Simulation of Tensile Deformation Behavior of PM-SiC\textsubscript{p}/2014Al Composite Based on RVE

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Abstract. Metal matrix composite (MMC) emerges at the right moment and is widely used in aviation, aerospace and other fields due to its intrinsic properties. Usually compression tests are used to study the mechanical properties and deformation behavior of MMC. However, it is very important to study the deformation damage and fracture behavior of MMC under tensile stress state. At present, the design basis for MMC tensile stress state test still need further study. To this end, this paper uses the representative volume element (RVE) model, to simulate and analyze the tensile deformation behavior of particle-reinforced metal matrix composites (PRMMCS) for PM-SiC\textsubscript{p}/2014Al as the typical materials, and the deformation damage and fracture are analyzed and discussed.

Keywords. PM-SiC\textsubscript{p}/2014Al, tensile, deformation behavior, damage, fracture.

1. Introduction

As a typical metal matrix composite material, SiC particle reinforced Al-based composite material has low density, high Young’s modulus, low thermal expansion coefficient, extremely high thermal conductivity, excellent thermal control characteristics, and unique anti-resonance ability, is widely used in aerospace, aircraft, civil automobiles, electronic packaging and other fields \cite{1,2}. Particle-reinforced metal matrix composites have good designability, and the types, sizes, volume fractions, distributions, and interfaces of the reinforced particles will have an impact on their performance. The effects of the above-mentioned different parameters are interdependent and complicated, and currently only rely on a single experimental method. It is difficult to precisely adjust particle characteristics and composite material properties.

At present, the experimental research on deformation damage and fracture of particle-reinforced metal matrix composites at home and abroad is mainly achieved by X-ray tomography. Williams \cite{3} et al. used tomographic X-ray photography to study the uniaxial tensile of SiC particle-reinforced 2028Al matrix composites. Tensile damage behavior, quantitative statistical analysis of the process of particle cracking and pore growth in composite materials, and the effect of particle size and axial ratio on fracture micromorphology were studied in detail. Su \cite{4} studied the micro-damage and fracture mechanism of TiB particle-reinforced 2024Al composite by monitoring the in-situ tensile test with scanning electron microscope. It was found that micro-cracks first initiated at the micro-particles and particle agglomerations. The research believes that the reason for this phenomenon is the increase of
the maximum equivalent plastic strain and stress triaxiality caused by particle agglomeration. Bao [5] simulated particle enhancement by establishing a damaged cell model and a multi-particle cell model.

At the level of meso-damage mechanics, the damage evolution of composite materials is mainly described by the evolution of the volume ratio of broken particles to unbroken particles. Tohgo and Chou [6, 7] and others proposed the incremental damage theory of particle-reinforced composites based on Eshelby equivalent inclusion theory and Mori-Tanaka mean field theory, the model considers the plastic deformation capacity of the matrix and the gradual peeling failure of the particles. Pranmanik et al. [8] studied the fracture surface and fatigue cracks of particle-reinforced aluminum matrix composites with different volume fractions, and found that the introduction of particles will greatly reduce the fatigue performance of the material. Tang et al. [9] studied the peeling damage of Ta particle-reinforced metal glass matrix composites under high strain rate loads, and found that under quasi-static and impact loads, the particle-matrix interface is both a crack nucleation source and an extension source. But at the same time, it also plays a role in hindering the further propagation of the crack. In the plastic deformation under the impact load, the deformation twins and grain refinement play a key role, but it is not obvious under the quasi-static load. Wang et al. [10] studied the effect of key microstructural parameters such as the degree of clustering, size and volume fraction of particles on the mechanical properties of high modulus steels through the crystal plastic fast Fourier transform method and a new phase field damage model. It was found that the distribution of TiB$_2$ particles is uniform, the volume fraction is in the range of 7%~15 %, and the initial solidification does not produce large TiB$_2$ particle dendrites, which is more conducive to obtaining high modulus steel with the best mechanical properties. However, the current research on the damage and fracture of particle-reinforced metal matrix composites mainly focuses on the damage caused by particle peeling, and the presence of particles will also have a significant effect on the deformation behavior of the matrix. In addition, the particles will also change the local stress state of the matrix, thereby changing its deformation behavior and causing damage evolution. In-depth systematic research on this aspect is still lacking. When using the finite element method for structural analysis and process description, P.V. Yasniy [11] attempted to develop a phenomenological model of degradation of the roller. S.V. Panin [12] used computer simulation to investigate the effect of low temperature on initiation of rotation deformation modes at the crack tip. P. V. Yasnii [13] described a procedure for modeling the influence of structural components on the deformation of AMg$_5$ alloy with the help of the ANSYS program package, based on the finite element method (FEM). This has a certain enlightening effect for the subsequent description of the deformation stage of the physical and model materials.

