Damage behavior analysis of Al/TiC particulate composite by acoustic emission monitoring and peridynamic modeling

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ABSTRACT

The aim of this study is to characterize different damage mechanisms in an Aluminum (Al)/TiC particulate composite using acoustic emission (AE) monitoring, microstructure-based peridynamic (PD) modeling, and scanning electron microscope (SEM) observations. The Al/TiC composite with a 20% volume fraction of TiC particles was produced using hot extrusion. Several representative volume elements (RVEs) were extracted from the SEM images by image processing, and the effect of particle morphology on the composite behavior was investigated. Rise time, energy, peak amplitude, and duration of the AE signals were utilized for clustering and relating the AE signals to deformation and damage mechanisms. PD modeling results and SEM pictures revealed that the damage mechanisms were initiated in the narrow TiC particles, Al matrix between close particles, and interface of the particle/matrix. The distribution of the particles had more effect on the damage initiation pattern than elastoplastic deformation before the damage initiation. Four sources of the AE signals were detected, i.e., plastic deformation of the Al, Al/TiC debonding, Al cracking, and fracture of the TiC particle. The AE signals of each mechanism were clustered by properties of waveform and by considering the predicted time interval of occurrence of each mechanism by PD modeling. PD model and AE technique predict the same sequence time of deformation and damage mechanisms, but the AE technique predicts the occurring time of each mechanism slightly earlier than the PD model.

1. Introduction

Aluminum (Al)/TiC particulate reinforced composites (PRCs) contain an Al matrix reinforced by hard TiC particles to enhance their mechanical properties. These PRCs combine the desirable properties of Al and ceramic. Al has high-temperature resistance, strength, and ductility, but it has relatively low stiffness, while TiC ceramic is brittle and has high strength and stiffness. Al/TiC composite materials are utilized in various applications in the electronics, automotive, and aerospace industries due to their excellent wear resistance, large strength to weight ratio, and high specific stiffness [1,2].

The ability to characterize damage mechanisms in composites is one of the important research subjects due to the importance of these mechanisms on their integrity and performance. Acoustic Emission (AE), as an in-situ non-destructive method, has the ability to characterize damage mechanisms in composites [3]. A lot of research used AE data solely to characterize damage mechanisms [4], while others have used experiential procedures to validate the AE interpretations [5]. Validation approaches such as scanning electron microscope (SEM) observations cannot be generalized to the whole specimen, as it is difficult to get in-situ data on damage propagation. A cheap and reliable validation method for AE results is to use Finite Element Methods (FEMs) that can predict damage initiation and propagation, making it possible to validate the AE results [6,7].

A lot of research was performed to model the deformation and fracture of PRCs. The distribution of particles in the matrix can affect the toughness, tensile strength, ductility, and fatigue strength of PRCs [8,9]. Two modeling approaches were used to study PRCs. In the first approach, PRC was considered as an anisotropic and homogeneous material, which can provide the macro elastic-plastic deformation of the
material, but it is not capable of predicting particles and the matrix
debonding failure [10]. The second approach is the multi-phase
modeling which considers each material phase in a PRC, where the
morphology, distribution, and fracture of particles are usually simpli-
fied. For example, the geometry of the particles was simplified as circles,
triangles, rectangles, and so on. Additionally, three types of distributions
were considered, i.e. uniform, random and real [11]. For real distribu-
tion, geometry and distribution of the particles were extracted from
image processing of SEM images [12].

The representative volume element (RVE) method has been widely
utilized in modeling multi-phase materials [13]. Multi-phase damage
modeling of composites encounters difficulties such as particle/matrix
interface modeling and crack initiation/propagation. These difficulties
are due to spatial differentials in the equation of motion, which cause
complications at discontinuities. To solve these problems, cohesive zone
modeling [14] and extended finite element method (X-FEM) [15] were
utilized in many studies, but they have convergence difficulties in
simultaneously multi-crack propagation modelings [16]. In addition,
molecular dynamics (MD) simulation is one of the competitive tech-
niques [21] for unit cell modeling, but this method is too
time-consuming for a real component.

