Study on Mechanical Properties of Composites with Regular Distribution of Single Layer Ellipsoid Particles

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Abstract. The impact of the size distribution of the reinforced particles on the mechanical properties of composite materials is studied, according to the corresponding parameters, the finite element model of the composites on the model of Al based SiC composites is established. With the method of finite element simulation, the surface displacement and stress distribution of particle reinforced composites whose surface is pressed by a line uniformly load is solved, the effects of reinforced particles buried depth, length to diameter ratio, the young’s modulus ratio of matrix and particles, and rotation angle on the mechanical properties of composites are also analyzed. The article outlines concrete influences of the structure parameters and spatial distribution parameters of particles which distribute in the composites on the surface displacement and stress distribution of the composites.

1. Introduction
The particle-reinforced composite with high specific strength, high specific stiffness, effective wear resistance and dimensional stability [1] has been widely used in aerospace, military, automotive and other fields [2-4]. In order to meet its application requirements, it is necessary to update the performance research of particle-reinforced composites with different parameters. In-depth research on particle debonding, particle breakage, crack and other failure modes in particle-reinforced composites has been conducted abroad [5-7], with the purpose of preventing its failure due to limitations of usage conditions. Study on the failure modes and processing methods of particle-reinforced composites in China has also delivered great progress [8-9]. Recent years, some scholars who have applied particle-reinforced composites in the field of elastic fluid lubrication [10, 11] to improve the lubrication environment of elastohydrodynamic lubrication (EHL). With the operability of production and experiment taken into consideration, most existing research takes the equivalent volume elements containing randomly distributed reinforced particles and single-particle composites as the object [12, 13], ignoring the mutual interaction between particles. Under static or dynamic load, the parameter of particle size and distribution of the particle-reinforced composites can affect the topography and internal stress distribution of the composite surface [14], which further influences the application of the composite in some areas. This paper establishes a two-dimensional finite element model of ellipsoidal particle-reinforced composites with single-layer regular distribution so as to explore the effects of the parameters of structure and spatial distribution on the mechanical properties and surface
morphology of particle-reinforced composites, aiming to further improve the comprehensive performance of the metal-based particle-reinforced composite material, and providing new ideas and basis for expanding its application.

2. Finite element geometric model of ellipsoidal particle-reinforced composites

This model is based on aluminium-based SiC composites and is appropriately adjusted during analysis. For detailed parameters, see Table 1. Based on the different parameters of particle structure performance and spatial distribution of ellipsoidal particle-reinforced composites with single-layer regular distribution, this paper establishes the finite element model of the composite materials with their corresponding parameters. Calculation and analysis are carried out at the same time, in which a two-dimensional model of a representative symmetry plane is used to reflect the stress state of each direction since the model is completely symmetrical. This paper takes a five-particle composite as the original model (see Figure 1 for the structure) to study the influence of the parameters of structural performance and spatial distribution of the particles with single-layer regular distribution on the amount of surface displacement and stress distribution of the material, by adjusting the corresponding parameters of the composites. The angle of inclination of the particle refer to the angle between the ellipsoid with its centre rotating its long axis counter clock wise and the x axis when the ellipsoidal centre is fixed. The principle is shown in Figure 1, in which $\theta$ is the angle of inclination of the particles.

![Figure 1. Geometric model of Al-based SiC composites](image)

Table 1. Material parameters used in calculation.

| Material | Young's modulus $E$(Pa) | Poisson's ratio |
|----------|--------------------------|----------------|
| Matrix   | $7.0 \times 10^{10}$     | 0.33           |
| Particle | $4.5 \times 10^{11}$     | 0.17           |

3. Calculation Results and Discussion of Ellipsoid Particle-reinforced composites

This paper explores the influence of the burial depth, particle draw ratio, particle-to-matrix elastic modulus ratio, angle of inclination of particle of the composite with single-layer regularly distributed ellipsoidal particles under the uniform load of 20 MPa on its surface morphology and stress distribution. At the same time, the calculation result of the continuous matrix material without reinforced particles and that of the above-mentioned discontinuous material are compared for analysis. Relating composite parameters to macroscopic mechanical calculations is of great significance to the study of mesoscopic parameter functions of materials.