Usually compression tests are used to study the mechanical properties and deformation behavior of MMC. However, it is very important to use the tensile stress state test of MMC for deformation damage and fracture behavior. At present, the design basis for MMC tensile stress state test is not enough. In this paper, typical uniaxial tensile simulation analyses were conducted to study the deformation damage and fracture behavior of PM-SiC$_p$/2014Al composites, and try to establish a mathematical relationship between the composite component characteristics and the macroscopic properties of the materials. The finite element numerical simulation method was used to study the tensile deformation damage and fracture behavior, interface damage initiation and development of SiC$_p$/Al composites with different particle characteristics, to provide a reference for the optimal design of composite materials and provide a basis for experimental design.

2. Analysis and Modeling

2.1. Test Material

The test material was PM-SiCp/2014Al. First, the original samples were homogenized and annealed at the temperature of 400°C and kept for 8 hours. After cooling in the furnace, aluminum alloy samples with the same initial state were obtained. The main chemical composition of 2014Al alloy as the matrix material is shown in table 1. The material characteristic parameters of the PM-SiCp/2014Al composite are shown in table 2.
In the finite element calculation, accurate material parameters need to be input, and different material properties need to be given for SiC reinforcement and 2014Al matrix, respectively, to simulate and solve the composite constitutive and fracture criterion. The elastic constitutive and linear elastic fracture criteria are used for SiC reinforcement. The fracture strength is defined by Weibull distribution model. The average fracture strength of SiC is 500 MPa. In 2014Al alloy matrix, a combination of constitutive and elliptical fracture criterion is selected. In order to simulate the interface between SiC and Al matrix, a layer of cohesive elements is introduced to describe the interface deformation and damage behavior of MMC. And the material subroutine including constitutive equation, damage variable and fracture criterion compiled by FORTRAN language is called by help of the corresponding interface of ABAQUS commercial software. The specific VUMAT subroutine process is shown in figure 1:

Table 1. Chemical composition of 2014 aluminum alloy in wt.%.  

| Element | Cu | Mg | Zn | Mn | Ti | Ni | Fe | Others | Al |
|---------|----|----|----|----|----|----|----|--------|----|
|         | 4.02 | 0.51 | 0.20 | 0.62 | 0.02 | 0.02 | 0.63 | <0.01 | Balance |

Table 2. Material characteristic parameters of PM-SiCp/2014Al composite.  

| Characteristics of SiC particles | Material | Volume fraction | Size | Shape | Matrix characteristics |
|---------------------------------|----------|-----------------|------|-------|-----------------------|
| Material                        | SiC      | 15%             | ~ 15μm | convex polyhedron | 2014Al               |

Figure 1. Flow diagram of VUMAT subroutine.
2.2. Analyze the Model

In order to truly return the three-dimensional morphology of SiCₚ/Al composites, the convex polyhedron is used to describe the morphology of SiC reinforced particles, and an algorithm for generating a geometric model of reinforced particles with controllable particle size, shape and volume fraction is established, and the corresponding Python is written. The subroutine realizes the true reduction of the morphology of the reinforced particles, and the corresponding relationship between the volume fraction and size of the reinforced particles and the geometrical size of the periodic representative volume element (RVE) is determined through simulation.

In the analysis and calculation, a reasonable value should be selected for RVE size. On the one hand, the size of RVE must be representative, that is, its deformation behavior can represent the macroscopic material; On the other hand, the size cannot be too large, to ensure the efficiency of finite element calculation. By continuously increasing the size of the RVE until the relative error of the simulation result is no more than 5%, the size is determined for the representative volume element (RVE) model analyzed in this paper, as shown in figure 2. Microscopic observation of the sample and statistical analysis of its SiC particle size with the help of SEM, it is found that the average size of the reinforcing particles is 15 μm, the overall size of the investigated volume is 75 μm, the load is applied as shown in figure 2, and the loading rate is 2 mm/min according to uniaxial tensile test standard.

![Figure 2](image)

**Figure 2.** Finite element model of 15% SiCₚ/Al composite.

3. Simulation and Analysis

Figure 3 shows the Mises equivalent stress distribution in the earlier deformation stage, middle deformation stage and after fracture of uniaxial tensile. In the early stage of deformation, as shown in figure 3 (a), the stress in SiC is large, which serves as the main load-bearing role of the strengthening phase. The matrix stress is small and the stress distribution is uneven. At the sharp angle of the particle along the tensile direction, there is an obvious stress concentration area on the center, and the stress is greater in the middle of the connection between the two particles. This is because the particles limit the deformation continuity of the surrounding matrix material and form a stress concentration. In the middle stage of tensile process, with the increase of the amount of deformation, the stress in stress concentration area in the particles continues to increase until it reaches a critical fracture strength. Fracture occurs when the critical fracture strength is reached, as shown in the red circle in figure 3 (b). The stress of the particles is still greater than that of matrix, and can effectively bear the load. As the strain continues to increase, SiC breaks one by one, as shown in figure 3 (c), finally, all particles are broken. The fracture of SiC mainly occurs at the boundary with the matrix. After the particle fractures, the stress at the end of the particle debonding along the stretching direction is released, but the stress at the end that is still connected is greater than the stress of the matrix, and there is a phenomenon of concentrated residual stress. It shows that the particles still retain a certain carrying capacity. As the strain continues to increase, a larger stress concentration begins to occur in the matrix. When the stress reaches the critical fracture stress of the matrix material, micro-cracks will be generated in the matrix, and when the strain continues to increase, the micro-cracks expand and polymerize, the matrix material even broke. It can be seen from figure 3 (d) that cracks are first generated inside the RVE and propagate along the particle boundary, which
eventually leads to the fracture of the composite material, which is consistent with the actual observation.

