Modeling the Dynamic Damage Process of the SiC₃d/Al Interpenetrating Phase Composites

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Abstract. In the current study, a 3D mesoscopic structure FE-Model of interpenetrating SiC₃d/Al composite is built based on the digital image-based modeling technique together with optimized methods of three-dimensional mesh generation. Subsequently, the finite element method is proposed to simulate the dynamic damage process of the interpenetrating phase composites SiC₃d/Al under dynamic axial crushing. The cracking process in micro 3D space is clearly presented in the current study. It is shown that the cracks initialization and propagation mainly appear in the region of interface between ceramic and metallic phase. Moreover, the ceramic phase attributes to the model’s damage predominantly. The method proposed in this paper would be of help in the microstructure design of Interpenetrating Phase Composites.

1. Introduction

Interpenetrating Phases Composites (IPC) are characterized by the ceramic skeleton and metallic matrix both continuous in three-dimensional space, and this special structure makes full use of the ceramic’s high specific strength stiffness and the metal’s high toughness. In the military materials filed, the IPC are receiving great attention on the research of the relationship between the mesoscopic structure characteristics and mechanical properties not only because it can effectively block the projectile’s penetration, efficiently absorb and reflex the impact energy, but also because it can maintain a certain macro-structural integrity.

To describe the deformation or damage behaviour of IPC, the representative volume element (RVE) model by computational mesomechanics [1, 2] was employed. Some researchers [3~5] used the idealized unit cell model as the RVE model to simulate the elastic and plastic behaviour of the IPC under uniaxial compression/tension. In such cases, however, the detail features such as shape of cross-section and three-dimensional orientations inside the cell were ignored. Leon[6] employed the RVE model based on the digital image-based (DIB) modelling technique together with voxel array based methods of three-dimensional mesh generation to simulate the overall mechanical behaviour of the IPC. Though such model could reflect the real structure compared with the idealized unit cell model, the model was composed of identically sized hexahedron elements generated by voxel array based
methods, leading to the phenomenon of jaggies in the interface between two-phase, thus influencing the calculation stability unavoidably.

In the current study, a 3D mesoscopic structure FE-Model of SiC₃d/Al with smooth interface is built based on the digital image-based modeling technique together with optimized methods of three-dimensional mesh generation. In addition, Johnson-Holmquist and Johnson-Cook constitutive models [7] are employed to describe the SiC ceramic phase and Al metallic phase, respectively. Subsequently, the model is imported into the commercial code LS-DYNA [8] to investigate the damage initiation and propagation under dynamic axial crushing.

2. Computation and modelling

2.1. CT data acquisition

3-D image scanning is performed using the Sky-Scan1172 Micro-CT. 50 kV and 800 μA are imposed respectively for the Voltage and the Current. In addition, the transmission X-ray image is set for 180 degrees of rotation. It is the active scanning mode that the sample as well as the sample stage is fixed, and the X-ray tube rotates on the sample stage plan's axis. Transmission X-ray images are recorded at 0.4° rotational steps for 180° of rotation. Subsequently, the transmission X-ray images are then reconstructed into cross-sectional images (voxel size of 2.2 × 2.2 × 2.2 μm) images using Sky-Scan’s cluster reconstruction software (NRecon).

2.2. Image segmentation and mesh generation

The process of the SiC₃d/Al 3D FE model generation based on Micro-CT scanning images (the above mentioned cross-sectional images) is presented as figure 1. Micro-CT scanning images (see figure 1 (a)) are imported into ScanIP module [9] and thresholded for values from 65 to 255 to create the respective masks (see figure 1 (b)). Then the ceramic phase 3D image model is built by 3D view operation as figure 1(c) presents. At the same time, by duplicating and inverting the above masks, the metallic phase 3D image model (see figure 1 (d)) is also created. As a result, the SiC₃d/Al 3D image model is generated as figure 1 (e) shows. Subsequently, the SiC₃d/Al 3D image model is imported into ScanFE module [10] and meshed with a mixture of hexahedral and tetrahedral elements. Generated SiC₃d/Al 3D FE model (see figure 1 (f)) is constructed with 480512 tetrahedral elements as well as 906577 brick elements.