To get over these difficulties, peridynamic (PD) theory was intro-
duced [17] with the equation of motion, which does not include spatial
derivatives. The PD equation of motion is valid anywhere in the material
regardless of whether or not there is any discontinuity.

In PD, the material is discretized in a set of points called material
points. By setting bonds between material points, deformation and
damage in the material can be modeled [18,19]. Many researchers used
PD for modeling damage initiation and propagation in composites [20,
21] and dual-phase steels [22,23]. They compared the final stage of the
damage path with experimental data but no results were reported
comparing progressive propagation of damage with experimental
methods.

This study aims to distinguish different deformation and damage
mechanisms in the Al/TiC particulate composite subjected to tensile
tests using AE and PD methods. During the experiment procedure, AE
signals were acquired by AE sensors and then using post-processing
procedures the AE signals were clustered and related to each damage
mechanism. PD was utilized to validate AE results, as PD can model the
initiation and propagation of damage mechanisms in PRC more reliably
and precisely than FEMs. Isotropic strain hardening was utilized for the
Al (matrix) material, and no plastic deformation was considered for the
TiC particles. The critical energy release rate was used for modeling
progressive damage propagation by eliminating the interactions be-
tween material points. The influence of shape and distribution of par-
ticles and the number of material points for material discretizing on
results were investigated. Additionally, SEM images of specimens were
compared with the AE and PD results.

Table 1
Material properties of the investigated Al and TiC [25, 26].

<table>
<thead>
<tr>
<th></th>
<th>E (GPa)</th>
<th>ν</th>
<th>σ_y (MPa)</th>
<th>σ_t (MPa)</th>
<th>G_c (kJ/m^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>73.9</td>
<td>0.33</td>
<td>127</td>
<td>182</td>
<td>129</td>
</tr>
<tr>
<td>TiC</td>
<td>450</td>
<td>0.14</td>
<td>–</td>
<td>260</td>
<td>28</td>
</tr>
</tbody>
</table>

Fig. 1. (a) Location of the AE sensors (c) Specimen’s dimensions (mm).

Fig. 2. Stress-strain curves of the investigated Al, TiC, and Al/TiC composite Al-TiC Metal Matrix Composites.
Fig. 3. The tensile test and AE acquisition setup.

Fig. 4. Schematic diagram of the AE acquisition system.

Fig. 5. Parameters of an AE waveform [27].
1.1. Specimen preparation

The Al-based particulate composite with 20% volume fraction of TiC particles produced by hot extrusion. Then the fabricated composite rod was machined to produce the final specimens with in-plane dimensions of 100 mm × 18 mm and thickness of 2.5 mm according to ASTM E8 [24] as depicted in Fig. 1 (b). The material properties of Al and TiC are detailed in Table 1 and the stress-strain curves of the Al, TiC, and Al/TiC composite are shown in Fig. 2.

1.2. Test setup

In this study, a quasi-static loading regime was performed with a strain rate of 0.00047 1/s at a temperature of 24 °C by a universal tensile machine with a load cell capacity of 50 kN (ASTM E8 [24]). The experimental setup is shown in Fig. 1. Output data of the AE acquisition system and tensile machine were continuously recorded during the experiments.

Two AE sensors were attached to each side of the specimens using silicon grease to improve the signal transmission. Each sensor has an equal distance of 15 mm from the center of the specimens (Fig. 1(a)). The resonance frequency of the sensors was 513 kHz with an optimum working range of 100–750 kHz. The preamplifier with a gain of 40 dB was utilized, and the sampling rate of the data acquisition system was 1 MHz.

To assure that the sensors were satisfactorily attached to the surface of the specimens, a pencil lead break method was performed. Before running the experiments, a noise test was performed to specify a suitable threshold level of amplitude, and the threshold level was set to 35 dB.

1.3. Acoustic emission technique

In Fig. 4 schematic diagram of the AE acquisition system is shown. Damage mechanisms and plastic deformation within a material produce AE signals which are captured by the sensors located on the surface of the material. Then signals are amplified and sent to the acquisition system for storage and analysis.