3.1 Calculation Results and Discussion of Stress Distribution of Particle-reinforced Composites

Figure 2 shows the stress distribution of composites with a non-dimensional burial depth $H$ of 0.05, 0.075, 0.1, 0.125, and 0.15 under 20 MPa external load (The legend is the two enhanced particles in the middle). The dimensionless depth $H$ is the ratio of the distance between the top of ellipsoidal particle and the surface. The curves in Figure 3 show the surface stress distribution of the particle-reinforced composites with different $H$ under the uniform load.

The maximum stress area of the composite is on the subsurface under the external load, as the particles closer to this area, the bigger stress the particles subjected as the figure 2 shows. Compared with the homogeneous matrix material without the reinforced particles, the local stress value of the
region with the particles is higher than that of the same region of the homogeneous material, which is because the elastic modulus of the reinforced region is higher than that of the matrix, thus imposing strain constraint on the adjacent matrix. It also shows that as the dimensionless burial depth of the inclusion particles increases, the pressure on the particles gets larger while the influence of the external force on the surrounding low stress regions is reduced, thus forming a hoof-shaped low stress zone between two particles. The closer the particle is to the surface, the more restrictive it is to the surface material, and the greater the surface stress as figure 3 shows.

Figure 2. Stress distribution with dimensionless burial depth $H$ of 0.05, 0.075, 0.1, 0.125 and 0.15

Figure 3. Surface stress curve with dimensionless burial depth $H$ of 0.05, 0.075, 0.1, 0.125 and 0.15

Figure 4 displays that when the aspect ratio is less than 4, the force that the particles are subjected to is getting bigger and the area of the circular low stress region in the intermediate matrix is reduced as the aspect ratio increases. The stress of particles reaches to the highest at $a/b=8$, which increases the risk of particle breakage. Figure 5 shows that the surface stress peak increases with the increase of the aspect ratio as $a/b<4$. The stress peak has a turning point when the aspect ratio is between 4 and 8. While, the surface stress at the area where between the particles decreased as the increase of the aspect ratio, and they are all smaller than that of no inclusions.
Figure 4. Stress distribution with the aspect ratio $a/b$ of 1, 1.5, 2, 4, and 8.

Figure 5. Curve of surface stress distribution with $a/b$ of 1, 1.5, 2, 4, and 8.

Figure 6. Stress distribution with the elastic modulus ratio of 0.1, 0.5, 1, 3, and 7.
Figure 6 illustrates that the restrictions comes from the soft particles on the materials around them is weak, this causes the matrix to withstand a large load and a hoof-shaped high stress zone is formed between the adjacent particles, as the elastic hardness of the particles increases, the hoof-shaped high stress area gradually becomes smaller. In addition, when the elastic modulus of the two-phase material differs greatly, the maximum stress peak will climb to a higher level. The harder the particle reinforcement is, the more pronounced the strain constraint effect on the surrounding matrix material. Figure 7 shows that the stress in the region where the hard particles \((E_b/E_a>1)\) are located is positive compared with the continuous matrix material \((E_b/E_a=1)\), while the stress in the region where the soft inclusions \((E_b/E_a<1)\) are located is negative. The above situation is reversed in the area between the particles.