Figure 1. The process of SiC₃d/Al FE model generation based on Micro-CT scanning images.
2.3. Boundary conditions and loads
In this investigation, the external load is applied on the nodes uniformly on plane \( z=H \) in the \( z \)-direction (see figure 2) by prescribing the velocity with a constant strain-rate of 3500/s. Subsequently, the displacements of nodes on plane \( z=0 \) are fixed (see figure. 2). The nodes on plane \( x=0 \), are free to displace in the plane but were all constrained to have the same normal displacement \( u \) during the deformation in order to maintain a flat surface. The nodes on plane \( x=L, y=0, y=W \) are defined in the similar way, which meet equation (2)~(4)respectively.

\[
\begin{align*}
\mathbf{u}(0, y, z) &= \mathbf{u}(0,0,0) \\
\mathbf{u}(L, y, z) &= \mathbf{u}(L,0,0) \\
\mathbf{v}(x,0, z) &= \mathbf{v}(0,0,0) \\
\mathbf{v}(x,W, z) &= \mathbf{v}(0,W,0)
\end{align*}
\]

\( (1), (2), (3), (4) \)

\( L, W \) and \( H \) is the the length, width and height of the model respectively.

![Figure 2. Boundary and loads of the SiC/Al FE model.](image)

3. Results and discussions

3.1. The damage analysis of the model
In this investigation, the average stress and strain in the model can be obtained from:

\[
\begin{align*}
\varepsilon_{ave} &= \Delta H / H \\
\sigma_{ave} &= F / A
\end{align*}
\]

\( (5), (6) \)

Where \( \Delta H \) is the is overall deformation of model along Z-direction, \( H \) is the length of model in z direction, \( F \) is the sum of reaction forces at nodes on the surface \( Z=H \) and \( A \) is the area of that surface.
Figure 3. The average Stress/strain curves of model under dynamic axial compression.

Figure 3 and figure 4 show the average stress-strain curve of the model and damage process respectively. It is seen that the average stress increases linearly from 0 to 0.939GPa with the average strain increasing from 0 to 0.3%; at the same time, the crack initiation appears at the region near the interface between the ceramic and metallic phases (see figure 4 (a)). The average stress of the model still increases linearly until to 1.81GPa when the average strain reaches to 0.68; subsequently, the average stress collapses rapidly due to the crack propagation, bridging and accumulation.

Figure 4. The overall damage process of the model.
3.2. Damage mechanisms
In order to investigate further the role of ceramic and metallic phase in the model under dynamic axial compression, the curves of residual mass ratio versus strain of the two phases are presented in figure 5. To describe the damage process, the residual mass ratio $\beta$ in this investigation is defined as:

$$\beta = 1 - \frac{m_{\text{erode}}}{m_0}$$

Where $m_{\text{erode}}$ is the mass of the eroded elements of ceramic phase or metallic phase in the model, and $m_0$ is the original mass of the corresponding phase.

![Figure 5](image.png)

Figure 5. The residual mass ratio of ceramic phase as well as metallic phase in the model.

It can be seen from figure 6 that both the mass of ceramic and metallic phases do not decrease when the average strain increases from 0 to 0.3%; subsequently, the residual mass ratio of ceramic phase decreases gradually to 96% while the one of metallic phase is still 100% when the average strain reaches to 0.68, which corresponds to the stress peak presented in figure 3. However, with the strain increasing to 0.87%, the mass of ceramic phase decreases sharply to 73%, while the mass of metallic phase changes little. Comparing with figure 3, it is evident that the ceramic phase attributes to the model’s damage predominantly. The underlying reason lies in the fact that the ceramic phase is with high strength but unavoidable intrinsic brittleness, while the metallic phase make little contribution to the model’s damage because of its toughness.
In this study, a part of the model is cut by a division plane to further investigate the damage process of ceramic phase as shown in figure 6. To illustrate the crack initiation and propagation locations of the ceramic phase, only the metallic phase and the cracks in ceramic phase are displayed, colored with green and pink, respectively. It can be seen from figure 6 (b) that the cracks are mainly initiated near the interface between the ceramic and metallic phase at the strain of 0.3%. When the strain increases to 0.68%, it is found that the cracks start to bridge and accumulate along the interface. When the cracks are accumulate to a certain amount, they will propagate inside the ceramic phase, thus leading to the collapse of the model finally.

4. Conclusions
In this study, a 3D mesoscopic structure FE-Model of interpenetrating SiC₃d/Al composite is established by using Micro-CT scanning technique. Subsequently, the finite element modeling is applied to investigate its dynamic damage process under axial crushing. The results show that, it is the silicon ceramic phase that makes the dominant contribution to the model’s damage due to its intrinsic brittleness, and the cracks initiate and propagate mainly appear in the region of interface between the ceramic and metallic phases.

5. References
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