Development of Mg-Graphene Composites and Effect on Microstructure and Mechanical Properties—A Review

J. Alias, N. F. A. Bakar, M. A. F. Romzi, M. I. M. Ramli, and N. A. Alang

Abstract The role of GNPs in magnesium matrix composites and their influence on the development of microstructure and mechanical properties are reviewed thoroughly. Magnesium (Mg) is a well-known light metal that is used in a variety of engineering applications, particularly as biodegradable implant materials and automotive engine parts. However, the potential of Mg in a wide range of applications is limited by its low strength and high activity in most environments. More research is needed to improve its strength and ductility, either through the development of alloys or composite materials. Because of their low density and superior specific properties, Mg metal matrix composites (Mg-MMCs) are appealing materials. Two-dimensional GNPs with distinct electrical, mechanical, and thermal conductivity properties are being considered as intriguing reinforcement. The use of GNPs as reinforcement in Mg-MMCs effectively serves as a strengthening potential for the development of new lightweight, high-strength, and high-performance Mg matrix nanocomposites. This paper discusses the effect of GNPs on the mechanical characteristics and microstructure of magnesium as a guide to the development of more promising Mg material.

Keywords Graphene · Magnesium · Grain refinement · Strengthening mechanism

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A. S. Abdul Sani et al. (eds.), *Enabling Industry 4.0 through Advances in Manufacturing and Materials*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-19-2890-1_14

1 Introduction

Magnesium, with a solid-state density of 1.74 g/cm^3, has piqued the interest of the aerospace and automotive industries as the lightest conventional structural metal state [1–4]. It facilitates weight reduction in the transportation industry, which improves fuel efficiency [5, 6]. When compared to other metals, magnesium is weak, ductile, and corrosion resistant. Many alloys and composite materials have been developed to help alleviate the problem [7–11].

Composite materials have the ability to integrate reinforcing phase qualities with matrix phase properties, resulting in composite materials that surpass their monolithic counterparts in terms of characteristics [12–14]. Their properties can be tailored to the end user by carefully choosing the reinforcement phase, matrix phase, and production technique. Magnesium-matrix composites (MMCs) can be made by dispersing reinforcing particles in the metal magnesium using either solid- or liquid-phase processes.

Carbon nanotubes (CNTs) have received a lot of attention in recent years as a reinforcement to boost the strength of magnesium and its alloys. However, the limitation of CNTs are its negative impact on ductility, and the application using CNTs as an industrial reinforcement for composites leads to poor dispersion in the matrix caused by agglomeration due to van der Waals forces between carbon atoms [7, 15–17]. Graphene has also been employed in various applications, such as metal-graphene composites, electronics material and polymer reinforcement. In the realm of thermal interface materials, graphene (a thermally conductive nanomaterial) was exploited as an outstanding filler (TIMs). The strong graphene bonding (a single atomic layer of sp2 hybridised carbon) to the metal matrix particles increased the heat conductivity of the resultant composite by up to 2300%. Nonetheless, there have been few research on the application of graphene for metal reinforcement [18–23]. As a result of its unique features, graphene is gaining extensive interest for usage as a reinforcing material.

The effect of graphene on the microstructure and mechanical properties of magnesium is reviewed in this article. The potential of graphene as a magnesium reinforcement material can be significant in the exploration of magnesium's wide range of applications.

2 Microstructure Development of Graphene-Mg Composites

GNPs have received a great deal of attention in recent years as a two-dimensional material. GNPs and their derivatives have been demonstrated in several studies to have the potential to be utilised as reinforcement to improve the performance of metals and composites. Various study reports have identified better mechanical, microstructural and interface properties of GNPs/Mg composites [19, 24–27], GNPs/Al [28–31] and GNPs/Ti [32–36]. However, an excessive number of carbon layers may degrade graphene's good characteristics [37].

Reference [38] investigated the microstructure of AZ80 magnesium alloy with incorporation of GNPs produced by rheo casting and hot extrusion process. The microstructure characterization was performed by field emission scanning electron microscopy (FESEM). The FESEM micrograph of GNPs is shown in Fig. 1. The GNPs is characterized by 4–12 μm in internal length, and thickness of 2–18 nm. The microstructure having significant carbon accumulation (Fig. 2), and the element map indicated the carbon element that can be found in the matrix of both composites. They concluded that the accumulation of carbon increases with the increase in GNPs. The Van der Waals interaction between carbon layers and the huge GNP surface area was implicated for the accumulation of carbon [37].

