditions:

\[ u_{i+}^* - u_{i-}^* = \hat{\varepsilon}_{ik} (x_{k+}^* - x_{k-}^*) = \hat{\varepsilon}_{ik} \Delta x_k \]

Obviously, the above equation satisfies the periodicity and continuity of the displacement on the boundary, and the displacement difference of the corresponding node on the parallel periodic boundary remains constant. Therefore, the above equation is adopted to apply boundary conditions to the unit cell in this paper.

2.3.2. Finite element realization of periodic boundary conditions. In the micro-mechanical analysis of composite materials, RVE can be a complete unit cell or 1/8 unit cell. However, periodic boundary conditions are closely related to the selection of unit cell. According to the different unit cell model, Li gives the simplified model considering mirror symmetry boundary conditions and not to consider a complete model of mirror symmetry boundary condition equation [6,19]. Considering model simplification, 1/8 cell was established as the interface layer microscopic mechanics finite element model analysis, the corresponding periodic boundary conditions are as follows [20]:

The boundary conditions for the case under \( \varepsilon_x^0 \) are in equation (3)

\[ u_{|x=0} = 0 \quad \text{and} \quad u_{|x=b} = b_x \varepsilon_x^0 \]
\[ v_{|y=0} = 0 \quad \text{and} \quad v_{|y=b} = b_y \varepsilon_y^0 \]
\[ w_{|z=0} = 0 \quad \text{and} \quad w_{|z=b} = b_z \varepsilon_z^0 \]

With similar considerations as given above, the boundary conditions for the unit cell under \( \varepsilon_y^0 \) and \( \varepsilon_z^0 \) are identical to those in equation (3). However, the boundary conditions under the shear load with mirror symmetry are completely different from equation (3).

The boundary conditions for the case under \( \gamma_{xy}^0 \) are in equation (4).

\[ u_{|x=0} = 0 \quad ; \quad u_{|x=b} = 0 \]
\[ u_{|y=0} = w_{|y=0} = 0 \quad ; \quad u_{|y=b} = w_{|y=b} = 0 \]
\[ u_{|z=0} = v_{|z=0} = 0 \quad ; \quad u_{|z=b} = v_{|z=b} = b_z \gamma_{yz}^0 \]

With similar considerations as given above, the boundary conditions for the unit cell under \( \gamma_{xy}^0 \) and \( \gamma_{xz}^0 \) are identical to those in equation (4).

The above formula is the boundary condition of the constraint surface, and different edge and corner nodes have different boundary conditions.

3. Prediction of effective elastic parameters of interface layer
3.1. Calculation method of material parameters in RVE

The unit cell of interface phase can be regarded as homogeneous anisotropy, and its equivalent constitutive relation vector can be expressed as

\[ \bar{\varepsilon}_i = S_{ij} \bar{\sigma}_j, (i, j = 1, 2, 3, 4, 5, 6) \]  \hspace{1cm} (5)

Where \( S_{ij} \) is the flexibility matrix, \( \bar{\varepsilon}_i, \bar{\sigma}_j \) are the mean stress and mean strain of the unit cell respectively. Where the relation between the flexibility coefficient matrix and the elastic constant is:

\[
S_{ij} = \begin{bmatrix}
\frac{1}{E_1} & \frac{\nu_{12}}{E_2} & \frac{\nu_{13}}{E_3} & 0 & 0 & 0 \\
\frac{\nu_{12}}{E_2} & \frac{1}{E_2} & 0 & 0 & 0 & 0 \\
\frac{\nu_{13}}{E_3} & 0 & \frac{1}{E_3} & 0 & 0 & 0 \\
0 & 0 & 0 & \frac{1}{G_{12}} & 0 & 0 \\
0 & 0 & 0 & 0 & \frac{1}{G_{23}} & 0 \\
0 & 0 & 0 & 0 & 0 & \frac{1}{G_{31}} \\
\end{bmatrix}
\]  \hspace{1cm} (6)

Where \( E_x, E_y, E_z \) are elastic modulus of interface layer element material in \( x, y \) and \( z \) directions respectively; \( G_{xy}, G_{yz}, G_{xz} \) are shear modulus in plane \( xy, yz \) and \( xz \) respectively; \( \mu_{xy}, \mu_{yz}, \mu_{xz}, \mu_{yx}, \mu_{zy}, \mu_{zx} \) are the Poisson’s ratio in plane \( xy, yz, xz, yx, zy \) and \( zx \) respectively.