![Surface stress curve with the elastic modulus ratio \(E_b/E_a\) of 0.1, 0.5, 1, 3, and 7](image)

Figure 7. Surface stress curve with the elastic modulus ratio \(E_b/E_a\) of 0.1, 0.5, 1, 3, and 7

![Stress distribution with particle rotation angles of 30°, 40°, 60°, 75°, and 90°](image)

Figure 8. Stress distribution with particle rotation angles of 30°, 40°, 60°, 75°, and 90°

Figure 8 shows the stress on the composite material under the uniform load of 20 MPa when \(\theta\) is 30°, 40°, 60°, 75°, and 90°, respectively. When the particle rotation angle \(\theta\) is small, the stress distribution inside the composite is more uniform and the stress gradient of the matrix is getting smoother. It also can be proved in Figure 9. As \(\theta\) increases, the stress inside the particles is increased, while the area of the high-load region gradually is decreased, more obvious stress concentration zones begin to appear inside the particles, at the same time the surface stress at the position where the
particles are located is also increased. Moreover, the position of the surface stress peak slowly shifts as the particle angle changes.

Figure 9. Surface stress curves with particle rotation angles $\theta$ of 30°, 40°, 60°, 75°, and 90°

3.2 Calculation results and discussion of surface displacement of particle-reinforced composites

Figure 10 shows that the particle has a limitation on the migration of the surrounding material, as the buried particles are closer to the surface, the strengthening effect of the particles on the matrix is stronger so the surface displacement at the position where the particles are located is smaller than that of no inclusions (between the adjacent particles). The inside particles enhanced the matrix material, and its overall displacement is smaller than that of the material without inclusions under the same load.

Figure 10. Surface displacement curve with dimensionless burial depth $H$ of 0.05, 0.075, 0.1, 0.125 and 0.15

Figure 11. Surface displacement curve of particle-reinforced composites with $a/b$ of 1, 1.5, 2, 4, and 8
Figure 11 shows the surface displacement of the composite material with the aspect ratio of 1, 1.5, 2, 4, and 8, respectively, under the uniform load of 20 MPa. The surface displacement $S_d$ of the composite material get the minimum value at the position of the particles are located as introduced above. As the increase of $a/b$, the surface displacement $S_d$ follow $S_d(a/b=1)< S_d(a/b=1.5)< S_d(a/b=2)< S_d(\text{no inclusions})< S_d(a/b=4)< S_d(a/b=8)$. Although the surface displacement is increased, the growth rate is not large.

Figure 12. Surface displacement curve of composites with $E_b/E_a$ of 0.1, 0.5, 1, 3, and 7

Figure 12 shows the surface displacement of the particle-reinforced composites with the elastic modulus ratio $E_b/E_a$ of 0.1, 0.5, 1, 3, and 7, respectively, under the uniform load of 20 MPa. The displacement at the soft particles is greater than that of the hard particles, and the average value is greater than that of no inclusions. That is because the hard particles can effectively hinder the strain of the matrix material in the vicinity, while the soft ones are easily deformed under the press of the matrix around them and leading to a larger deformation. As $E_b/E_a$ increases, the strain constraint of the particles to the matrix gradually increases, the surface displacement decreases as shown in figure 12.

Figure 13. Surface displacement curve of composites with $\theta$ of 30°, 40°, 60°, 75°, and 90°

In actual processing and production, the reinforced particles are not regularly, but rather freely distributed in the matrix. Therefore, it is necessary to study the influence of $\theta$ on the performance of composites. Figure 13 shows the surface displacement of the particle-reinforced composites with different ellipsoidal inclination angles and fixed ellipsoidal particle centre as the ellipsoid rotates around its centre. It can be seen that as the angle between the long axis of the ellipsoidal particle and the $X$ axis changes from 30° to 90°, the average surface displacement gradually decreases, and the position where the maximum displacement occurs also shifts. Moreover, the larger the inclination angles, the smaller the minimum displacement, and the decreasing gradient of the displacement curve
from peak to valley is also slowed down. The rotation of angle also changed the region of the deformation, that is, as the rotation angle increases, the amplitude of the longitudinal deformation increases, while the span of the lateral deformation decreases.

4. Conclusions
The problem of matrix with ellipsoidal particles was studied herein. The influences of particle burial depth, aspect ratio, and ellipsoidal inclination angles on the stress distribution and the surface displacement of the composites were analyzed. Moreover, the salient conclusions that can be drawn from this study are as follows.

