Micro-mechanical damage analysis of Al-Tic particulate reinforced composites by Peridynamic theory

Morteza Ahmadi[1], Hossein Hosseini Toudeshky[2*], Mojtaba Sadighi[1]

[1]Mechanical Engineering, Amirkabir University of Technology (Tehran Polytechnic), Tehran, Iran
[2]Aerospace Engineering, Amirkabir University of Technology (Tehran Polytechnic), Tehran, Iran

ABSTRACT

The aim of this study is microstructure modeling and deformation and damage analysis of aluminum-based metal matrix reinforced by Tic particles by using the Peridynamic theory and experiment. The particulate composite was fabricated by mixing aluminum and Tic powder and then the mixture was hot-extruded. Tensile tests were carried out to validate the Peridynamic model. Four representative volume elements were extracted from surface images of specimens. The location of Particles in the matrix was obtained by image processing. Due to restriction on bond-based Peridynamic, state-based Peridynamic was utilized for modeling. Overall stress-strain curve, the destitution of equivalent stress and plastic strain, distribution of damage parameter, the total plastic stretch of all interactions, and the number of damaged interactions were used to analyze the results. At matrix surrounded by particles, matrix/particle interface, and narrow particles stress concentration were detected. The damage was initiated at these regions, but the damage was mostly propagated in matrix and matrix/particle interfaces. In the loading process, several damage mechanisms were initiated and propagated, and finally, a principal crack was created that led to the final fracture. By comparing scanning electron microscope images of the fractured surface, modeling, and experimental result, it is shown that the developed Peridynamic model can precisely predict the progressive damage behavior of particulate composites.

KEYWORDS

Aluminum-matrix composites; Peridynamics; progressive damage growth, Quasi-static loading

Introduction

Due to the high wear resistance, stiffness, and strength to weight ratio compared to conventional alloys, particulate reinforced composites (PRCs) have been widely used in the automotive, aerospace, and electronics industries [1].

There are several theoretical and numerical methods to model composites, and the most utilized method is the finite element method (FEM) [2]. FEM uses spatial partial differential equations; therefore, it experiences difficulties at discontinuities such as cracks. In PRCs, this problem is more critical due to the existence of many sharp corners at the particle boundaries and voids. Consequently, fracture modeling needs additional techniques such as cohesive zone modeling, re-meshing, or extended finite element method [3].

Peridynamic (PD) theory [4] was presented to get over these complications. The PD equation of motion does not contain spatial derivatives; accordingly, it can be utilized in any discontinuities, such as cracks; therefore, no additional techniques are necessary for damage modeling. This formulation makes PD an excellent method for multi-scale modeling of multi-phase materials. While research on PD subjects is rapidly growing [5], additional research is necessary for validation against experimental data. PD is used for modeling the elastic deformation and damage behavior of homogeneous materials [6], and stress and damage investigation in composites [7]. Also, some studies predicted the deformation and damage behavior of dual-phase materials by employing PD theory [8].

Microstructure-based modeling is an accurate method for predicting the elastoplastic and damage behavior of PRCs [9].

This study aims to utilize a PD theory for modeling the deformation and damage behavior of the PRCs. Due to limitations in bond-based PD, state-based PD was employed. In the computational framework of the state-based PD domain, methods were suggested for obtaining the surface correction factor and assigning interface properties and boundary conditions.

Methodology

Silling et al. [10] presented the concept of a state-based PD. As shown in Fig.1, the material point k has displacement, $u_{(k)}$, and position vector, $y_{(k)}$. Each material point interacts with its family members. Family members are placed inside of the circle with a radius δ (horizon).

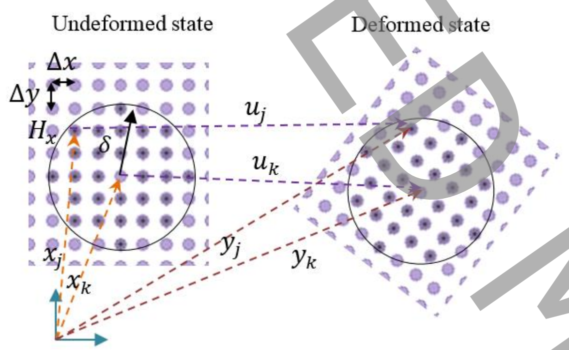

Fig.1. Parameters definition in PD

The PD equation of motion is given by:

