Behavioral Characteristics of Graphite /AA6061 Alloy Particle-Reinforced Metal Matrix Composites

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Abstract: In the current work, the AA6061/graphite metal matrix composites were manufactured at 10% and 30% volume fractions of graphite. The composites were subjected to mechanical and thermal loads. The microstructure of AA6061 alloy/graphite reveals the fracture of interphase and particle. As the volume fraction increases, the particle fracture is initiated at low temperature of thermal loading. The fracture of graphite particle is on account of decrease of thermal conductivity and negative thermal expansion with increase of temperature above 125°C.

Keywords: AA6061, graphite, spherical nanoparticle, RVE model, finite element analysis, interphase fracture.

1. INTRODUCTION

A recent trend in composites research, especially in nanocomposites, is the use of graphite as a reinforcing material. The bond between graphite particles and metal matrix material is critical to the effectiveness of graphite as a reinforcement to enhance mechanical properties. There are interactions between the graphite and the matrix, such as the attractive van der Waals interactions. Particle composites typically contain a matrix material and inclusions. The interface between the inclusion and the matrix is a bonding surface, across which both weak and strong discontinuities occur [1]. The overall performance of a composite depends on the material properties of each phase as well as the interfacial properties between the matrix and inclusions [2]. These material and interfacial properties govern how the material fails, including such failure modes as brittle fracture, ductile rupture, debonding, yielding, and excessive deformation [3]. Composites commonly fail along the interface between the matrix and inclusion. This type of failure is called interfacial material failure and is defined as the formation of two new surfaces from a previously bonded interface between two materials. Interfacial decohesion is usually observed in composites with very low strength matrices relative to the inclusion, (i.e., ceramic inclusions in a pure aluminum matrix), while particle fracture usually occurs with a medium to high strength matrix [4]. Given the significance of interfacial damage progression on the bulk strength and toughness of composite materials, it is not surprising that one of the major research areas in composites is the modeling of bonding interfaces between phases. The interfacial zone has been modeled in a number of ways, including as a narrow region of continuum with graded properties, as an infinitely thin surface with springs, and as a cohesive zone with traction-separation relations. Micromechanical methods have been widely used for decades to study stress/strain distributions within composites, as well as the correlation between constituent properties and macro (effective) properties of composite materials [5-21].

Graphite (Gr) is a crystalline form of carbon. Graphite is the most stable form of carbon under standard conditions. Graphite has a layered, planar structure. In each layer, the carbon atoms are arranged in a honeycomb lattice with separation of 0.142 nm, and the distance between planes is 0.335 nm. Atoms in the plane are bonded covalently, with only three of the four potential bonding sites satisfied. The fourth electron is free to migrate in the plane, making graphite electrically conductive. Bonding between layers is via weak van der Waals bonds, which allows layers of graphite to be easily separated, or to slide past each other. The two known forms of graphite, alpha (hexagonal) and beta (rhombohedral), have very similar physical properties. The acoustic and thermal properties of graphite are highly anisotropic, since phonons propagate quickly along the tightly-bound planes, but are slower to travel from one plane to another. Graphite's high thermal stability and electrical conductivity facilitate its widespread use as electrodes and refractories in high temperature material processing applications. Graphite and graphite powder are valued in industrial applications for their self-lubricating and dry lubricating properties. There is a common belief that graphite's lubricating properties are solely due to the loose interlamellar coupling between sheets in the structure. Graphite (carbon) fiber and carbon nanotubes are also used in carbon fiber reinforced plastics, and in heat-resistant composites such as reinforced carbon-carbon (RCC). Commercial structures made from carbon fiber graphite composites include fishing rods, golf club shafts, bicycle frames, sports car body panels, the fuselage of the Boeing 787 Dreamliner and pool cue sticks and have been successfully employed in reinforced concrete.

In the current work, the effect of thermo-mechanical loading on the fracture in AA6061 alloy/Gr composites was predicted. The shape of Gr nanoparticle considered in this work is spherical. The periodic particle distribution was a square array and
corresponding representative volume element (RVE) is showed in figure 1. Both microscopic and micromechanics methods were employed to assess fracture in the composites.

![Figure 1: Graphite nanopowder (a); Gr particles (b); Crystal structure of Gr (c); Square array of particles (d); Representative volume element (e); and Discretization of RVE (f).](image)

2. MATERIALS METHODS
The matrix material was AA6061 alloy. The reinforcement material was Gr nanoparticles of average size 100nm. The mechanical properties of materials used in the present work are given in table 1.

![Figure 2: Tensile testing: UTM with temperature controlled chamber and (b) shape and dimensions of tensile specimen.](image)

<table>
<thead>
<tr>
<th>Property</th>
<th>AA6061</th>
<th>Gr</th>
</tr>
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<tbody>
<tr>
<td>Density, g/cc</td>
<td>2.70</td>
<td>2.51</td>
</tr>
<tr>
<td>Elastic modulus, GPa</td>
<td>68.9</td>
<td>445.0</td>
</tr>
<tr>
<td>Coefficient of thermal expansion, 10^{-6}/°C</td>
<td>23.6</td>
<td>5.6</td>
</tr>
<tr>
<td>Specific heat capacity, J/kg/°C</td>
<td>896</td>
<td>1288</td>
</tr>
<tr>
<td>Thermal conductivity, W/m²/°C</td>
<td>167</td>
<td>90</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.33</td>
<td>0.19</td>
</tr>
</tbody>
</table>
AA6061 alloy/Gr composites were fabricated by the stir casting process and low pressure casting technique with argon gas at 3.0 bar. The composite samples were given solution treatment and cold rolled to the predefined size of tensile specimens. The heat-treated samples were machined to get flat-rectangular specimens (figure 2) for the tensile tests. The tensile specimens were placed in the grips of a Universal Test Machine (UTM) with temperature controlled chamber at a specified grip separation and pulled until failure. The test speed was 2 mm/min. A strain gauge was used to determine elongation. In the current work, a cubical representative volume element (RVE) was implemented to analyze the tensile behavior AA6061/Gr nanoparticle composites at two (10% and 30%) volume fractions of Gr and at different temperatures. The large strain PLANE183 element was used in the matrix in all the models. In order to model the adhesion between the matrix and the particle, a CONTACT 172 element was used.