According to Parizi et al. [38], GNPs were also found to be embedded within the Mg matrix and segregated at the eutectic particle distribution (Fig. 3). GNPs may be present in α-Mg grains as a result of α-Mg grains nucleating on GNP surfaces and engulfing GNPs within the solidification front. As depicted in Fig. 4, the grain structure of as-cast AZ80 alloy composed a typical semi-coarse dendrites structure. Addition of GNPs revealed a transition of much coarser and globular dendritic structure. The change in grain morphology is attributed to the increase molten slurry friction caused by the presence of GNPs during the stirring process.

Earlier, by using a semi powder metallurgy method followed by hot extrusion, Rashad [39] produced a magnesium-10 wt% titanium alloy with the addition of 0.18 wt% GNPs. The surface of pure magnesium is smooth and free of macrostructural defects, indicating good bonding between magnesium particles and reinforcement. The grain boundaries are visible from the micrograph and also presence of small pores. However, the presence of Ti-GNPs nanoparticles in the Mg matrix is

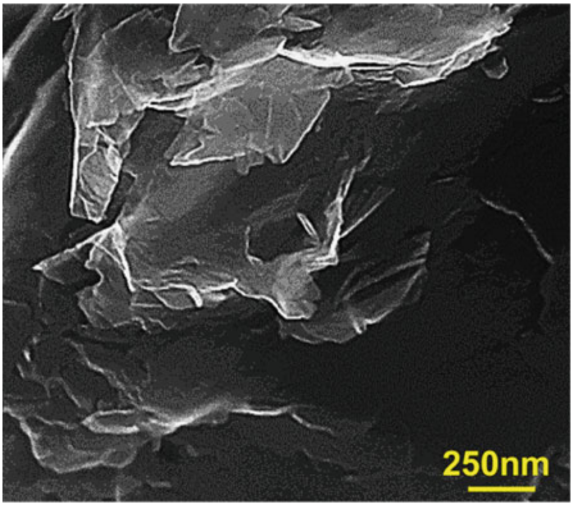

Fig. 1 FESEM micrograph of as received GNPs [38]

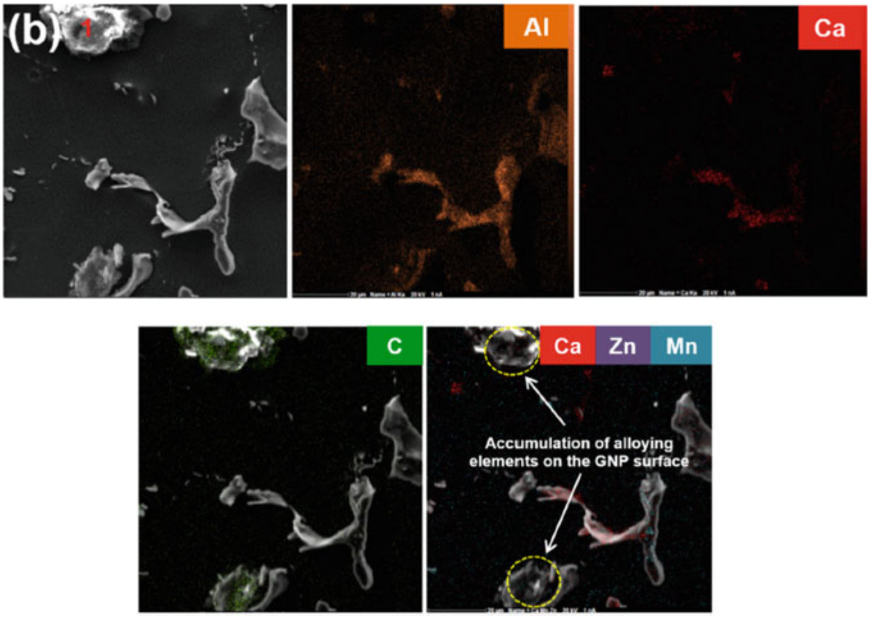

Fig. 2 FESEM images and element maps of AZ80 with 0.1 GNPs composite [38]

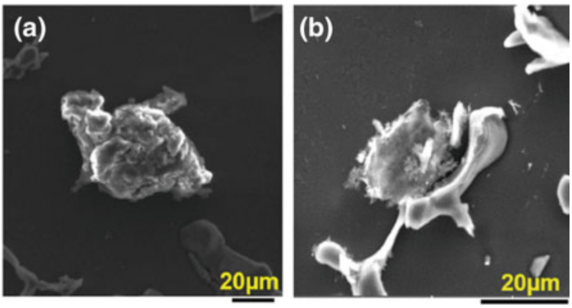

Fig. 3 FESEM images indicated the distribution of GNPs **a** within the α-Mg matrix grain, **b** in close vicinity to the eutectic phase [38]