$$\rho(x)\ddot{u}(x,t)=\int_{H}\mu(\mathbf{x}-\mathbf{x},t)\times \left(\mathbf{t}(\mathbf{u}-\mathbf{u},\mathbf{x}-\mathbf{x},t)-\mathbf{t}(\mathbf{u}-\mathbf{u},\mathbf{x}-\mathbf{x},t)\right)dH+\mathbf{b}(x,t) \quad (1)$$

where $b_{(k)}$, $V_{(k)}$, and $\rho_{(k)}$ are body load, volume, and mass density of material point k, respectively. $\mu_{(k)(j)}$ is the $k-j$ interaction damage parameter. $t_{(k)(j)}$ is the force density vector of $k-j$ interaction and is given by:

$$t_{(k)(j)}=\frac{1}{V_{(j)}}\frac{\partial W_{(k)}}{\partial\left(\left|y_{(j)}-y_{(k)}\right|\right)}\frac{y_{(j)}-y_{(k)}}{\left|y_{(j)}-y_{(k)}\right|} \quad (2)$$

where $W_{(k)}$ is strain energy density. Eq.(1) can be written in the discretized form:

$$\rho_{(k)}\ddot{u}_{(k)}=\sum_{j=1}^{N}\mu_{(k)(j)}\left(\mathbf{t}_{(k)(j)}-\mathbf{t}_{(j)(k)}\right)V_{(j)}+b_{(k)} \quad (3)$$

The RVE was modeled as a square with length L and thickness h (Fig. 2). Material points were distributed with equal distance Δx in x and y-direction and $h=\Delta x$.

Four fictitious layers with width δ were attached to the RVE to implement boundary conditions as depicted in Fig. 2.

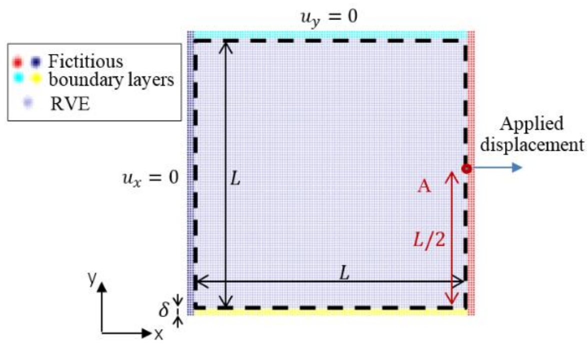

Fig. 2 Geometry of RVE and BCs

Discussion and Results

In Fig. 3 specimens after failure are depicted, and the stress-strain curve of specimens is shown in Fig. 4.

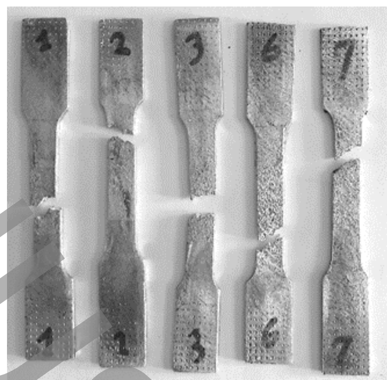

Fig. 3 specimens after failure

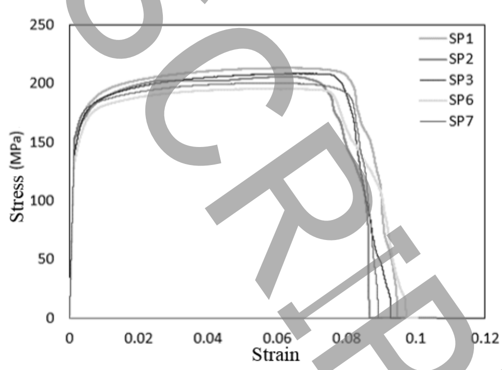

Fig. 4 stress-strain curve of specimens

The overall stress-strain curves of RVEs modeled by PD theory are shown in Fig. 5 that are consistent with experimental results (Fig. 4).

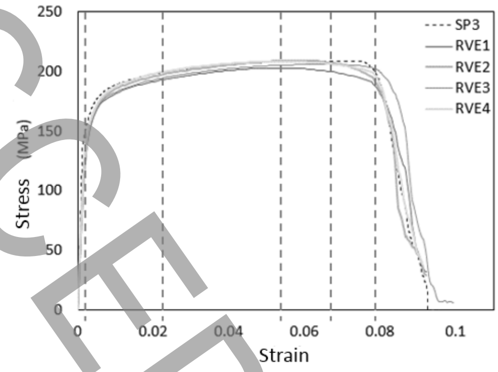

Fig. 5 stress-strain curve of RVEs

By evaluating damage patterns (Fig.6), damage initiation occurred in three areas, i.e., trapped aluminum matrix, the thin Tic particles, and interfaces of matrix-particle. Fracture of coarse Tic particles did not frequently happen. Multiple microcracks were initiated and propagated in the RVEs.

