Influence of geometry factors on the mechanical behavior of particle- and fiber-reinforced composites

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Abstract

By utilizing the finite element method (FEM) combined with cell models, the mechanical behavior of metal matrix composites (MMCs) with stripes consisting of reinforcing particles was investigated numerically. The results show that the mechanical behavior of MMC with aligned particles can be changed by varying the distance between the stripes even if the volume fraction of reinforcing particles is kept constant. It was also found that the shape of reinforcing particles had little effect on the mechanical behavior of material. In the same way, the transverse mechanical behavior of fiber-reinforced material was studied and similar trends with respect to the mechanical behavior were found. It is also found that even if particles are strongly aligned, the particle-reinforced materials behave strongly different compared to topologically similar fiber-reinforced materials. © 1999 Elsevier Science B.V. All rights reserved.

1. Introduction

It is well known that the mechanical properties of metals can be improved or elevated by adding ceramic particles. The factors that can influence the mechanical behavior have been studied thoroughly including the mechanical properties, the volume fraction and the shape of the reinforcements and even the arrangement in space of reinforcements [1–7].

In these analyses, the finite element method combined with cell models is frequently used [8,9]. The reinforcing particles are widely assumed to be scattered in the matrix uniformly and the distance between the two nearest neighbour particles is the same in the two main directions. In this paper, another micro-structure (Al/10%SiC) shown in Fig. 1(a) will be investigated. In Fig. 1(a), we can see that the particles are aligned in stripes along the direction 1. The distance between the particles in the stripes is different from that between two stripes. The average distance between two nearest particles inside a stripe amounts to $2L_a$ and the average distance between two neighbouring stripes amounts to $2L_b$. In the following the ratio of $2L_a$ to $2L_b$ is denoted as $r = L_a/L_b$. The micro-structural model of the material for calculation is shown in Fig. 1(b) and the ratio here is $r = 2/1$. By changing these distances, the mechanical behaviour of this kind of composite can be changed. Another problem which will be investigated in this paper is how the geometric shape of the inclusion influences the mechanical behaviour of the composite.
2. Calculational model

As the particles are aligned in the stripes, the cell model can be used. The problem considered here is axisymmetric as in other analyses [5,10]. We use $2L_{a}$ and $2L_{b}$ to represent the distance between the stripes and the distance between two adjacent particles in one stripe. From Fig. 1(a), we can get...
the cell as shown in Fig. 1(b). Because of the symmetry of the cell, only a quarter of it is enough for the analysis. The external loading is applied along the Z-axis.

During the loading process, the reinforcing particles are taken as elastic bodies and the matrix is taken to be elastic–plastic and obeys the von Mises yield criterion. The flow stress is expressed as follows [11,12].

\[
\sigma_f = \sigma_0 + H(\bar{\varepsilon}_p)^n,
\]

where \(\sigma_f\) is the flow stress, \(\sigma_0\) the initial yield stress, \(H\) the coefficient of hardening and \(n\) the power of hardening while \(\bar{\varepsilon}_p\) is the von Mises equivalent plastic strain.

By changing the ratio of \(L_a\) to \(L_b\), we can find the influence of the particles’ geometric pattern on the mechanical behaviour of composites with aligned particles.

3. Numerical results and discussion

We take Al as the matrix and SiC as the particle. The mechanical parameters of phases are presented below [11,12].

\[
E_1 = 69 \text{ GPa}, \quad \sigma_0 = 43 \text{ MPa}, \quad v_1 = 0.3, \quad H = 137.2 \text{ MPa}, \quad n = 0.3, \quad E_2 = 440 \text{ GPa}, \quad v_2 = 0.25
\]

where \(E\) is Young’s modulus, and \(v\) Poisson’s ratio. The subscripts 1 and 2 represent the matrix and reinforcement, respectively.