Popular parameters of the AE waveforms for analysis are depicted in Fig. 5. By investigating these parameters for each deformation and damage mechanism, the AE signals were clustered into two classes, i.e., burst and continuous signals (Fig. 6). For the burst signals, the rise time and duration of signals are shorter, and the amplitude of signals is larger.
than the continuous signals. Therefore, the function $\psi$ was introduced as:

$$\psi = \frac{\text{Amplitude}}{\text{max(Amplitude)} \times \text{Duration}/\text{max(Duration)}}$$  \hspace{1cm} (1)$$

Large values of $\psi$ can be contributed to the burst signals, and contrariwise small values of $\psi$ can be contributed to the continuous signals.

Plastic deformation of Al, deboning of Al/TiC interface, and Al cracking and TiC fracture can be assumed as sources of the AE signals during the loading process. The AE signals energy of these sources can be compared with the PD’s released strain energy by fracture of interactions between material points.

### 1.4. Peridynamic modeling

In state-based PD theory presented by Silling et al. [28], the material is discretized into material points (Fig. 7). Each material point interacts with its family members ($H_x$) located inside of the circle with a radius $\delta$ (horizon). In Fig. 7, $u(k)$ is displacement and $y(k)$ is final location of the material point $k$.

The PD equation of motion is given by:

$$\rho(x)\ddot{u}(x,t) = \int_{H} \mu(x',t')(t(u' - u, x' - x, t) - (u' - u, x' - x, t))\,dH + b(x,t)$$  \hspace{1cm} (2)$$

where $b(x,t)$, $V(k)$ and $\rho(k)$ are body load vector, volume, and mass density, respectively. The scalar-valued function $\mu(kj)$ is the damage parameter of $kj$ interaction, and its value is zero for damaged interaction and unity for undamaged interaction. In state-based PD $t(kj)$, force density vector which point $j$ acts on the point $k$, can be calculated from:

$$t(kj) = a_k a_\mu 2 \delta_s(x(k)), y(k), y(j), x(j) \delta_s(kj) V(j) + 2 \delta_s x(kj)$$  \hspace{1cm} (3)$$

where $s(kj)$ is the stretch of $kj$ interaction, $s'_{(kj)}$ is the elastic portion of $s(kj)$, $a_k, a_\mu, b$ and $d$ are PD parameters. $a_k, a_\mu$ depend on geometry and property of material but $b$ and $d$ depend on geometry and property of a material and also the size and shape of the horizon. The calculation procedure of PD parameters is mentioned in [29] for homogeneous materials. For composite material, if the point $k$ and its family are located in the same material (matrix or particle), the calculation of PD parameters is the same as [29]. Otherwise, the PD parameters and
materials properties are calculated as explained in Section 1.5. If the material has plastic deformation, the loading history must be included in the calculation procedure. The initial yield condition was defined as:

$$W_{\text{yield}} = \frac{\sigma_0}{6\mu} (\frac{\sigma}{\sigma_0})^2$$

(4)

where $W_{\text{yield}}$ is distortional part of PD strain energy density and $\sigma_0$ is the yield stress. Therefore, equivalent stress can be defined as:

$$\sigma_{eq} = \sqrt{6\mu W_{\text{yield}} (\frac{\sigma}{\sigma_0})^2}$$

(5)

For predicting plastic deformation of composite isotropic strain hardening was considered for the Al, and TiC particles are considered as elastic. For Al material points with $F_i(k) > 0$ plastic deformation is calculated; where $F_i(k)$ is the yield function of material point $k$ and can be given as:

$$F_i(k) = \frac{W_{i(k)}}{\mu} - \left(\frac{\sigma}{\sigma_0}\right)^2$$

(6)

where $\sigma$ is strain hardening function, and $\sigma_0$ is an equivalent plastic stretch. For an increment of the applied displacement:

$$\Delta S_{i(k)} = \Delta S_{i(k)} + C_i (S_{i(k)} | x_0 - x_f |)$$

(7)

where $C_i$ is obtained by setting the yield function to zero.