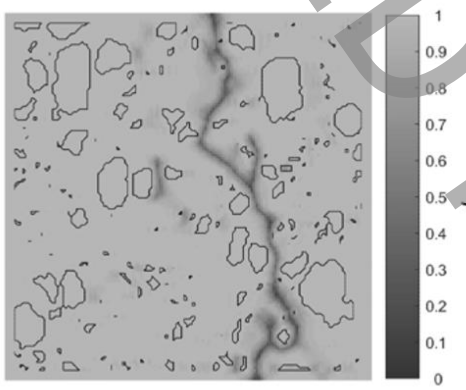

Fig.6. Distribution of damage parameter, $\phi_{(k)}$

In Fig.7 SEM images of the fractured specimens are shown, in this figure fracture mechanisms of Tic particle and matrix fracture and debonding of particle and matrix is observed.

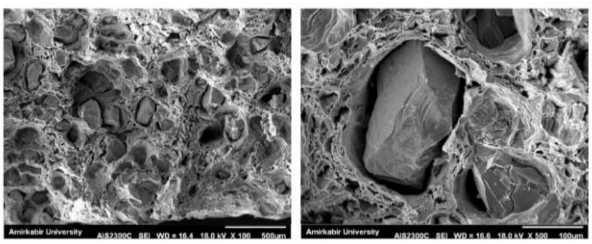

Fig.7. SEM images of the fractured specimens

Conclusions

This study has successfully employed the PD theory to model the deformation and damage behavior of aluminum/Tic particulate composite. The geometry of Tic particles was extracted by using the image processing method. Particle, matrix, and interface damages were predicted and were verified by using experimental results and SEM images. Main plastic deformation happened in the matrix. The stress concentration happened at the sharp corners of particles. The damage was initiated at the sandwiched matrix, the thin particles, and matrix/particle interfaces. In the loading process, several microcracks are initiated and propagated, then microcracks were coalesced and made the principal crack.

References

[1] S. Prabanjan, K. Karthick, J.R. Kumar, S. Ramkumar, A.R. Ahmed, Wear behavior and metallurgical characteristics of particle reinforced metal matrix composites produced by hardfacing: A review, Materials Today: Proceedings, (2020).

[2] J.N. Dastgerdi, G. Marquis, B. Anbarlooie, S. Sankaranarayanan, M. Gupta, Microstructure-sensitive investigation on the plastic deformation and damage initiation of amorphous particles reinforced composites, Composite Structures, 142 (2016) 130-139.

[3] D. Krause, A physically based micromechanical approach to model damage initiation and evolution of fiber reinforced polymers under fatigue loading conditions, Composites Part B: Engineering, 87 (2016) 176-195.

[4] S.A. Silling, Reformulation of elasticity theory for discontinuities and long-range forces, Journal of the Mechanics and Physics of Solids, 48(1) (2000) 175-209.

[5] A. Javili, R. Morasata, E. Oterkus, S. Oterkus, Peridynamics review, Mathematics and Mechanics of Solids, 24(11) (2019) 3714-3739.

[6] H. Zhang, P. Qiao, A two-dimensional ordinary state-based peridynamic model for elastic and fracture analysis, Engineering Fracture Mechanics, 232 (2020) 107040.

[7] M. Rädel, C. Willberg, D. Krause, Peridynamic analysis of fibre-matrix debond and matrix failure mechanisms in composites under transverse tensile load by an energy-based damage criterion, Composites Part B: Engineering, 158 (2019) 18-27.

[8] M. Ahmadi, H. Hosseini-Toudeshky, M. Sadighi, Peridynamic micromechanical modeling of plastic deformation and progressive damage prediction in dual-phase materials, Engineering Fracture Mechanics, 235(C) (2020).

[9] S. Yin, Y. Xie, J. Cizek, E.J. Ekoi, T. Hussain, D.P. Dowling, R. Lupoi, Advanced diamond-reinforced metal matrix composites via cold spray: properties and deposition mechanism, Composites Part B: Engineering, 113 (2017) 44-54.

[10] S.A. Silling, M. Epton, O. Weckner, J. Xu, E. Askari, Peridynamic states and constitutive modeling, Journal of Elasticity, 88(2) (2007) 151-184.