Interphase effect on the strengthening behavior of particle-reinforced metal matrix composites

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Abstract

Interphase effect on the strengthening behavior of particle-reinforced metal matrix composites is numerically investigated, in which the stiffness, thickness and debonding location of interphase are considered. Embedded cell model and finite element method are used in analysis. The numerical results indicate that hard and soft interphases result in the increase and significant decrease of the strength of composite, respectively. Location of debonding has quite different effects. Pole debonding results in a remarkable decrease of the overall strength of composite, while equator debonding results in a slight decrease of the strength of composite. Debonding between the interphase and matrix has more significant effect than that between the interphase and particle.

Keywords: Metal matrix composites (MMCs); Interphase; Strength; Plastic deformation; Finite element analysis (FEA)

1. Introduction

Interface and/or interphase are important for composites, which affects the microscopic fields and then the overall properties of composites significantly [1–6]. However, interface is only an idealized mode and extensive work has been carried out. Interphase is really the third phase between the reinforced phase and matrix of composites and exists inevitably, which is due to the coated material to enhance the bond between matrix and inclusion in manufacture process, the chemical diffusion between inclusion and matrix, special design (e.g. functionally graded interphase, adsorbed contaminants on the surface of fiber/particle results in a third material phase) and others.

Extensive analytical and numerical work has been devoted to the elastic solutions of the interphase problems, including homogeneous [7–10] and inhomogeneous [6,11–16] interphases. Up to now, relatively less work has been carried out on the inelastic solutions of the interphase problem. Veazie and Qu [17] developed a spring-layer model without thickness to describe the interphase and then studied the interphase effect on the transverse deformation behavior of unidirectional fiber reinforced metal matrix composites (MMCs). Wang and Yang [18] employed unit cell to numerically study the energy dissipation of particle reinforced MMCs with ductile interphase. Su et al. [19] studied the effects of interphase strength on the damage modes and mechanical behavior of MMCs. Interphase may be harder or softer than the matrix [20]. Based on the secant modulus approach, Ding and Weng [21] theoretically studied the effect of ductile interphase on the overall stress–strain curves of particle-reinforced composites, in which both hard and soft interphases are considered. However, due to the limitation of their theoretical approach, the initial yield stress could not be predicted exactly and the local deformation field could not be presented. Zhang and Wang [22] carried out the 3D numerical analysis to study the effect of ductile interphase on the deformation behavior of MMCs with regularly distributed particles.

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Interphase debonding is another important factor to affect the mechanical behavior of composites. Haddadi and Teodosiu [23] studied the effect of debonding process on the plastic behavior of two-phase composites through the finite element analysis with a 3D unit cell. Ghassemieh [24] developed a finite element model to simulate the stress–strain behavior of particulate composites with an interfacial crack.

Basically, the ductile interphase may be harder or softer than the matrix [20], and debonding may have different locations. However, the effects of ductile interphase and the effects of debonding modes, especially when interphase exits, on the overall mechanical behavior of composites with randomly distributed particles are not well understood up to now. The previous analytical method is only suitable for some ideal cases and is difficult to predict the overall mechanical property of composites with partial debonding interphase.

The purpose of this work is to numerically investigate the effect of ductile interphase on the strengthening behavior of particle-reinforced metal matrix composites (PMMCs), in which the stiffness, thickness and debonding location of interphase are considered. Embedded cell model is employed to consider the random distribution of particles. In Section 2, the embedded unit cell model and the calculation procedures are presented. Effects of the stiffness and thickness of interphase and the location of debonding on the overall mechanical behavior of composites are presented and discussed in Section 3. Finally, concluding remarks are presented in Section 4.

