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

Xu Wang[1,2], Guoqin Chen[1], Gaohui Wu[1], Daming Jiang[1] and Junsheng Liu[3]
([1] School of Materials Science and Engineering, Harbin Institute of Technology, P. O. 433, Harbin, Heilongjiang, 150001, P. R. China;
[2] 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 (Gr_f/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). Gr_f/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 Gr_f/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 Gr_f/Al-17Mg-2Nd was very flat without significant pulled-out fiber. Very little Al_4C_3 was observed in Gr_f/Al-17Mg composite, while large Al_3Mg_2 was detected by energy dispersive X-ray detector (EDX) and selected area electron diffraction (SAED). When Nd content was arised, size and amount of Al_4C_3 and Al_3Mg_2 increased. In addition, an Nd_3Al_{11} transition layer was observed between fiber and Al matrix in Gr_f/Al-17Mg-2Nd composite, which should be due to non-equilibrium of Al matrix.

Keywords: *Gr_f/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 Al_4C_3 at C-Al interface was vertical at low temperature (708℃), and Al_4C_3 was small with large aspect ratio. At higher temperature (748℃), it showed lateral growth mechanism and Al_4C_3 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 Al_4C_3 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]. Urña [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 $NiAl_3$ suppressed the formation of Al_4C_3. Vidal-Setif [12] deposited pyrocarbon coating on M40 fiber by physical vapor deposition (PVD), which separated carbon fiber from brittle Al_4C_3 and Mg_2Si. 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 Gr_f/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 Gr_f/Al composite are rarely reported.

In this paper, M40 graphite fiber reinforced aluminum (Gr_f/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 Gr_f/Al composite were discussed.

2. Experimental

Our former study showed that addition of Mg content was beneficial to microstructure and mechanical of Gr_f/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. Gr_f/Al composites were fabricated by squeeze casting method. Temperatures for melting Al alloy and mould were 750℃ and 500℃, 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%)

	Alloy	Mg	Nd	Al
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.

Table 2 Basic properties of fiber

Material	Density (g/cm^3)	Tensile Strength (MPa)	Elastic Modulus (GPa)	Fiber Diameter (μm)
M40	1.76	4410	377	5

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.

Gr_f/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 Gr_f/Al after 3-point bend were observed by S-4700 scanning electron microscopy (SEM).

3. Results and Discussion

3.1 Microstructure of Gr_f/Al composites

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

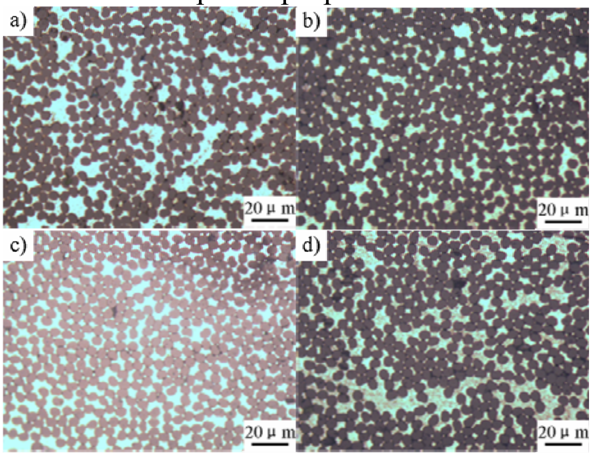

Fig.1. Optical micrographs of four Gr_f/Al composites
(a) Al-17Mg (b) Al-17Mg-0.2Nd (c) Al-17Mg-0.5Nd (d) Al-17Mg-2Nd

3.2 Mechanical properties of Gr_f/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/cm^3). 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 3 Density and hardness of four Gr_f/Al composites

	Aluminum Matrix Composite				Matrix Alloy
Sample	**Theoretical density (g/cm^3)**	**Measured density (g/cm^3)**	**Relative density**	**HBS**	**HBS**
Gr_f/Al-17Mg	2.12	2.09	98.5%	150±4	140±7
Gr_f/Al-17Mg-0.2Nd	2.13	2.11	99.0%	157±18	146±5
Gr_f/Al-17Mg-0.5Nd	2.17	2.14	98.6%	147±6	143±8
Gr_f/Al-17Mg-2Nd	2.20	2.17	98.6%	164±10	150±9

Bending properties of four Gr_f/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 (Gr_f/Al-17Mg) to 791MPa (Gr_f/Al-17Mg-2Nd).