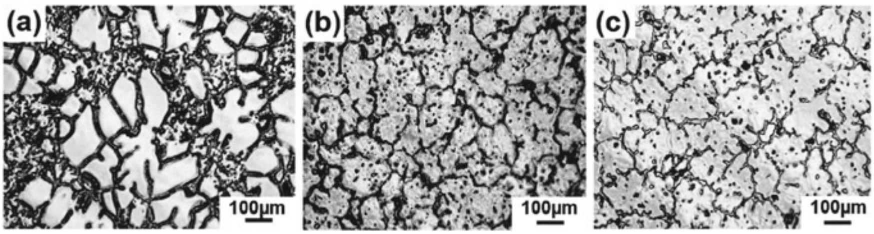

Fig. 4 Optical micrograph of as cast **a** AZ80 alloy, **b** AZ80 with addition of 0.1GNPs and **c** AZ80 with addition of 0.6GNPs composites [38]

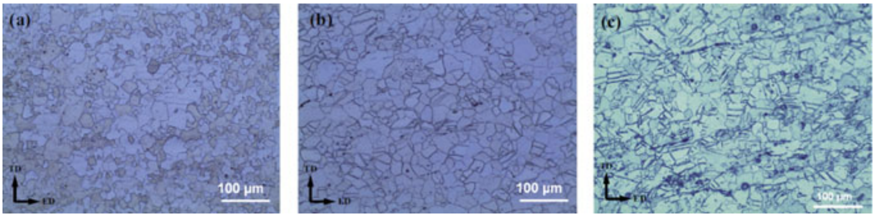

Fig. 5 Micrographs of **a** pure Mg, Mg matrix composites with **b** 0.10 wt% GNPs and **c** 0.25 wt % GNPs [40]

rather difficult to detect, due to the very low content of Ti-GNPs nanoparticles in the composite.

Rashad et al. [18] produced GNPs reinforced AZ91D composites by thixomolding process. They investigated the homogeneous distribution of GNPs reinforcement act as obstacles in the magnesium matrix with high dislocation density, and thus, increases the strength of composites.

Xiang et al. [40] investigated the addition of 0.25 wt% GNP to Mg using disintegrated melt deposition technique, and revealed the correlation of microstructure with inhomogeneous deformation pattern. The micrographs of the Mg and composites are shown in Fig. 5a–c. Uniform grain refinement of Mg matrix occurred followed by induced twin lamellae in the composites.

A study was conducted by [41] to study the microstructure, mechanical, tribological properties of GNPs assimilated AZ31 magnesium through friction stir processing (FSP). The composites exhibit a grain refined microstructure with presence of GNPs. The base modal has a typical bimodal microstructure with fine grains about $\sim$10.2 μm.

Chen et al. [42] studied the addition of GNPs to Mg composites reduces defects of thixomolded products. The composites have grain refinement, reduction in porosity, and improvement in fluidity. However, it is also observed that, with addition of GNPs more than 0.6 wt%, can resulted to poor grain refinement (Fig. 6).

Kavimani et al. [5] revealed a uniform dispersion of carbonaceous particles in the Mg matrix located at the vicinity of micro-crack, which formed as a consequence of weaker bonding between the matrix and its reinforcement particles. The increase in r-GO addition emphasizes the enormous distribution of porosity, which jeopardized the mechanical strength of magnesium matrix.

Turan et al. [43] investigated the effects of GNPs contents (0.1, 0.25 and 0.5 wt%) on pure magnesium. Figure 7 shows a segregation of the GNPs along the grain boundaries. This occurrence was because of the properties of graphene with high surface area and Van der Waals bonding between the carbon atoms. Sun et al. [20] confirmed that GNPs can act as effective nucleation substrates for Mg heterogeneous nucleation. The heterogeneous nucleation requires less energy and, the GNPs preferably nucleate at the Mg grains by heterogeneous nucleation and causing grain refinement.