2. Micromechanics approach

2.1. Embedded cell model and constitutive equations

For random particle reinforced composites, one can choose a sufficiently large representative volume element (RVE) to describe the features of microstructures as many as possible [25,26] and then to numerically obtain the overall mechanical behavior of composites, which needs a great number of calculations and becomes increasingly feasible with development of the computer technology. An alternative approach is using the generalized self-consistent model (GSCM), which proposed by Christensen and Lo [27] in predicting the elastic moduli of composites, as shown in Fig. 1a. Chen et al. [16], Veazie and Qu [17], and Dong and Schmauder [28] have extended the original idea of GSCM to numerically study the elastoplastic deformation of composites, which is the so-called embedded cell model. The numerical results obtained by embedded cell model agree very well with experiments. This approach has high accuracy and saves calculations, and can be used to study the mechanical behavior of composites with much more complex microstructures, such as imperfect interphase [16], damage [19], voids [29], etc.

In what follows, an axisymmetric embedded cell model is employed to study the effect of ductile interphase on the overall mechanical properties of particle reinforced MMCs. The coordinate system is shown in Fig. 1b in which outer size \( L \) of the model is large enough so that the external boundary conditions have no influence on the deformation of the embedded cell. \( R_1 \), \( R_2 \) and \( R_3 \) are radius of the particle, outer radius of the interphase and radius of the cell, respectively. Dong and Schmauder [28] indicated that if \( L/R_3 \geq 5 \), the boundary effect can be neglected. In calculation, we take \( L/R_3 = 10 \) and fix \( R_3 \), \( R_1 \) and \( R_2 \) are changed to obtain various volume fractions of particle by \( f_p = R_1^3/R_3^3 \). Small deformation assumption is adopted in analysis.

The inclusion, e.g. SiC particle, is assumed to be linear isotropic and to obey Hook’s law. The matrix, e.g. aluminum, is assumed to be isotropic and to obey von Mises yield criterion and the following stress–strain relation:

\[
\sigma = \begin{cases} 
E_m \varepsilon, & \varepsilon \leq \varepsilon_0, \\
\sigma_0 \left( \frac{\varepsilon}{\varepsilon_0} \right)^n, & \varepsilon > \varepsilon_0,
\end{cases}
\]

where \( \sigma \) and \( \varepsilon \) are the uniaxial stress and strain in matrix. \( E_m \), \( \sigma_0 \) and \( \varepsilon_0 \) are the Young’s modulus, initial yield stress and yield strain of matrix, respectively, and have the relation of \( \varepsilon_0 = \sigma_0/E_m \). \( n \) is the strain hardening exponent of matrix.

It is assumed that the interphase has the same strain hardening exponent and Poisson ratio, and obeys the following stress–strain relation:

\[
\bar{\sigma} = \begin{cases} 
\beta E_m \bar{\varepsilon}, & \bar{\varepsilon} \leq \bar{\varepsilon}_0, \\
\beta \sigma_0 \left( \frac{\bar{\varepsilon}}{\bar{\varepsilon}_0} \right)^n, & \bar{\varepsilon} > \bar{\varepsilon}_0,
\end{cases}
\]

where \( \beta \) is a constant. Obviously, \( \beta = 1 \) corresponds to the case of no interphase, and \( \beta < 1 \) and \( \beta > 1 \) correspond to the soft and hard interphases, respectively. The smaller the value of \( \beta \) is, the softer the interphase is, and vice versa.

The overall stress \( \bar{\sigma}_{ij} \) and strain \( \bar{\varepsilon}_{ij} \) in the composites can be calculated as

\[
\bar{\sigma}_{ij} = \frac{1}{V} \int_V \sigma_{ij} dV, \quad i, j = 1, 2, 3
\]

\[
\bar{\varepsilon}_{ij} = \frac{1}{V} \int_V \varepsilon_{ij} dV, \quad i, j = 1, 2, 3
\]

where \( \sigma_{ij} \) and \( \varepsilon_{ij} \) are the local stress and strain, respectively, and \( V \) volume of the embedded cell. According to [28], the equivalent overall stress \( \bar{\sigma}_e \) and strain \( \bar{\varepsilon}_e \) of the embedded cell can be calculated as