Medenci et al. [29] related the total work required to eliminate all interactions across the initiated crack to the value of nonlinear energy release rate ($G$) as:

$$G_{i(k)} = \frac{V_{i(k)} V_j}{(\Delta x)^k} \int_0^{x_f(x_0)} t_{i(k)} | x_j - x_0 | ds_{i(k)}$$

(8)

By defining:

$$w_{i(k)} = \int_0^{x_f(x_0)} t_{i(k)} | x_j - x_k | ds_{i(k)}$$

(9)

the failure criteria for each interaction between two material points can be given as:

$$w_{i(k)} \geq \frac{G_C}{N_C(\Delta x)^k} = w_{i(k)}$$

(10)

where $w_{i(k)}$ is the critical value of $w_{i(k)}$ and $G_C$ is the critical energy release rate of the material. The number of interactions that are eliminated by creating a unit crack surface, $N_C$, is 34 for two-dimensional analysis [29]. Damage parameter for material point $k$, $\phi_{i(k)}$, is obtained by the ratio of a broken number of bonds to the total number of interactions [30]:

$$\phi_{i(k)} = 1 - \frac{\sum_{i=1}^{N_C} V_{i(k)}}{\sum_{i=1}^{N_C} V_j}$$

(11)

The energy released by fracture of interaction $kj$ can be calculated as:

$$E_{kj} = w_{i(k)} \times V^2$$

(12)

Therefore, the released energy due to fracture of damaged interactions is given as:

$$E = \sum w_{i(k)} \times V^2$$

(13)
1.5. Micromechanical modeling

Three types of material points are considered: Al (type 1), TiC (type 2), and the interface of Al and TiC (type 3). In type 1, the material point and its family members are in the Al matrix. Similarly, in type 2, the material point and its family are in the TiC particles. In type 3, the material point is in the Al matrix and at least one of its family is in the TiC particles or the material point is in particles and at least one of its family is in the Al matrix.

In the PD framework for material points of types 1 and 2, Al and TiC properties were considered, respectively. The properties of material points of type 3 were assumed to be a function of two variables. The first variable is the distance of the point from the Al matrix, as shown in Fig. 8 (b). Points $k_1$ and $k_2$ in Fig. 8(a) have the same distance from the Al matrix.

Fig. 11. The distribution of $\gamma$ for each RVE.

Fig. 12. Geometry of RVE and BCs.

Fig. 13. Sensitivity analysis of $N$ on the stress-strain curve (a) and maximum stress of the stress-strain curve (b).
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matrix but have different family members. If only the distance variable is considered, the same properties will be obtained for points \( k_1 \) and \( k_2 \), therefore the number of ferrite points in family members is considered as second variable.

The flowchart of the PD model is shown in Fig. 9. Three nested loops were utilized for displacement calculation, i.e., displacement convergence loop plastic loop, and damage loop. In the first loop, the displacement of the material points is calculated by using adaptive dynamic relaxation. When convergence is achieved in this loop, the yield function for each point is investigated in the second loop. In the plastic loop if the yield function is positive, \( \Delta S^p(k,j) \) will be obtained. After convergence is achieved in the plastic loop, the third loop is executed. In the damage loop, each interaction is investigated by the failure criterion and each interaction between \( k \) and \( j \) points is removed by applying \( \mu(k,j) = 0 \) when failure criterion is satisfied.

Several SEM images from surfaces of the specimens were taken, and four RVEs were selected with equal volume fracture of the TiC particles (20%) as shown in Fig. 10. Location and the shape of particles were obtained by image processing.

After detecting Al/TiC boundaries, the area, \( S \), and perimeter, \( P \), of TiC particles, and the circularity (roundness of particles), \( \gamma \), were obtained by Eq.(14).

\[
\gamma = \frac{4\pi S}{P^2}
\]  

(14)

The distribution of \( \gamma \) for each RVE is depicted in Fig. 11. The values of \( \gamma \) for RVEs 4 and 3 are higher than RVEs 1 and 2.