In this paper, six sets of linearly independent boundary conditions of strain load equation are applied to 1/8 cellular model respectively.

For cubic cells, in this paper, unit cell strain \( \varepsilon_i \) is already know as the displacement boundary condition, and \( \sigma_j \) can be expressed as:

\[ \bar{\sigma}_j = \frac{(P_j)}{S_j} \]  \hspace{1cm} (7)

Where \( (P_j) \) is the sum of the constrained counter-forces in the direction of node \( i \) on plane \( j \); \( S_j \) is the \( j \) plane of the unit cell.

The elastic constant of a unit cell can be calculated from equation (8).

\[ E_i = \frac{\bar{\sigma}_i}{\bar{\varepsilon}_i}, (i, j = 1, 2, 3; ) \]

\[ \mu_i = \frac{\bar{\varepsilon}_j}{\bar{\varepsilon}_i}, (i, j = 1, 2, 3, 4, 5, 6; ) \]  \hspace{1cm} (8)

\[ G_i = \frac{\bar{\sigma}_i}{\bar{\varepsilon}_i}, (i, j = 4, 5, 6; ) \]

3.2. Finite element calculation of element material parameters

Finite element method is widely used to solve material characteristic parameters. In this paper, finite element large commercial software ABAQUS is used to calculate the material parameters of unit cell
of interface phase. The unit cell size established in this paper is \(2 \times 10^{-2}\) um. In order to make the mesh division smooth, we used the swept central axis algorithm to divide the mesh, and selected C3D8R linear hexahedral element. The metal phase and the matrix phase in the model are bound together. In this paper, the epoxy coating commonly used in underwater anti-corrosion equipment and the material properties of steel pipe are selected, as shown in table 1. Boundary conditions are applied as described above. It should be noted that when there are common edge nodes on both sides, boundary constraints must be imposed on edge nodes alone to prevent excessive constraints, as well as common angle nodes.

**Table 1.** Properties of metal particles and epoxy materials.

| Material         | E (GPa) | v   |
|------------------|---------|-----|
| Epoxy matrix     | 3.43    | 0.38|
| Metal particles  | 207     | 0.3 |

In this paper, the global size of grid is 0.46 and 0.30 respectively to study the size of this effect. As shown in table 2, material parameters of cells with metal phase volume fraction of 30%, 40% and 50% are calculated in both grid sizes, and the parameter corresponding to the 0.30 grid ruler in brackets. It can be seen that grid has little influence on the calculation results. In this paper, the global size of the grid is selected as 0.46, and the divided cell model is shown in figure 4.

**Table 2.** The calculation difference of effective material parameters with global grid size between 0.46 and 0.30.

| volume ratio of Metal (%) | \(E_1=E_2=E_i\) (GPa) | \(G_{12}=G_{23}=G_{ij}\) (GPa) | \(v_{12}=v_{13}=v_{23}=v_{ij}\) |
|--------------------------|------------------------|-------------------------------|--------------------------------|
| 30                       | 8.45318                | 2.19234                      | 0.315176                       |
|                          | (8.4642)               | (2.19862)                    | (0.31489)                      |
| 40                       | 11.79322               | 2.6409                       | 0.284402                       |
|                          | (11.82504)             | (2.6495)                     | (0.285554)                     |
| 50                       | 16.50422               | 3.22862                      | 0.241836                       |
|                          | (16.63406)             | (3.25118)                    | (0.252542)                     |

**Figure 4.** Mesh of the unit cell for interface layer single layer.

When the y-plane of the interface unit is subjected to a displacement load of \(0.005 \times 10^{-3}\) um, the stress and displacement fields of the unit cell are obtained through finite element calculation, as shown
in figures 5(b) and 5(d). As the material unit is symmetric in the direction of the coordinate system spindle, the finite element calculation results show that the symmetry still exists in the stress, strain, and displacement fields of the unit cell.

Figure 5. Unit cell finite element calculation results with 30% volume fraction of metal phase: (a) contours of von Mises stress without coating matrix. (b) contours of equivalent displacement without coating matrix. (c) contours of von Mises stress with metal particles. (d) contours of equivalent displacement with metal particles.

4. Results
The relationship between the volume fraction of the metal phase and the material parameters of the local interface layer and the whole interface phase is discussed below.