\[
\bar{\sigma}_e = \sqrt{\frac{3}{2} \bar{\sigma}_{ij} \bar{\sigma}_{ij}},
\]

\[
\bar{\varepsilon}_e = \frac{1}{1 + \nu} \sqrt{\frac{3}{2} \bar{\varepsilon}_{ij} \bar{\varepsilon}_{ij}},
\]

where \( \bar{\sigma}_{ij} \) and \( \bar{\varepsilon}_{ij} \) are overall deviator stress and strain tensors, respectively, \( \nu \) is the apparent Poisson ratio of nonlinear.
ear deformation which is defined as the negative ratio of the strain normal to the loading direction to the strain along the loading direction. \( \bar{\varepsilon} \) increases gradually from the elastic Poisson ratio to 0.5 with the increase of deformation from the elastic to plastic states [28].

2.2. Numerical implementation

Uniaxial loading is applied to the upside of the axisymmetric embedded unit cell, in \( z \)-direction as shown in Fig. 1b. For the present problem, there are only three non-zero components of overall stress and strain tensors, i.e. the radial \( \tilde{\sigma}_r \) and \( \tilde{\varepsilon}_r \), the axial \( \tilde{\sigma}_z \) and \( \tilde{\varepsilon}_z \), and the circumferential \( \tilde{\sigma}_\theta \) and \( \tilde{\varepsilon}_\theta \). From the deformation theory of plasticity, one can obtain the Poisson ratio \( \bar{\nu} \) by using the following stress–strain relation:

\[
\begin{bmatrix}
\tilde{\varepsilon}_z \\
\tilde{\varepsilon}_r \\
\tilde{\varepsilon}_\theta
\end{bmatrix} = \frac{1}{E} \begin{bmatrix}
1 & -\bar{\nu} & -\bar{\nu} \\
-\bar{\nu} & 1 & \bar{\nu} \\
-\bar{\nu} & -\bar{\nu} & 1
\end{bmatrix} \begin{bmatrix}
\tilde{\sigma}_z \\
\tilde{\sigma}_r \\
\tilde{\sigma}_\theta
\end{bmatrix},
\tag{6}
\]

where \( E \) is the secant modulus of nonlinear deformation of the embedded cell. When the deformation of composite is elastic, \( E \) and \( \bar{\nu} \) reduce to the overall Young’s modulus and Poisson ratio of composite. To the authors’ knowledge, the explicit formula Eq. (6) was not seen in literature. Practically, the three equations in Eq. (6) are linearly dependent for \( E \) and \( \bar{\nu} \). So, any two of them can be used to determine \( E \) and \( \bar{\nu} \) in calculation. After calculation converges, \( \tilde{\sigma}_z \) and \( \tilde{\sigma}_\theta \) vanish because the composite subjected to a uniaxial tensile loading.

For the present problem, we have the following boundary conditions:
\[ u_r = 0 \quad \text{at} \ r = 0, \]  
\[ u_z = 0 \quad \text{at} \ z = 0, \]  
\[ u_z = U \quad \text{at} \ z = L, \]  

where \( u_r \) and \( u_z \) are the displacements in \( r \)- and \( z \)-directions, respectively. Boundary of the model at \( r = L \) is enforced to hold straight during deformation.

ANSYS software is used for calculation. The finite element meshes are shown in Fig. 2. The material parameters are \( E_m = 69 \text{ GPa}, \sigma_m = 43 \text{ MPa} \) and \( v_m = 0.33 \) for matrix, and \( E_p = 440 \text{ GPa} \) and \( v_p = 0.25 \) for particle. Five different values of \( \beta \), i.e. 0.01, 0.1, 1, 10 and 100 are considered to study the effects of soft (\( \beta < 1 \)) and hard (\( \beta > 1 \)) interphases. Let \( \text{Nite} \) denotes the number of iteration. The iteration procedures are as follows:

**Step 1**: Initiation. \( \text{Nite} = 0 \); Let the property of the effective composite be that of the matrix.

**Step 2**: Calculation.

1. Apply the boundary conditions to obtain the local fields by using the ANSYS software, and further calculate the average stress and strain of the embedded cell by using Eqs. (3) and (4).
2. Calculate the overall Young’s modulus and Poisson ratio of composite by using Eq. (6) and then obtain the equivalent stress–strain curve by Eq. (5).