The two-dimensional PD model was utilized. The geometry of the RVE is a square with length \( L \) and thickness \( h \) (Fig. 12). Material points are distributed with equal distance \( \Delta x = h \) in \( x \) and \( y \) directions. Therefore, the number of particles in the \( x \)- and \( y \)-directions are equal \( (N_x = N_y = N) \). The equation of motion of PD does not contain spatial derivatives consequently fictitious regions are attached to material for applying the boundary conditions (BCs). To ensure that the imposed prescribed BCs are sufficiently reflected on the material, four fictitious regions with equal width \( \delta = 3\Delta x \) are attached to the RVE. BCs that are shown in Fig. 12 are applied to these regions. Therefore, the total material points \( (N_t) \) in model is given as:

\[
N_t = (N + 3 + 3) \times (N + 3 + 3)
\]  

(15)

The sensitivity study was performed on the number of particles in the \( x \)- and \( y \)-directions \( (N) \). In Fig. 13(a) the stress-strain curves of the RVE 3 for different values of \( N \) are shown. In Fig. 13(b) the maximum stresses in stress-strain curves of Fig. 13(a) are depicted. Maximum stress values after \( N = 130 \) were converged therefore the value of \( N \) was chosen as 130 and consequently RVE has 16, 900 main material points and 1524 boundary material points.

2. Results and discussions

2.1. PD model and experiment results

In Fig. 14, fractured specimens after the tensile test are shown, the results of specimens 4 and 5 are not considered in this research due to the failure being outside the gage length. The obtained stress-strain curve by the PD model and experimental tests are shown in Fig. 15. The PD model predictions are in good agreement with the experimental data. The stress-strain curve of the RVEs was affected by the size,
morphology, and volume fraction of the TiC particles. RVEs with higher circularity values of the TiC particles have a lower stress concentration at the boundary of the particles than the RVEs with lower circularity values. The RVEs with lower circularity values have a higher stress concentration at the boundary of particles.

In Fig. 16, the distribution of damage parameter of the RVEs at 0.055 strain is shown. At this strain, damage mechanisms were initiated in the narrow TiC particles (square sign), Al matrix between the close particles (circle sign), and interface of the particle/matrix (triangle sign).

As selected RVEs have approximately the same volume fracture of the TiC particles, the distribution and size of the particles have more effect on the damage initiation behavior by changing the stress.
condition than elastic and plastic deformation of the composite before the initiation of damage.

In Fig. 17 final stage of propagated damage mechanisms of the RVEs are shown. In the matrix, damages propagated at 45° to the loading direction. In general, the damage path avoids passing through the TiC particles because of lower fracture energy in the Al matrix. Interface damage happened near the sharp corners of the particles because of higher stress concentrations relative to other points on the boundaries of particles.

During the composite failure process, several microcracks propagated inside the RVE, and finally, the main crack propagated. The main crack stopped the extension of other short cracks due to the relief of stress. As seen in Fig. 17, the PD model can predict multi-crack propagation and crack branching simultaneously.

In Fig. 18, SEM images of the fractured surface of the specimens are shown. Three damage mechanisms i.e., TiC/Al debonding, Al fracture, and TiC particle fracture, were detected in these SEM images.

2.2. Comparison between PD and AE results

The detected sources of AE signals were plastic deformation and damage mechanisms that are indicated in Fig. 18. Fig. 19 shows the
cumulative energy and distribution of the amplitude of acquired signals for specimen 3. At the start point of the final failure, i.e. time equals to 230 s, the cumulative AE energy is increased significantly, and most of the AE events have relatively low amplitudes.

By investigating the AE signals’ waveforms, two major types of burst and continuous signals were detected as depicted in Fig. 6. As explained (Section 1.3), the function $\psi$ was introduced for clustering the AE signals. Typical waveforms for different values of $\psi$ are shown in Fig. 20 (specimen 3). The distribution of $\psi$ versus experimental time of the three specimens (3, 6, and 7) is shown in Fig. 21. The AE events with $\psi < 0.009$ are considered as noise signals. Distribution of $\psi$ can be clustered into two main distinct groups, i.e., $\psi = 0.009–0.25$ (continuous signals) and $\psi = 0.35–0.45$ (burst signals). As seen in Fig. 14, location of the fracture in specimen 3 has approximately the same distance from the two sensors, and in Fig. 21 number of the recorded AE events from the two sensors are approximately the same. On the contrary, for specimens 6 and 7, the nearer sensor to the location of the fracture received more AE events than the other sensor.

