Effect of Nd Content on the Mechanical Properties of Grf/Al Composite

Xu Wang¹,³, Guoqin Chen¹, Gaohui Wu¹, Daming Jiang¹ and Junsheng Liu³

(¹ School of Materials Science and Engineering, Harbin Institute of Technology, P. O. 433, Harbin, Heilongjiang, 150001, P. R. China; ³ School of Mechanical Engineering, Liaoning Shihua University, P. O. 141, Fushun, Liaoning, 113001, P. R. China; ³ Harbin Institute of Supervision and Testing of Product Quality, Harbin Bureau of Quality and Technical Supervision, Harbin 150001, P. R. China)

Graphite fiber reinforced aluminum (Grf/Al) composites with high Mg and different Nd content (Al-17Mg-xNd) were fabricated by squeeze casting method. Furthermore, microstructure were analyzed by transmission electron microscopy (TEM) and scanning electron microscopy (SEM). Grf/Al composites were well infiltrated with good fiber dispersion and no apparent porosity or significant casting defects. Density of composites increased with the increase of Nd content. Bending strength of composites decreased sharply with the increase of Nd content, while elastic modulus changed little. Fracture surface of Grf/Al-17Mg could be characterized by pull-out of single fiber and bundles. With the increase of Nd content, the pulled-out single fiber and bundles decreased. Corresponding to its low bending strength, the fracture surface of Grf/Al-17Mg-2Nd was very flat without significant pulled-out fiber. Very little Al₄C₃ was observed in Grf/Al-17Mg composite, while large Al₃Mg₂ was detected by energy dispersive X-ray detector (EDX) and selected area electron diffraction (SAED). When Nd content was arised, size and amount of Al₄C₃ and Al₃Mg₂ increased. In addition, an Nd₃Al₁₁ transition layer was observed between fiber and Al matrix in Grf/Al-17Mg-2Nd composite, which should be due to non-equilibrium of Al matrix.

Keywords: Grf/Al composite; Mechanical properties; Fracture mechanism; Interface

1. Introduction

Metal Matrix Composites (MMCs) are one of the newest concepts which are thought to bring a major step forward in aerospace applications [1]. Recently, continuous fiber reinforced metal matrix composites have been receiving considerable attention due to their high specific strength and modulus for application in automobile, aerospace, and electrical cable industries [2-4].

Unfortunately, interfacial reaction between carbon fiber and Al matrix is very severe, which is unfavorable for their mechanical properties. The current efforts to control C-Al reaction are mainly focused on fabrication method, fiber types and surface modification [5-8]. It is reported by Yang [9] that growth mechanism of Al₄C₃ at C-Al interface was vertical at low temperature (708°C), and Al₄C₃ was small with large aspect ratio. At higher temperature (748°C), it showed lateral growth mechanism and Al₄C₃ was large with small aspect ratio. Seong [10] reported that, interfacial reaction between graphite fiber-Al is weaker than carbon fiber-Al. A lot of large Al₄C₃ phase was observed at carbon fiber-Al interface. However, only a thin Al-O-C layer was detected at graphite fiber-Al interface, and the weak interface reaction is beneficial to the strength of composite, which is consistent with Cheng’s research [8]. Urn [11] sprayed Ni coating on carbon fiber, which improved the wettability between fiber and Al matrix. Moreover, the reaction of Ni with Al to form NiAl₃ suppressed the formation of Al₄C₃. Vidal-Setif [12] deposited pyrocarbon coating on M40 fiber by physical vapor deposition (PVD), which separated carbon fiber from brittle Al₄C₃ and Mg₂Si. Pyrocarbon coating is much denser than M40 fiber, meanwhile its multilayer structure is favorable for crack deflection and interface sliding, which improved mechanical properties of composites.
As an effective method to improve wettability and reaction, the addition of alloying elements is also studied. Our former research [13] revealed that high Mg content was beneficial to decrease interface reaction and improve mechanical properties of Grf/Al composite. Furthermore, it is reported by Wu [14] that addition of rare earth element was beneficial to interfacial reaction and mechanical properties. However, effect of Nd element on microstructure and mechanical properties of Grf/Al composite are rarely reported.

In this paper, M40 graphite fiber reinforced aluminum (Grf/Al) composites with high Mg and different Nd content (Al-17Mg, Al-17Mg-0.2Nd, Al-17Mg-0.5Nd and Al-17Mg-2Nd) were fabricated by squeeze casting method. Effect of Nd on microstructure and mechanical properties of Grf/Al composite were discussed.