**Step 3**: Judge. \( \text{Nite} = \text{Nite} + 1 \); Calculate the absolute value of maximum difference of the equivalent stress at the same equivalent strain between the \( \text{Nite} \) step and the \( \text{Nite}-1 \) step. If the relative difference is less than 0.5%, then stop, otherwise, go to Step 4.

**Step 4**: Iteration. Replace the overall property of the effective composite with the newly obtained one, and then go to Step 2.

Fig. 3a and b shows two examples of the convergence procedures for the composites with different volume fractions of particle (\( f_p = 10\% \) and \( 50\% \)) and without interphase (\( \beta = 1 \)). It is seen that for a lower value of \( f_p \), the stress–strain curve converges more rapidly (2 steps) than that for a higher value of \( f_p \) (at least 5 steps). So, the convergence rate of calculation depends on the volume fraction of particle.
3. Results and discussion

The effect of ductile interphase on the strengthening and overall deformation behavior of particle reinforced MMCs is discussed in this section. Three kinds of interphases are considered, i.e. hard ($\beta = 10$ and $100$), soft ($\beta = 0.01$ and $0.1$) and no ($\beta = 1$) interphases. Thickness of the interphase can be calculated as $h = tR_3$. In Sections 3.1 and 3.2, the
particle, interphase, matrix and composite are perfectly bonded each other. In Section 3.3, we will also consider four different locations of debonding, i.e. pole debonding between the interphase and the matrix (PDIM), pole debonding between the interphase and particle (PDIP), equator debonding between the interphase and matrix (EDIM) and equator between the interphase and particle (EDIP). Five values of particle volume fraction, i.e. $f_p = 10\%, \ 20\%, \ 30\%, \ 40\% \ \text{and} \ 50\%$ are considered in analysis, which were considered by Dong and Schmauder [28] to study the particle volume fraction effect on the strengthening of composites. The overall stress–strain curves obtained herein for the composites with different particle volume fractions and without interphase are shown in Fig. 4, which agree very well with the results of Dong and Schmauder [28].

According to Bao et al. [30], Dong and Schmauder [28] and Zhang et al. [31], $\sigma_c/\sigma_m$, the ratio of overall stress $\sigma_c$ of composite to the strength $\sigma_m$ of pure matrix for the same overall strain, does not significantly change for composite when the deformation approaches certain critical value. So, the ratio $\sigma_c/\sigma_m$ can be used to characterize the strengthening level of composites.

### 3.1. Effect of interphase stiffness

The stiffness of interphase is described by the value of $\beta$ as discussed in Section 2.1. Here, $t = 0.055$ for calculations. Effects of interphase stiffness ($\beta = 100, 10, 1, 0.1$ and $0.01$) on the overall stress–strain curves of composites with different particle volume fractions ($f_p = 10\% \ \text{and} \ 50\%$) are shown in Fig. 5a and b, respectively. It is seen that hard interphase (i.e. $\beta > 1$) results in the enhancement of com-

![Figure 8](image_url) **Fig. 8.** Thickness effect of the soft interphase on the overall stress–strain curves (a) and the strengthening (b) of composite with particle volume fraction $f_p = 30\%$ and $\beta = 0.1$. (a) Overall stress–strain curves and (b) $\sigma_c/\sigma_m$ vs thickness $t$.