In Fig. 22 the stress-strain curve of RVE3, and the associated released energy due to fracture of damaged interactions ($E$) for the TiC particles ($E_{\text{TiC}}$) and Al ($E_{\text{Al}}$), and debonding of Al/TiC interface ($E_{\text{Al/TiC}}$) versus time are shown. As seen $E_{\text{Al}}$ has higher values than $E_{\text{Al/TiC}}$, and $E_{\text{Al/TiC}}$ has higher values than $E_{\text{TiC}}$. The predicted time intervals of each deformation and damage mechanism by the PD model are listed in Table 2. The PD model predicts that the plastic deformation occurs at an early stage of the loading and the damage mechanisms occur in the sequence of Al fracture, debonding of Al/TiC interface, and fracture of TiC particles.

By considering PD modeling results, continuous and burst nature reported in previous studies [31–33], values of $\psi$ for each mechanism are clustered and listed in Table 2. As expected plastic deformation of Al was observed from the beginning to the end of PD simulation. This deformation mechanism happened continuously at almost all material points and therefore it is expected that this mechanism has more AE events and a lower AE energy than the other damage mechanisms due to the continuous nature of this mechanism. PD model predicted that the mechanism of TiC particle fracture starts after the other damage mechanisms and happens to a small number of points therefore it is expected that this damage mechanism has fewer AE events and also more AE energy than other damage mechanisms due to the burst nature of this mechanism. The results show that the AE technique predicts the damage initiation time of each mechanism slightly earlier than the PD model.

By clustering the AE signals of each deformation and damage mechanism, the energy of signals related to these mechanisms (Fig. 23) can be compared with the PD released energy (Fig. 22). Cumulative AE energy of signals related to fracture of TiC particle and Al, and debonding of Al/TiC interface are shown in Fig. 23. As seen the signal energy for the burst signals is considerably less than the continuous signals, and the AE method detected the initiation of damage earlier than the PD model.

3. Conclusion

In this study, during tensile load of Al/TiC composite deformation and damage mechanisms were investigated by the AE method, and re-
sults were validated by PD modeling and experimental data. Following conclusions have been reached:

- Four deformation and damage mechanisms were detected by the PD modeling and SEM images of specimens as AE sources (i.e., TiC particle fracture, Al/TiC debonding, and Al matrix plastic deformation and fracture). PD model predicts initiated damage mechanisms at the narrow particles, matrix between close particle and interface of the TiC particle and Al matrix. In general, the damage path avoids passing through TiC particles because of the lower fracture energy in the Al. With equal volume fracture of the TiC particles, the size, shape, and distribution of particles had more effect on the damage initiation behavior than elastic and plastic deformation of the composite before the damage initiation. The RVEs with higher circularity values of the TiC particles have a lower stress concentration at the

Fig. 21. The value of $\psi$ versus test time of specimen 3 (a), 6 (b), and 7(c).
interface of the particles/matrix than the RVEs with the lower circularity values.

- By investigating the AE signals, two major types of burst and continuous signals were distinguished and the function $\psi$ was defined (using rise time, duration, and amplitude of the signals). The AE signals were clustered using the predicted time range of occurrence of each mechanism by the PD and the $\psi$ values.

- The AE energy of signals ($E_{AE}$) and the PD released energy ($E_{PD}$) of the burst signal, associated with fracture of the TiC particles, and the continuous signal, associated with fracture of the Al and debonding of the Al/TiC interface, have approximately the same behavior. The PD model and AE technique predict the same sequence of deformation and damage mechanisms, but the AE technique predicts the damage initiation time of each mechanism slightly earlier than the PD model.

**Declaration of Competing Interest**

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