The maximum fraction of reinforcement can be determined if the ratio \(r = L_a/L_b\) is given. For example, the particles are spherical and we take the ratio \(r = L_a/L_b = 2.0\). The biggest spherical particle in the cell is the one whose radius is taken as \(R = L_b\). Then, the maximum fraction of the reinforcement in this axisymmetric problem will be

\[
\frac{\frac{1}{2} \times \frac{4}{3} \times \pi \times R^3}{\pi \times L_a \times L_b^2} = 33.33\%.
\]

On the other hand, if the volume fraction of reinforcement is known, the smallest value of the ratio \(r\) can be obtained. For example, we take the volume fraction of the spherical particle as 40%. The smallest value of ratio \(r\) occurs when \(L_a = R\).

\[
L_a = rL_b,
\]

Substituting Eq. (2) into Eq. (3), we can get

\[
\frac{1}{2} \times \frac{4}{3} \times \pi \times L_a^3 = 40\%.
\]

We take the ratios \(r = 3/1, 2/1, 1/1\) and 1/2 for the calculations of the mechanical behavior of the composite whose reinforcement volume fraction is 10% and present the results in Fig. 2. When the ratio \(r\) is less than 1 \((r < 1.0)\), the stripe Fig. 1(b) direction will change from direction R to direction Z Fig. 1(b). In Fig. 2, it can be observed that the curves representing the results of \(r = 3/1, 2/1\) and 1/1 almost cluster together and we can hardly separate the curve representing the result of \(r = 3/1\) from that of \(r = 2/1\). The curve reflecting the strength of \(r = 1/2\) is the highest in these results which means that we can get the highest strength in the direction of the particle stripes.

Another two groups of calculations are made for the materials whose volume fractions of reinforcement are 20% and 40%, respectively. The results are shown in Figs. 3 and 4. From these two results, it can be again concluded that the highest strength will occur in the material whose ratio \(r\) is less than 1. We can also conclude that the influence
of the ratio $r$ is stronger when the volume fraction of reinforcements increases as in the non-aligned case [5,9].

In the following, we change the shape of the spherical particle to the double cones without tips whose cross section in plane $R-Z$ is hexagonal shown in Fig. 5. The same calculations as for the spherical particle were performed. The differences between this kind of particle and the spherical were very small. The comparisons are presented in Figs. 6–8.

The model shown in Fig. 1(b) can also be used to study the transverse mechanical behavior of continuous fiber-reinforced materials if the problem
alters from the axisymmetric problem to a plane strain one. The material with the volume fraction of reinforcement being 20% is taken into calculation and the result is shown in Fig. 9. The ratio $r$ changes from 1/3 to 3/1. It can be seen in Fig. 9 that when the ratio $r$ is bigger than 1 ($r > 1.0$) which means that the direction of loading is perpendicular to the direction of the fibers' transverse alignment, the differences among the results become very small. On the other hand, it also can be seen that when the ratio is less than 1 ($r < 1.0$) which means loading in the direction of the fibers' transverse alignment, the strength of material is much elevated with the ratio decreasing. From this result, we can conclude that the transverse strength of continuous fiber-reinforced materials can be improved much in one direction (direction 2 which coincides with the direction of the fibers' transverse alignment) while the strength in another direction (direction 1 which is in the cross-section plane and perpendicular to the direction of the fibers' transverse alignment) loses little.

The results reported above are in qualitative agreement with recently calculated stress-strain curves for artificial micro-structures with particles randomly distributed and aligned to different degrees, respectively, [13].

The axial stress of a long fiber-reinforced material is usually expressed as follows [14].

$$\sigma = f \cdot \sigma_2 + (1 - f) \cdot \sigma_1.$$  (4)
When a displacement loading is applied on the material along the axial direction and the matrix material is in an elastic state, equation can be written as follows.

\[ \sigma_z = f \cdot E_2 e_z + (1 - f) \cdot E_1 e_z, \]  

where \( e_z \) is the axial strain and the subscript \( z \) represents the axial direction.

If the matrix material is in the plastic state, the composite stress is written as

\[ \sigma_z = f \cdot E_2 e_z + (1 - f) \cdot \left[ \sigma_0 + H(e_{zp})' \right], \]

where \( e_{zp} \) is the axial plastic deformation.

The comparison of the mechanical behavior between the particle- and long fiber-reinforced material is shown in Fig. 10. It is obvious that the strength of the long fiber-reinforced material is much higher than that of the particle-reinforced material. The soft behavior of particle-reinforced metal matrix composites (MMCs) can be explained by the development of shear bands between the particles [13].

4. Conclusion

1. The strength of MMCs along the stripe direction \( (r < 1.0) \) is higher than that along other directions. The difference of the mechanical behaviour between the spherical particle-reinforced material and the double cones without tips particle-reinforced material is small and can be neglected.

2. The transverse strength of continuous fiber-reinforced MMC materials can be elevated in one direction by changing the ratio \( r \) while the reduction in the value of strength in other directions is very small.

3. Strong differences are found between aligned particles-reinforced MMCs and topologically similar fiber-reinforced MMCs.

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References