![Figure 9](image_url) **Fig. 9.** Distributions of microscopic von Mises strain in the composites with different interphases ($f_p = 30\%, \ t = 0.055$). (a) Without interphase ($\beta = 1$), (b) hard interphase ($\beta = 10$), (c) soft interphase ($\beta = 0.01$).
posite strengthening and further enhancement becomes unclear while $\beta > 10$. The soft interphase (i.e. when $\beta < 1$) deteriorates the strengthening effect. If the interphase is very soft, e.g. $\beta = 0.01$, the particle has no reinforce effect and behaves as a void. Fig. 6 shows the variations of the ratio $\sigma_c/\sigma_m$ with the value of $\beta$, from which one can clearly see the effects of interphase stiffness and particle volume fraction on the strengthening behavior of composites. It is interesting to note that there is a fixing point near $\beta = 0.1$ for the composites with different volume fraction of particle. This indicates that the average property of hard particle and soft interphase with proper thickness and stiffness is just identical to the matrix. It can be concluded that there exists specific stiffness for the soft interphase, with which the hard particles have no reinforcement to the matrix even though the volume fraction of particle is high.

3.2. Effect of interphase thickness

Here, the volume fraction of particle is fixed at $f = 30\%$, and $\beta = 10$ and 0.1 for hard and soft interphases, respectively. Effect of the thickness of hard interphase on the overall stress–strain curves of composites is shown in Fig. 7a. It is readily seen that the reinforcement of particle becomes more significant with the increase of interphase thickness. Fig. 7b shows the corresponding strengthening effect for different interphase thicknesses, which can be approximately expressed by a cubic polynomial function of the interphase thickness $t$ as

$$\frac{\sigma_c}{\sigma_m} = 2.454 + 11.114t + 105.513t^2 + 1019.395t^3. \quad (8)$$

For soft interphase, the effect of interphase thickness on the overall stress–strain curves of composites and the variation of $\sigma_c/\sigma_m$ with interphase thickness $t$ are shown in Fig. 8a and b, respectively. It is seen that if there is a soft interphase between hard particle and matrix, the hard particle will have no reinforcement to the matrix. Even the very thin soft layer between particle and matrix can result in a significant decrease of the overall strengthen of composites. This conforms the conclusion obtained in Section 3.1 once again.

Comparisons of the distribution of local von Mises strain in the composites without and with hard and soft

Fig. 10. Locations of the debonding and finite element meshes. (a) PDIM, (b) PDIP, (c) EDIM, and (d) EDIP.
interphases are shown in Fig. 9a–c, respectively. It is readily seen that if there is no interphase (i.e. \( \beta = 1 \)), the local deformation concentrates mainly in the matrix, as shown in Fig. 9a. For the case of hard interphase (\( \beta = 10 \)), the situation is similar to the case of no interphase, that is, the deformation is also concentrates mainly in the matrix, as shown in Fig. 9b. However, the situation is very different for the case of soft interphase, the deformation concentrates mainly in the interphase, which can explain why the soft interphase can not make the composite strengthening. So, one should pay much more attention to the soft interphase when studying the overall behavior of composites.

### 3.3. Effect of debonding locations

Some investigations were carried out to study the effect of interfacial debonding process on the overall mechanical properties of composites without interphase, e.g. Haddadi and Teodosiu [23] and Ghassemieh [24], etc. Here, we further consider the effect of debonding location on the overall stress–strain curves and strengthening of composites with interphase for more detail. We assume four debonding modes (PDIM, PDIP, EDIM and EDIP) mentioned at the beginning of Section 3 before calculations. The locations of debonding and finite element meshes are shown in Fig. 10. The thickness of interphase and the volume fraction of particle are fixed in calculations, e.g. the interphase thickness parameter \( t = 0.103 \) and the particle volume fraction \( f_p = 30\% \). Here, we use \( f_d = S_d/S \) to describe the degree of debonding, in which \( S_d \) and \( S \) are the debonding area and the whole interface area, respectively. The ratio \( f_d \) can be interpreted as the average debonding ratio of all the interphase.