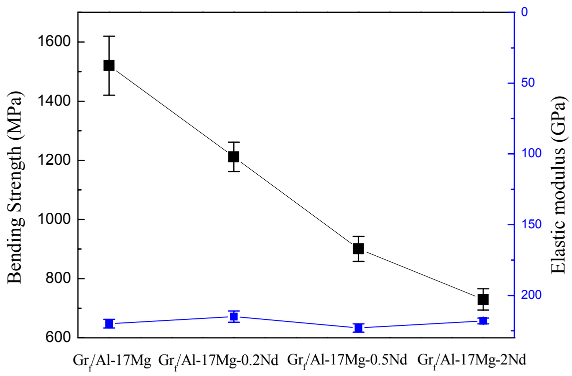

Fig.2 Bending properties of four Gr_f/Al composites

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 Gr_f/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 Gr_f/Al-17Mg-2Nd was very flat without significant pulled-out fiber, which implies that the interfacial bonding of Gr_f/Al-17Mg-2Nd is very strong.

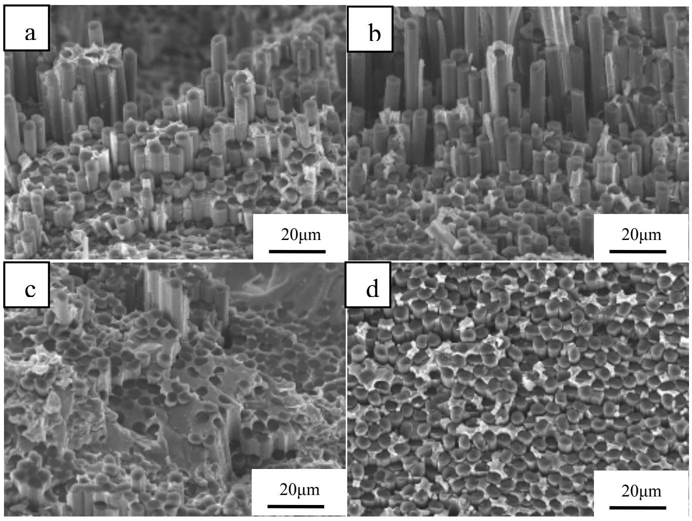

Fig.3. SEM photographs on fracture surface of four Grf/Al composites
a) Grf/Al-17Mg, b) Grf/Al-17Mg-0.2Nd, c) Grf/Al-17Mg-0.5Nd, d) Grf/Al-17Mg-2Nd