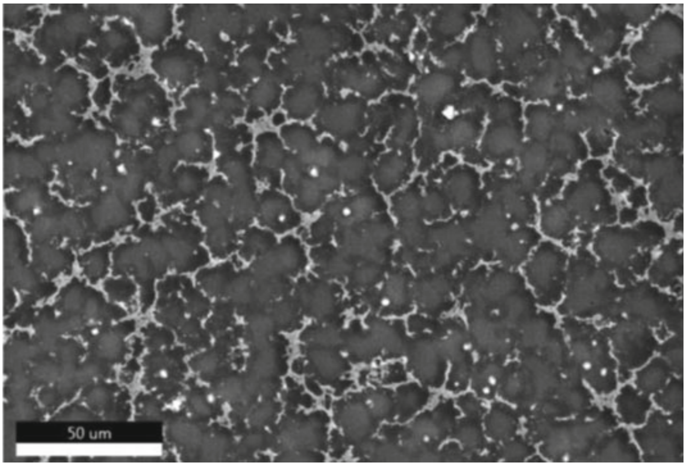

Fig. 6 SEM image of AZ91D with 0.6 wt% GNPs [42]

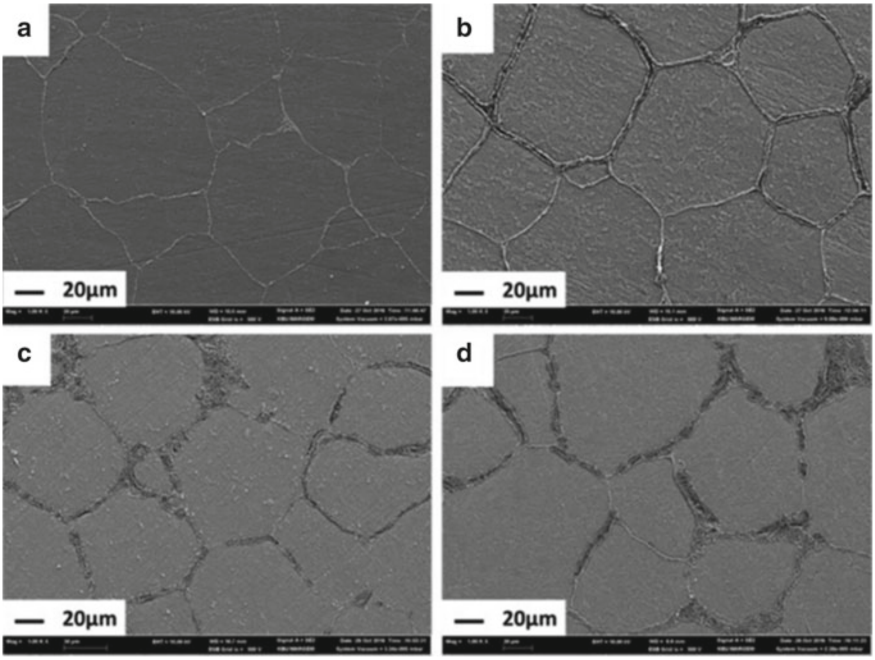

Fig. 7 SEM micrographs of samples: **a** Pure Mg, **b** Mg with 0.1 wt% GNP, **c** Mg-0.25 wt% GNP, and **d** Mg-0.5 wt% GNP [43]

3 Effect of Graphene on the Mechanical Properties of Mg

Parizi et al. [44] produced AZ80 magnesium alloy by two stages process including semi-solid powder metallurgy and rheocasting method. Existence of GNPs was found segregated at the eutectic phase by solidification front, which is also at the vicinity of micro crack. They obtained an improvement in microhardness, tensile yield strength (TYS) and compressive yield strength (CYS) with increasing GNP content as observed in Fig. 8. The dispersion of GNPs decreases the slip distance of dislocations and suppress the dislocation activities. However, as cracks are located at the GNPs accumulation, it is also lead to decrease mechanical properties. The arrangement of GNPs also responsible for the performance of mechanical strength.

Das and Harimkar [45] conducted an experiment to study the effect of GNPs reinforcement on the mechanical behaviour of magnesium matrix composites by using spark plasma sintering method. It was observed that the hardness was relatively increasing with increasing GNP content until 2-vol.% GNPs as tabulated in Table 1 together with its compressive strength and as shown in Fig. 9.