For the case of pole debonding, we consider \( f_d = 4.9\%, 10.9\% \) and \( 29.3\% \) for both hard and soft interphases. The effects of pole debonding on the overall stress–strain curves of the composites with hard and soft interphases are shown in Fig. 11a–d. For the case of hard interphase, debonding between the interphase and matrix has more significant effect on the overall deformation of composites than that between the interphase and particle, as shown in Fig. 11a and b, respectively. For the case of soft interphase, debonding between interphase/matrix and/or interphase/particle has similar effect on the overall deformation of composites, as shown in Fig. 11c and d. It should be mentioned that the
finite element analysis used for interfacial debonding did not adopt the singular element and due to the difficulty in numerical convergence, the overall stress–strain curve can only be obtained in a small range of strain for the case of soft interphase.

For the case of equator debonding, we consider $f_d = 30\%, 45\%$ and $59\%$ for both hard and soft interphases. The effect of equator debonding on the overall stress–strain curves of the composites with hard and soft interphases are shown in Fig. 12a–d. It is seen that the equator debonding has much smaller effect compared to the pole debonding.

For the case of hard interphase, EDIM results in the decrease of overall strength of composites, but EDIP has almost no effect on the overall strength of composites, as shown in Fig. 12a–b. The distributions of microscopic von Mises stress in the composites without debonding ($f_p = 30\%, t = 0.103$, macroscopic strain $\varepsilon_z = 0.01$) are shown in Fig. 13a–b. It is seen that the EDIM results in a decrease of overall strength of composites, while EDIP has almost no effect on the overall strength of composites, as shown in Fig. 13a–b.

Fig. 12. Overall stress–strain curves of the composites with debonding at equator ($f_p = 30\%, t = 0.103$). (a) EDIM, hard interphase ($\beta = 10$), (b) EDIP, hard interphase ($\beta = 10$), (c) EDIM, soft interphase ($\beta = 0.1$), (d) EDIP, soft interphase ($\beta = 0.1$).

Fig. 13. Distributions of microscopic von Mises stress in the composites without debonding ($f_p = 30\%, t = 0.103$, macroscopic strain $\varepsilon_z = 0.01$). (a) Hard interphase ($\beta = 10$), (b) soft interphase ($\beta = 0.1$).
shown in Fig. 12a and b, which is quite different from the case of pole debonding. For the case of soft interphase, the effects of EDIM and EDIP are almost the same even for a very large debonding ratio, as shown in Fig. 12c and d.
Distributions of the microscopic von Mises stress in the composites with or without debonding are shown in Figs. 13–15 for different locations of debonding at macroscopic strain $\bar{e}_e = 0.01$. For the case of hard interphase, debonding between the interphase and matrix has more significant effect on the distribution of microscopic stress than the debonding between the interphase and particle, as shown in Fig. 14a and b and Fig. 15a and b. For the case of soft interphase, (see Fig. 13b, Fig. 14c and d and Fig. 15c and d), debonding locations have considerably small effects on the distribution of microscopic stress in the composites, as shown in Fig. 14c and d and Fig. 15c and d.

4. Conclusions

Embedded cell model has been used to numerically study the effect of interphase on the strengthening behavior of particle reinforced metal matrix composites. The stiffness, thickness and debonding locations of interphase were considered in analysis.

It can be concluded that the hard interphase between the particle and matrix enhances the reinforcement of particle to the matrix, but the soft interphase deteriorates the strengthening effect of PMMC significantly. A very soft interphase makes the particle behave as a void, so the overall stress–strain curve of composite decreases with the particle volume fraction. Also, debonding modes has different effects on the strengthening of composites. Pole debonding has more significant effect on the overall mechanical behavior of composites than equator debonding. For the case of hard interphase, debonding between the interphase and matrix has clearer effect on the overall strengthening of composites than the debonding between the interphase and particle.

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