4.1. Parameter properties of local interface layer
In the finite element calculation results of the model, the stress, strain, and displacement fields of the analysis model are given priority to, and the material microscopic parameters are obtained through the calculation of equations (5)-(8). The finite element model established in this paper, due to the symmetrical nature of the geometric structure, presents a high degree of orthogonal isotropy. Therefore, in the subsequent result analysis, plane y is selected to apply the load for solution. The calculated parameters of the model are shown in table 3.

The functional relationship between material parameters of local interface phase and volume fraction of metal phase can be obtained by interpolation fitting. As shown in figure 6(a), when the volume fraction of the metallic phase changes from 30% to 40%, the linear characteristics of the equivalent elastic modulus of the thin layer material of the interface phase are significant. At the same
time, it can be found that the change relation of equivalent elastic modulus of local interface layer materials can also be well expressed by exponential function and power function. Considering the simplicity and accuracy of the function form, it is recommended to use the linear function as the change rule of the equivalent elastic modulus of the local interface phase.

Table 3. Effective material properties of interface unit cell for the volume ratio of metal from 30% to 40%.

| volume ratio of metal (%) | $E_1=E_2=E_3$ (GPa) | $G_{12}=G_{23}=G_{13}$ (GPa) | $\nu_{12}=\nu_{13}=\nu_{23}$ | $\nu_{21}=\nu_{32}=\nu_{31}$ |
|--------------------------|---------------------|-----------------------------|-----------------|-----------------|
| 30                       | 8.4532              | 2.1923                      | 0.3152          |                 |
| 31                       | 8.7366              | 2.2327                      | 0.3101          |                 |
| 32                       | 9.0304              | 2.2739                      | 0.3094          |                 |
| 33                       | 9.3349              | 2.3162                      | 0.3093          |                 |
| 34                       | 9.6507              | 2.3586                      | 0.3089          |                 |
| 35                       | 9.9778              | 2.4040                      | 0.3059          |                 |
| 36                       | 10.3170             | 2.4499                      | 0.3005          |                 |
| 37                       | 10.6608             | 2.4926                      | 0.2935          |                 |
| 38                       | 11.0244             | 2.5407                      | 0.2871          |                 |
| 39                       | 11.4014             | 2.5901                      | 0.2849          |                 |
| 40                       | 11.7932             | 2.6409                      | 0.2844          |                 |

Figure 6. (a) Diagram of the relationship between the equivalent elastic modulus of the local material in the interface phase and the volume fraction of the metal phase; (b) Diagram of the relationship between the local equivalent shear modulus of the interface phase and the volume fraction of the metallic phase.

Figure 6(b) is an interpolation diagram of the equivalent shear modulus of the interface phase material and the volume fraction of the metal phase. The change relation of the equivalent shear modulus of the local interface layer material with the increase of the metal phase is similar to that of the equivalent elastic modulus, which can also be expressed in three functional forms.

As shown in figure 7, the linear or exponential relationship can only be established between very small layers. In other words, the material parameter only satisfies the linear distribution or exponential distribution within the small change range of the volume fraction of the metal phase. when the local interface layer contains more thin layers, the change trend of material equivalent Poisson's ratio and metal phase volume fraction is closer to the logistic growth model, and the form of logistic function is shown in equation (9), where the first term represents the Poisson's ratio component of the surface in the cell affected by the lateral deformation of the metal-phase restricted cell, and the second term represents the Poisson's ratio component of the surface in the cell not affected by the lateral deformation of the metal-phase restricted cell.
\[ \nu = \frac{A_1 - A_2}{1 + (\nu / \nu_0)^p} + A_2 \] (9)

![Figure 7. Diagram of the relationship between local material equivalent Poisson's ratio of interface phase and volume fraction of metal phase.](image)

When the metal phase volume fraction is between 30% and 60%, the equivalent Poisson's ratio of the interface phase material changes greatly. When the volume fraction of the metal phase exceeds 36%, the equivalent Poisson's ratio of the composite interface is smaller than the Poisson's ratio of the two single-phase materials. This is because the reaction between the metal particles and the substrate contact surface in the model greatly limits the lateral deformation of the composite system, thereby reducing the equivalent lateral strain of the unit cells.