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

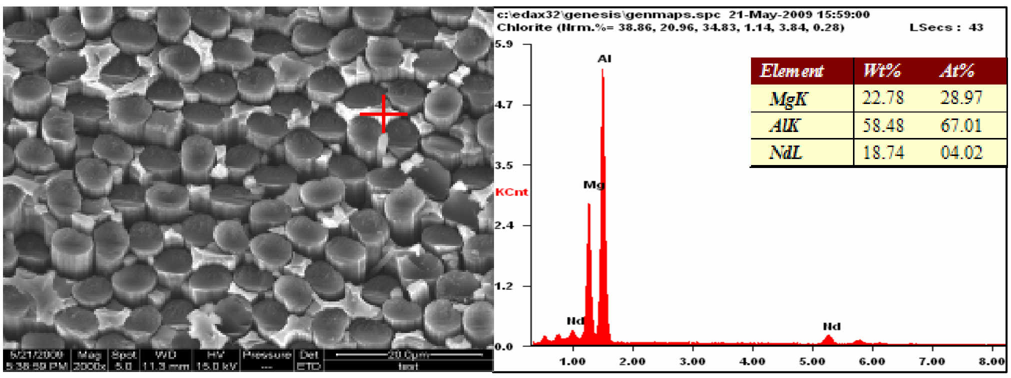

Fig.4. EDX analysis of Al matrix in Gr_f/Al-17Mg-2Nd composite

3.3 XRD analysis

Fig. 5 shows the XRD patterns of four Gr_f/Al composites. No Al_4C_3 phase was detected in four Gr_f/Al composites due to the little content. However, Al_3Mg_2, formed by eutectic reaction, was observed. Moreover, $Al_{11}Nd_3$ 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 Gr_f/Al composites. Very little Al_4C_3 was observed in Gr_f/Al-17Mg composite (Fig.6a), while large Al_3Mg_2 was detected by EDX and SAED. Al_4C_3 with the size of 20×50nm was observed in Gr_f/Al-17Mg-0.2Nd composite, and some precipitates were also revealed at the interface region (Fig.6b). Moreover, more larger Al_4C_3 with size of 20×200nm were observed and more precipitates were detected in Gr_f/Al-17Mg-0.5Nd composite (Fig.6c). In Gr_f/Al-17Mg-2Nd composite, a large amount of Al_4C_3 with size of 50×250nm were formed, and a transition layer, which was identified to be Nd_3Al_{11}, was observed between fiber and Al matrix (Fig.6d).

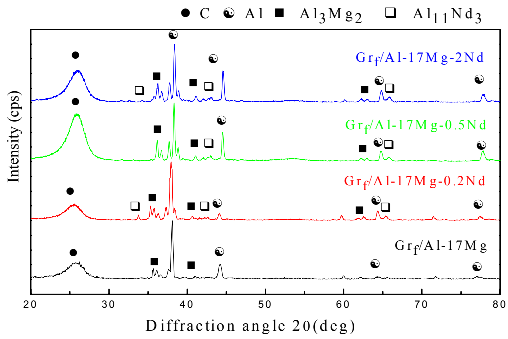

Fig. 5 XRD analysis of four Gr_f/Al composites

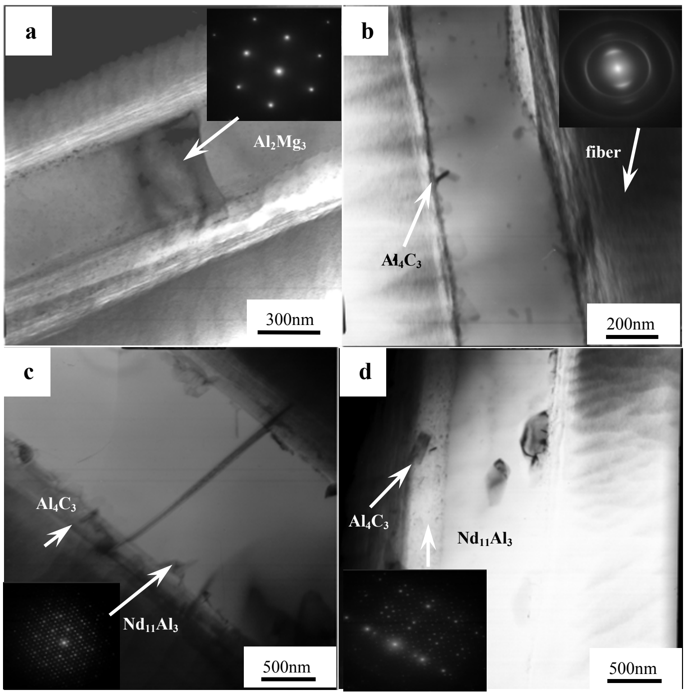

Fig.6 TEM observation of fiber/matrix interface of four Gr_f/Al composites

a) Gr_f/Al-17Mg, b) Gr_f/Al-17Mg-0.2Nd, c) Gr_f/Al-17Mg-0.5Nd, d) Gr_f/Al-17Mg-2Nd

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 Gr_f/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 (Al_3Mg_2) and $Nd_{11}Al_3$ phases are observed at near interface region.

4. Conclusions

In this paper, M40 graphite fiber reinforced aluminum (Gr_f/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) Gr_f/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 Gr_f/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 Gr_f/Al-17Mg-2Nd was very flat without significant pulled-out fiber, corresponding to its low bending strength.

(3) Very little Al_4C_3 was observed in Gr_f/Al-17Mg composite by TEM. Size and amount of Al_4C_3 and Al_3Mg_2 increased with increase of Nd content. An Nd_3Al_{11} transition layer was observed between fiber and Al matrix in Gr_f/Al-17Mg-2Nd composite, which should be due to the non-equilibrium of Al matrix.

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