2. Experimental

Our former study showed that addition of Mg content was beneficial to microstructure and mechanical of Grf/Al composite [11]. Thus, in this paper, adjustment of Nd content was based on Al-17Mg alloy (Al-17Mg, Al-17Mg-0.2Nd, Al-17Mg-0.5Nd and Al-17Mg-2Nd). The chemical composition of Al alloy used in this paper is listed in Table 1. M40 graphite fibers, of which reaction with Al is weaker than carbon fiber, were selected as reinforcement. Table 2 shows basic properties of M40 fiber. Grf/Al composites were fabricated by squeeze casting method. Temperatures for melting Al alloy and mould were 750°C and 500°C, respectively. During the infiltration process, a pressure of 5MPa was applied and kept for 10 min, and then the composites were solidified in air.

| Table 1 Chemical composition of Al matrix alloys (wt%) |
|-----------------|-----------------|-----------------|-----------------|
| 1 | Al-17Mg | 16.50 | 0 | Bal. |
| 2 | Al-17Mg-0.2Nd | 17.30 | 0.22 | Bal. |
| 3 | Al-17Mg-0.5Nd | 16.55 | 0.54 | Bal. |
| 4 | Al-17Mg-2Nd | 17.13 | 2.02 | Bal. |

<p>| Table 2 Basic properties of fiber |
|-----------------|-----------------|-----------------|-----------------|</p>
<table>
<thead>
<tr>
<th>Material</th>
<th>Density (g/cm³)</th>
<th>Tensile Strength (MPa)</th>
<th>Elastic Modulus (GPa)</th>
<th>Fiber Diameter (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M40</td>
<td>1.76</td>
<td>4410</td>
<td>377</td>
<td>5</td>
</tr>
</tbody>
</table>

The morphology of composite was observed by ZEISS-40MAT optical microscope. Further observation was carried on Philips CM-12 transmission electron microscope (TEM) with an accelerated voltage of 120kV. The XRD analysis was performed on Rigaku D/max-rB X-ray equipment at a rate of 0.02° per 0.5s in step-scan mode using monochromatic Cu Kα radiation.

Grf/Al composite specimens were machined into flat 3-point bending strength specimens with dimension of 2mm×10mm×60mm. Specimens were tested with a constant gauge length of 40mm on an Instron5569 universal testing machine at a crosshead speed of 0.5 mm/min at room temperature. The fractographs of Grf/Al after 3-point bend were observed by S-4700 scanning electron microscopy (SEM).

3. Results and Discussion

3.1 Microstructure of Grf/Al composites

Fig.1 shows typical micrographs of Grf/Al-17Mg, Grf/Al-17Mg-0.2Nd, Grf/Al-17Mg-0.5Nd and Grf/Al-17Mg-2Nd, respectively. Four Grf/Al composites were well infiltrated with good fiber
dispersion and no apparent porosity or significant casting defects. The microstructure without significant deflections was beneficial to composite properties.

![Micrographs of four Grf/Al composites](image)

3.2 Mechanical properties of Grf/Al composite

Densities and hardness of four composites are listed in Table 3. Densities of four composites increased with Nd content due to its high density (7g/cm³). The relative densities of four composites are more than 98%. Moreover, hardness of composites and Al matrix increased with the increase of Nd content.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Aluminum Matrix Composite</th>
<th>Matrix Alloy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Theoretical density (g/cm³)</td>
<td>Measured density (g/cm³)</td>
</tr>
<tr>
<td>Grf/Al-17Mg</td>
<td>2.12</td>
<td>2.09</td>
</tr>
<tr>
<td>Grf/Al-17Mg-0.2Nd</td>
<td>2.13</td>
<td>2.11</td>
</tr>
<tr>
<td>Grf/Al-17Mg-0.5Nd</td>
<td>2.17</td>
<td>2.14</td>
</tr>
<tr>
<td>Grf/Al-17Mg-2Nd</td>
<td>2.20</td>
<td>2.17</td>
</tr>
</tbody>
</table>

Bending properties of four Grf/Al composites are plotted in Fig.2. Elastic modulus changed little with the increase of Nd content, and was in good agreement with rule of mixture (ROM). However, bending strength decreased sharply with the increase of Nd content, from 1463MPa (Grf/Al-17Mg) to 791MPa (Grf/Al-17Mg-2Nd).