1) As the depth of the particle reinforcement changes slightly, the closer the particle is to the surface layer, the sharper the stress peak rises and the more rapid the stress transition.

2) When the difference between the long semi-axis and the short semi-axis of the ellipsoidal particle is larger, the surface displacement of the composite material is greater than that of no particles. As the long semi-axis and the short semi-axis are closer, the surface displacement is reduced and less than that of no inclusions.

3) The soft particles cause the interior of the matrix material to be "cavitated", and the equivalent elastic modulus of the composite material is lower than that of the continuous matrix material, on the contrary, the hard particles make the matrix material equivalent to being locally strengthened. The presence of particles effectively hinders the strain of the surrounding matrix material, and the deformation valley occurs in the region where the particles are located, but the particles also bear higher stress. In addition, the greater the difference in the elastic modulus of the material the bigger the relative deformation amplitude of the surface.

4) As the inclination angle increases, stress concentration begins to migrate into the interior of the particle, causing the surface average displacement to decrease. While, the surface deformation amplitude is increased as the inclination angle increases, and the deformation trend becomes more and more sharp.

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References
[1] Wang T, Fan Z J 2009 Influence of reinforcement morphology and distribution on mechanical properties of aluminum-based alloy composites Material Heat Treatment Technology 38(16):62-64 153
[2] Wu H D, Zhang Hui, Chen Shuang, Fu D F J 2015 Flow stress behavior and processing map of extrude 7075Al/SiC particle reinforced composite prepared by spray deposition during hot compression T. Nonfree. Metal. Soc. (3) 692698
[3] Li Wei, Chen M L, Chen Y Y J 2002 Research Status and Prospect of Cast Metal-Based Particle Reinforced Composites Foundry 51(4) 205208
[4] Dong X Y, Ming Z D, Kun Y, Yu C S J 2012 Two-Scale Finite Element Analysis of Elastic Structure of Particle Reinforced Composites Journal of Mechanical Engineering 48(8) 034-038
[5] Keiichiro T, Yu I J 2010 A constitutive model of particulate-reinforced composites taking account of particle size effects and damage evolution Composites Part A 41 313321
[6] Abedini A, Z.T. Chen J 2014 A micromechanical model of particle-reinforced metal matrix composites considering partial size and damage Computational Materials Science 85 200205
[7] Zhou K, Wang R B J 2014 Modeling cracks and inclusions near surfaces under contact loading. International Journal of Mechanical Sciences 83 163171
[8] Zhang M H, Chen J K, Zhao F, Bai S L J 2016 A new model of interfacial adhesive strength of fiber-reinforced polymeric composites upon consideration of cohesive force International Journal of Mechanical Sciences 106 5061
[9] Liu J, Yang S, Xia W S, Jiang X, Gui C B J 2016 Microstructure and wear resistance performance of Cu-Ni-Mn alloy based hardfacing coatings reinforced by WC particles Journal of Alloys and Compounds 654 6370
[10] Zhang Y Y, Wang X L, Yan X L C 2014 Study on the influence of material heterogeneity on elastohydrodynamic lubrication performance Proceedings of the 11th Tribology Conference
[11] Dong Q B, Zhou K J 2015 Modeling heterogeneous materials with multiple inclusions under mixed lubrication contact International Journal of Mechanical Science 103 8996
[12] Azra Rasool, Helmut Böhm J 2012 Effects of particle shape on the macroscopic and microscopic linear behaviors particle reinforced composites International Journal of Engineering Science 58 2134
[13] Luo J X, Tang Chun J 2010 Application of X-VCFEM Element in Crack Simulation of Particle Reinforced Composites Materials Review: Research 24(9) 8083
[14] Hugo Boffy, G E Morales-Espejel, C H Venner C 2015 Multigrid solution for 3D rough contact problems in presence of subsurface heterogeneities Proceeding of the 42th Leeds-Lyon Symposium on Tribology September 7-9 Lyon France