4.2. Parameter characteristics of global interface phase

Generally, researchers believe that the variation law of the global material parameters of the gradient interface phase is the same as that of the local interface phase. In this paper, thin material parameters with volume fraction of 0, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90% and 100% were selected to fit the relationship between the global material parameters of interface phase and the volume ratio of metal phase. The selected thin material parameters are shown in table 4.

| volume ratio of Metal (%) | \(E_1=E_2=E_3\) (GPa) | \(G_{12}=G_{23}=G_{13}\) (GPa) | \(\nu_{12}=\nu_{13}=\nu_{23}\) | \(\nu_{22}=\nu_{23}=\nu_{31}\) |
|--------------------------|-------------------------|--------------------------|-----------------|-----------------|
| 0                        | 3.4300                  | 1.2428                  | 0.3800          |
| 0.1                      | 4.5322                  | 1.5284                  | 0.3649          |
| 0.2                      | 6.1268                  | 1.8351                  | 0.3422          |
| 0.3                      | 8.4532                  | 2.1923                  | 0.3152          |
| 0.4                      | 11.7932                 | 2.6409                  | 0.2844          |
| 0.5                      | 16.5042                 | 3.2286                  | 0.2418          |
| 0.6                      | 23.5278                 | 4.1029                  | 0.2222          |
| 0.7                      | 33.9836                 | 5.4632                  | 0.1962          |
| 0.8                      | 52.4520                 | 8.0405                  | 0.1840          |
| 0.9                      | 89.7366                 | 14.7388                 | 0.1854          |
| 1                        | 207                     | 79.6154                 | 0.3000          |
Exponential function, double exponential function and power function were used to fit the volume fraction of the metal phase and the material parameters of the global interface phase. The fitting effect of the exponential function and the power function is poor. The numerical results show that the relationship between the global equivalent elastic modulus of the interface phase material and the metal phase gradient can be well expressed by the double exponential function, as shown in figure 7(a). The form of the double exponential function is shown in equation (10), which reflects the contribution of the two components of the interface phase to the equivalent elastic modulus.

\[ E = E_0 + A_1 e^{A_2 v} + A_3 e^{A_4 v} \] (10)

When the volume fraction of the metallic phase is lower than 80%, the equivalent elastic modulus of the gradient interface phase material changes slowly with the volume. In combination with the research of section 4.1, it is found that when the volume fraction of the metal phase is lower than 80%, the local interface phase material parameter changes have the characteristics of linear distribution. When the volume fraction of the metal phase exceeds 80%, the equivalent elastic modulus of the interface phase increases rapidly in a small range, which is consistent with the change characteristics of double-exponential function. The equivalent shear modulus of the global interface phase has similar laws, as shown in figure 8(b).

Figure 8. (a) Diagram of the relationship between the equivalent elastic modulus of the interface phase integral material and the volume fraction of the metallic phase; (b) Diagram of the relationship between the equivalent shear modulus of the interface phase integral material and the volume fraction of the metallic phase.

According to the characteristics of the data, the equivalent Poisson's ratio of the interface phase material is segmented and fitted, as shown in figure 9. When the metal phase volume fraction is less than 80%, the logistic growth model better reflects the relationship between the equivalent material Poisson's ratio of the interface phase and the metal phase volume fraction. When the metal phase volume fraction is greater than 80%, the equivalent Poisson's ratio increases rapidly in a small range, and the exponential function can well express the relationship of the equivalent Poisson's ratio in this range.
Figure 9. Diagram of the relationship between equivalent Poisson's ratio of interface phase integral material and volume fraction of metallic phase.

4.3. Prediction of Interface Phase Equivalent Material Parameters

Before the interface phase equivalent material parameters are predicted, the following assumptions are proposed in this paper:

- when uniaxial load is applied to the thin layer of interface phase material, only corresponding internal stress is generated in different thin layers, and other internal stress components are zero.
- The internal stresses in different thin layers are equal under axial action.

According to sections 4.1 and 4.2, the equivalent material parameters of interface phase are distributed continuously and regularly. Combined with the above assumptions, the mixing rate model can be used to predict the value of interface phase equivalent material parameters.

\[ E_i = \sum_{k=1}^{N} E_i^k v_k \approx \int_0^1 E(v)d(v) \]  

(11)

\[ G_i = \sum_{k=1}^{N} G_i^k v_k \approx \int_0^1 G(v)d(v) \]  

(12)

\[ v_i = \sum_{k=1}^{N} v_i^k v_k \approx \int_0^1 v(v)d(v) \]  

(13)

Combined with equations (11)-(13), the equivalent elastic modulus, equivalent shear modulus and equivalent Poisson's ratio of interface phase can be calculated to be 33.5075 GPa, 7.1857 GPa and 0.1412 respectively.