Figure 3. Mises stress distribution of uniaxial tension: (a) earlier deformation stage; (b) middle deformation stage; (c) later deformation stage; (d) after fracture.

Figure 4 shows the damage distribution of the composite matrix in the earlier deformation stage, middle deformation stage, later deformation stage and after fracture of uniaxial tensile. It can be clearly seen that the white area in figure 4 (a) is SiC reinforced particles. Due to its strength is very high compared with the matrix, the damage is not defined in this part of the area. And the blue area is the matrix which the damage value is 0 under the initial condition. With the damage gradually accumulates as the different stages of tensile process, as shown in figure 4 (b), figure 4 (c) and figure 4 (d). It can be seen that the damage of each part of the matrix increases in different degrees, until the damage limit achieves 1, the matrix becomes completely invalid. The damage of the matrix is generated after the reinforced particles are ruptured. As the number of particles cracks increases, the damage of the matrix also gradually increases. When the particles completely lose the bearing capacity, the matrix damage value will reach to 1, and then quickly be cracked, as shown in figure 4 (c), the obvious damage band formed in tensile process can be seen.

Figure 4. Damage distribution of the matrix of uniaxial tension: (a) earlier deformation stage; (b) middle deformation stage; (c) later deformation stage; (d) after fracture.
Subsequently, the uniaxial tension stress-strain curve of the composite material is calculated and compared with the test results. As shown in figure 5, it can be seen that the two curves have large discrepancies in the earlier stage of deformation. From the simulation results, the material has a clear elastic deformation stage, and the elastic modulus is large. From the test results, the material has no obvious earlier elastic stage and the stiffness is relatively small. This is because the simulation considers that the material is only composed of reinforcing particles and matrix with no consideration of the micro-defects inside the material, so it has a high elastic modulus. However, due to the preparation process, there are a large number of micro-defects in the material that weaken the elastic properties of the material. In the middle stage of the deformation, the two curves are in good agreement. At this stage, the reinforced particles basically fail (part of the interface debonds, part of the particles are broken) and lose the bearing capacity. Therefore, the deformation behavior is similar to that of the aluminum matrix with holes. The role of material micro-defects becomes the secondary factor, and the main factor is the larger holes caused by particle debonding and cracking, so that experimental and simulation curves are in good agreement. In the later stage of deformation, the micro-cracks are aggregated, the material is weakened and the final fracture occurs. Hence in the calculation process, the simulation of fracture is achieved by deleting the element. So, in the later stage of deformation, the failed element is gradually deleted, but the actual damage cracking gradually develops from the point to the line, and to the fracture surface. Because the size of the element is relatively large, and it will accelerate the failure process of the material by deleting the element, so the simulated fracture stress is lower than the actual fracture stress. Further research can be based on hierarchical decomposition techniques, such as such as multiscale extended finite element method (MsXFEM) or variational multiscale method (VMM). These methods emphasize the influence of micro field, so it can be got more accurate results at macro level.

![Figure 5. Comparison between simulative and experimental engineering stress-strain curves of 15% SiCp/Al composite.](image)

After analysis and verification, the accuracy of the simulation method can be basically determined, which can be used to simulate the actual deformation behavior, damage process and fracture results of the PM-SiCp/2014Al composite.

4. Conclusion
A three-dimensional characteristic representative volume element model reflecting the microstructure was established, and a typical uniaxial tensile test simulation was conducted to study the deformation damage and fracture behavior of the PM-SiCp/2014Al composite, and the following conclusions are obtained:
(1) The stress distribution is not uniform during the stretching process: first, the stress in the hard reinforced particles is significantly higher than that of the relatively soft matrix material; second, the stress distribution inside the particles is not uniform, the stress value in the center of particles is smaller, and the stress value at the edge of particles, especially at the sharp corner of particles is larger; the third is the uneven distribution of matrix stress. The matrix stress near the particles is higher, while the matrix stress far away from the particles is smaller, especially the matrix around the particles in the tensile direction has a higher stress concentration, which is determined by the incongruous deformation of each phase of materials.

(2) From the simulation results, the damage and fracture mechanism of the composite mainly includes three forms: interface debonding, particle fracture and matrix cavity growth. The sequence of the three failure modes is closely related to the material properties of matrix, interface and particle. Both interface debonding and particle fracture will make the particles lose the strengthening effect and release the stress concentration on the reinforced particles. The common causes of matrix damage and failure are interface debonding and particle fracture.

(3) From the simulation results, the material has obvious elastic deformation stage and large elastic modulus, while from the test results, the material has no obvious elastic stage and small stiffness, because in the simulation, the material is only composed of reinforced particles and matrix, and the micro defects inside the material are not considered, so it has high elastic modulus. While in the actual material, due to the preparation process, many micro defects in the material weaken the elastic properties of the material.

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