3. RESULTS AND DISCUSSION
The tested tensile specimens are shown in figure 3. Almost 50% specimens fail at center with a little no necking formation. The optical micrograph as shown in figure 4 reveals uniform distribution of Gr particles in AA6061 alloy matrix.

3.1 Thermo-Mechanical Behavior
Figure 5 signifies the tensile stresses induced in the AA6061/Gr composites along the load direction. The tensile stress increases with increase of temperature and it decreases with increase of volume fraction of AA6061/Gr in AA6061 alloy.
matrix. It is observed that the stress induced exceeds the allowable stress as the temperature is increased. The normalized elastic modulus is shown in figure 6a. The elastic modulus is normalized with the elastic modulus of AA6061 alloy. The stiffness of the composites decreases with increase of temperature. The stiffness of AA6061 alloy/10% Gr composites is higher than that of AA6061 alloy/30% Gr composites with regard to increase of temperature. The normalized stiffness along the normal direction is lower than that along the load direction. The normalized shear modulus increases with volume fraction of Gr (figure 6b). Initially, the major Poisson’s ratio decrease from 30°C to 100°C and later on it increases with temperature from 100°C to 300°C (figure 6c).

![Figure 6: Effect of temperature on micromechanical properties of AA6061/Gr composites.](image1)

![Figure 7: Criterion for interfacial debonding (a) and for particle fracture (b).](image2)

### 3.2 Fracture Behavior

If the particle deforms in an elastic manner (according to Hooke’s law) then,

\[ \tau = \frac{\sigma_p}{n} \tag{1} \]

where \( \sigma_p \) is the particle stress. If particle fracture occurs when the stress in the particle reaches its ultimate tensile strength, \( \sigma_{p,uts} \), then setting the boundary condition at

\[ \sigma_p = \sigma_{p,uts} \tag{2} \]

The relationship between the strength of the particle and the interfacial shear stress is such that if

\[ \sigma_{p,uts} < \frac{2\tau}{n} \tag{3} \]

Then the particle will fracture. From the figure 7b, it is observed that the Gr nanoparticle was not fractured as the condition in Eq. (3) is not satisfied below 250°C for the composites AA6061/10% Gr composites and below 125°C for the composites AA6061/30% Gr, respectively. The particle fracture occurs above 250°C for the composites AA6061/10% Gr composites and above 125°C for the composites AA6061/30% Gr, respectively. This is due to CTE and stiffness mismatches between Gr nanoparticles and AA6061 alloy matrix. For the interfacial debonding/yielding to occur, the interfacial shear stress reaches its shear strength:

\[ \tau = \tau_{\text{max}} \tag{4} \]

For particle/matrix interfacial debonding can occur if the following condition is satisfied:
\[ \tau_{\text{max}} < \frac{n \sigma_p}{2} \]  

(5)

It is observed from figure 7a that the interphase debonding occurs between Gr nanoparticle and AA6061 alloy matrix as the condition in Eq.(5) is satisfied below 250°C for the composites AA6061/10% Gr composites and below 125°C for the composites AA6061/30% Gr, respectively. The debonding phenomenon is high in the composites comprising of 30% Gr.

Figure 8: Images of von Mises stresses obtained from FEA: (a) AA6061/10% Gr and (b) AA6061/30% Gr composites.

Figure 9: SEM images showing interphase debonding (A) and particle fracture (B).

Figure 10: Thermal properties of graphite.

The von Mises stress induced at the interface are higher than that induced in the nanoparticle (figure 8). Hence, the interfacial interphase fracture was occurred between the particle and the matrix. The particle fracture is initiated in AA6061/30% Gr.
composites at 125ºC of thermal loading and in AA6061/ 10% Gr composites at 250ºC of thermal loading, respectively, due to thermal shock. The microstructure shown in figure 9 confirms the occurrence of interphase and particle fractures in the composites. The interphase debonding increases with increase of temperature. As observed from figure 10, the thermal conductivity of graphite increases from 0ºC to 150ºC and it decreases later on with increase of temperature. The graphite demonstrates negative thermal expansion with increase of temperature. These may be the reasons for the fracture of graphite particles in AA6061 alloy matrix with increase of temperature above 125ºC. The fracture of graphite is clearly visible as shown in figure 10 when heated graphite particles in a muffle furnace at 300ºC.

4. CONCLUSION
The microstructure of AA6061 alloy/Gr composites reveals the uniform distribution of Gr nanoparticles in the matrix. The shear stress is high at the interface resulting to interphase debonding in AA6061/Gr composites. The particle fracture has occurred above 250ºC in AA6061/10% Gr composites and above 125ºC of thermal loading in AA6061/30% Gr composites, respectively. The microstructures obtained from the experimental samples confirm the fracture of interphase between the Gr particles and AA6061 alloy matrix and particle fracture. The fracture of graphite particle is due to decrease of thermal conductivity and negative thermal expansion with increase of temperature.

REFERENCES