Rashad et al. [15] studied the synergetic effect on mechanical properties of pure magnesium of GNPs and multi-wall carbon nanotubes (MW-CNTs), with correlation to texture. The results, listed in Table 2, showed that the addition of GNPs improved elongation, ultimate tensile stress, and Vickers hardness when compared to pure

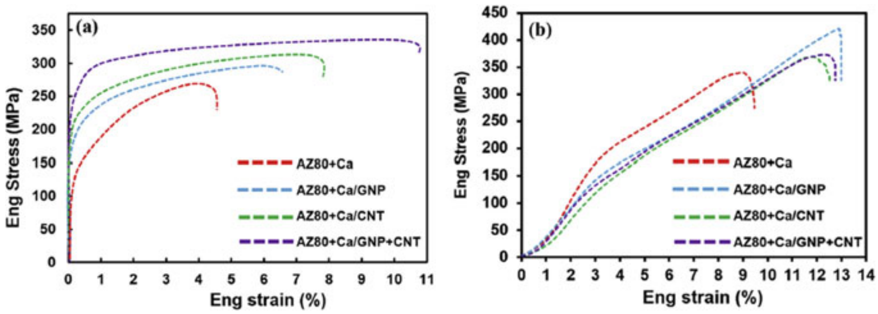

Fig. 8 Stress–strain graph for AZ80 alloy and its composites [38]

Table 1 Hardness and compressive strength of Mg and Mg-GNP composites

Materials	GNP content (wt%)	Hardness (HV)	Compressive strength (MPa)
Magnesium	0	46	220
Mg-GNP	1	54	159
Mg-GNP	2	63	201
Mg-GNP	5	50	123

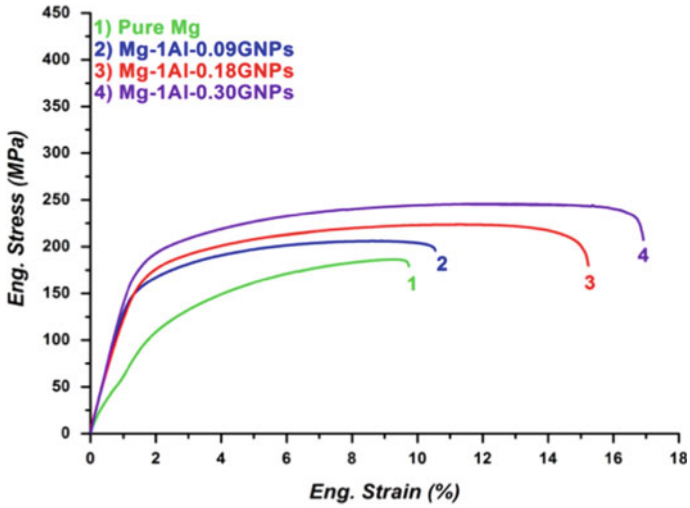

Fig. 9 Tensile stress–strain curves for magnesium and its composites [46]

Table 2 Mechanical properties of Mg and its composites with addition of GNP [15]

Material (wt%)	Vickers hardness (HV)	0.2% YS (MPa)	UTS (MPa)	Failure strain (%)
Mg	41 ± 3.5	5.98	186 ± 6	9.7 ± 3
Mg-1Al-0.09GNP	48 ± 2.9	13.40	206 ± 4	10.5 ± 3.4
Mg-1Al-0.18GNP	51 ± 3	12.18	223 ± 5	15.2 ± 2
Mg-1Al-0.30GNP	55 ± 4	13.84	246 ± 3.5	16.9 ± 3

magnesium. The mismatch in the coefficient of thermal expansion of magnesium-GNPs leads to the strengthening of composites. The change in texture was also revealed with the presence of GNPs.

Grain refinement, load transfer, thermal mismatch, and Orowan loops are among the strengthening mechanism in composite material. According to Xiao et al. [47], shear stress generated at the AZ31B-GNPs interface can transmit load from the matrix to the reinforcement in GNPs-reinforced composites. It limited dislocation movement, leading in an increase in yield stress.

Munir et al. [48] investigated the improvements in mechanical properties with addition of GNPs that caused by the strengthening efficiencies. A lower GNP content resulted in fewer defects in their graphitic structure and uniform dispersion within the Mg matrix, contributing to the grain refinement of the Mg composite. The strengthening factors including thermal mismatch and grain refinement in the Mg matrix with the reinforced GNPs are responsible to the improvement in mechanical strength.

4 Conclusions

This review expands on the potential of GNPs as a reinforcement in magnesium matrix composites. Their properties can be tailored to the end-user by carefully selecting the reinforcement phase, matrix phase, and processing technique. Overall, GNPs presence in magnesium, led to grain refinement and thus, increases strengthening and improve mechanical properties of magnesium-based composite.

Acknowledgements The authors would like to thank the Ministry of Higher Education for providing financial support under Fundamental Research Grant Scheme (FRGS) No. FRGS/1/2019/TK05/UMP/02/5 (University reference RDU1901128) and Universiti Malaysia Pahang for laboratory facilities.

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