The relationship between the material parameters of the interface phase materials in the volume fraction of different metal phases was studied, and the functional form of the local interface layer and the global interface phase material along with the metal volume fraction was obtained in this paper. It can provide a basis for further study of interface phase materials.

5. Conclusions

Based on the homogenization method, the finite element cell model of composite interface layer material was established in this paper. It is necessary to pay attention to the division of scale in the
mechanical analysis and research of coating - metal gradient interface phase. The elastic parameters of the materials vary with the volume fraction of the two-phase components at different scales. By calculating and analyzing the parameters of the cell material, the following conclusions are obtained:

- The elastic modulus and shear modulus in interface layer have linear relations with volume fraction of metal in local interface layers, and the equivalent Poisson's ratio has a linear relation with volume fraction in thinner interface layers, but in local layers it can be expressed by the logistic function.
- The relationship between the overall interface phase material parameters and the volume fraction of the metal phase is different from the local material parameter distribution law. The equivalent elastic modulus and equivalent shear modulus of the global interface phase material satisfy the double exponential function distribution. The change rule of equivalent Poisson's ratio is significantly affected by the volume fraction of metal phase, which can be expressed piecewise by logistic function and exponential function.

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References
[1] Du Z Q, Zhang W F et al 2011 Application of fused epoxy powder coating technology in submarine pipelines Steel Pipe 40
[2] Kwei T K and Kumins C A 1964 Polymer- filler interaction: Vapor absorption study Appl Polym Sci. 8 1483-90
[3] Fan J Z, Yao Z K et al 1997 Research progress on interface of aluminum matrix composites reinforced with silicon carbide Rare Metal. 2 55-9
[4] Xia Y F, Jiang W G and Wu Z K 2015 Analysis of residual stresses and failure of aluminum honeycomb with Al2O3 coating under thermal loads Transactions of Materials and Heat Treatment 37 193-7
[5] Sun Z G, Li L et al 2010 Effect of interface layer parameters on uniaxial tensile behavior of ceramic matrix composites Journal of Aerodynamics 25 597-602
[6] Li S G and Wongsto A 2004 Unit cells for micromechanical analyses of particle-reinforced composites Mechanics of Materials 36 543-72
[7] Leslie B S, Leiderman V and Fang D 1997 On the effect of particle shape and orientation on elastic properties of metal matrix composites Composites Part B 28B 465-81
[8] Wakashima K, Hirano T and Nino M 1990 Space application of advance structure materials ESP 303 97-100
[9] Delate F and Erodgan F 1988 On the mechanic modeling of the interface region in bonded half- planes ASME J Appl Mech. 55 317-24
[10] Choil J 1997 A periodic array of cracks in a functionally graded nonhomogeneous edium loaded under in-plane normal and shear Int J Fract. 88 107-28
[11] Wang X Y, Zou Z Z and Wang D 1997 On the penny-shaped crack in a nonhomogeneous interlayer of adjoining two different elastic materials Int J Solids Struct. 34 3911-21
[12] Li C Y and Weng G J 2001 Dynamic stress intensity factors of a cylindrical interface crack with a functionally graded interlayer Mech Mater. 33 325-33
[13] Wang B L, Hang J C and Du S Y 1999 Dynamic response for functionally graded materials with penny-shaped cracks Acta Mech Solida Sin 12 106-13
[14] Wang Y S and Ross D G 2000 Analysis of a crack in a functionally gradient interface layer under static and dynamic loading Key Engn Mat. 183-187 331-6
[15] Gao T K 2005 A series of boundary value problems of partial differential equations in plane fracture of functionally gradient materials and composites Journal of Shanxi Normal University 19 52-6
[16] Delale F and Erdogan F 1988 On the mechanical modeling of the interface region in bonded half-planes *Journal of Applied Mechanics* **55** 317-24
[17] Li T and Yao M F 2017 Natural fractals--application of Voronoityson polygons in architectural design *Chinese and Foreign Construction* **7** 139-44
[18] Xia Z H, Zhang Y F and Ellyin F 2003 A unified periodical boundary conditions for representative volume elements of composites and applications *International Journal of Solid and Structures* **40** 1907-21
[19] Li S 2000 General unit cells for micromechanical analyses of unidirectional composites *Composites: Part A* **32** 815-26
[20] Li S G 2008 Boundary conditions for unit cells from periodic microstructures and their implications *Composites Science and Technology* **68** 1962-74