![Bending properties of four Grf/Al composites](image)
To understand the fracture mechanism, bending specimens were examined by SEM. Generally, the bending strength and failure mechanism of composite are dominated by the nature of the fibre/matrix interface. If interface bonding is weak, crack propagation would occur in interface region, and fracture surface is characterized by pull-out and fracture of single fibres. In composite of high interface bonding, strength correlates with brittle fracture as known from ceramics due to stress concentration in the interface region. Therefore, the interface reactivity should be medium to enable the maximum use of the fibre strength, and failure process is as follows, applying load → fibre bundles pulling-out → fracture of individual fibre bundles → composite failure. It is obvious that the fracture surface of Grf/Al-17Mg was characterized by pull-out of single fiber and bundles. However, with addition of Nd content, the pulled-out of single fiber and bundles decreased. The fracture surface of Grf/Al-17Mg-2Nd was very flat without significant pulled-out fiber, which implies that the interfacial bonding of Grf/Al-17Mg-2Nd is very strong.

![Fig.3. SEM photographs on fracture surface of four Grf/Al composites](image)

EDX analysis revealed the segregation of Nd and Mg at the interface in Grf/Al-17Mg-2Nd (Fig.4), which should due to segregation at solidification front during fabrication.

![Fig.4. EDX analysis of Al matrix in Grf/Al-17Mg-2Nd composite](image)

### 3.3 XRD analysis

Fig. 5 shows the XRD patterns of four Grf/Al composites. No Al₄C₃ phase was detected in four Grf/Al composites due to the little content. However, Al₃Mg₂, formed by eutectic reaction, was observed. Moreover, Al₁₁Nd₃ was observed in composites with Nd.
3.4 TEM analysis of interface reaction

TEM was used to identify the reaction products which might be formed at the fiber/matrix interface. Fig. 6 shows the TEM observation of four Grf/Al composites. Very little Al$_4$C$_3$ was observed in Grf/Al-17Mg composite (Fig. 6a), while large Al$_3$Mg$_2$ was detected by EDX and SAED. Al$_4$C$_3$ with the size of 20×50nm was observed in Grf/Al-17Mg-0.2Nd composite, and some precipitates were also revealed at the interface region (Fig. 6b). Moreover, more larger Al$_4$C$_3$ with size of 20×200nm were observed and more precipitates were detected in Grf/Al-17Mg-0.5Nd composite (Fig. 6c). In Grf/Al-17Mg-2Nd composite, a large amount of Al$_4$C$_3$ with size of 50×250nm were formed, and a transition layer, which was identified to be Nd$_3$Al$_{11}$, was observed between fiber and Al matrix (Fig. 6d).

Fishkis [15] assumed that the solidification of Al matrix alloy is from region away from fiber to fiber surface, resulting in segregation of alloying elements (such as Nd) at the fiber/matrix interface. Moreover, fibers provide extra energy for heterogeneous nucleation, resulting in predominantly growth of these phases at the interface. These alloying elements could improve wettability between fiber and Al matrix.
Fabrication process of Grf/Al composites is non-equilibrium. It cools down very quickly and the rate of crystallization is larger than diffusion. Unfortunately, solute equilibrium partition coefficient (K) of Al-Mg alloy is less than 1, implying that there would be composition gradient in alloy. K of Nd is far less than 1, and most of Nd is enriched at liquid front, which increase the potential of Mg atom through liquid front. The addition of Nd element decreases the K of Mg in liquid Al alloy. Thus, Mg tends to form eutectic with Al, increasing segregation of alloying element. Primary α phase nucleates and grows up between fibers. With solidification of matrix, more Nd and Mg would enrich in unsolidified Al, and finally solidify at fiber surface. Therefore, β (Al₃Mg₂) and Nd₁₁Al₃ phases are observed at near interface region.

4. Conclusions

In this paper, M40 graphite fiber reinforced aluminum (Grf/Al) composites with high Mg and different Nd content (Al-17Mg, Al-17Mg-0.2Nd, Al-17Mg-0.5Nd, Al-17Mg-2Nd) were fabricated by squeeze casting method. The following conclusions can be drawn:

1) Grf/Al composites with four Nd content were well infiltrated with good fiber dispersion and no apparent porosity or significant casting defects. Density of composites increased with the increase of Nd content.

2) Bending strength of composites decreased sharply with the increase of Nd content, while elastic modulus changed little. Fracture surface of Grf/Al-17Mg was characterized by pull-out of single fiber and bundles. With the increase of Nd content, the pulled-out of single fiber and bundles decreased. The fracture surface of Grf/Al-17Mg-2Nd was very flat without significant pulled-out fiber, corresponding to its low bending strength.

3) Very little Al₄C₃ was observed in Grf/Al-17Mg composite by TEM. Size and amount of Al₄C₃ and Al₃Mg₂ increased with increase of Nd content. An Nd₃Al₁₁ transition layer was observed between fiber and Al matrix in Grf/Al-17Mg-2Nd composite, which should be due to the non-equilibrium of Al matrix.

References