Influence of Solution Heat Treatment on Microstructure and Tensile Properties of Gd-Treated Al-15% Mg_2Si *In-Situ* Composites

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Microstructural alteration and tensile properties of Al-15% Mg_2Si composite specimens was examined after addition of gadolinium (Gd) and conducting solution heat treatment. Various percentages of gadolinium (0.5, 1.0, 2.0 and 5.0 wt. % Gd) were added to the composite Al-15% Mg_2Si composite. The specimens then solutionized at 500 °C for 4h followed by quenching. The results showed that regular morphology and small size of primary Mg2Si particles is achieved after addition of 1.0 wt.% Gd compared to untreated composite. Due to solutionizing effect, Mg_2Si dissolution occurred which led to alter the morphology of primary Mg_2Si particles to round shape. Tensile testing results revealed that enhancement in UTS and El% values owns to influence of both Gd addition and solution heat treatment on the Al-15% Mg_2Si composite. The fracture surface of untreated composite depicted a cellular fracture, while the fracture surface of Gd treated and heat treated composite showed a ductile surface containing fine dimples, in which alteration of fracture mode is due to the role of Gd and heat treatment on microstructural modification, which results in reduction of potential sites for stress concentration and crack initiation areas.

Keywords: Mg_2Si, in-situ composite, Gd addition, solution heat treatment, tensile properties

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1. Introduction

In recent decades, aluminium matrix composites (AMCs) play an important role in many applications such as aerospace, automotive and structural industries owning to their low density and high particular strength [1–3]. Among them, high performance of hypereutectic $Al - Mg_2Si$ in-situ composite is a promising material to meet the demand for further applications due to its excellent properties. The reinforcing Mg_2Si intermetallic phase existed in the Al matrix possess significant features such as high hardness, low density, high melting point, high Young's modulus and low coefficient of thermal expansion [4, 5]. However, formation of the coarse and dendritic morphology of primary Mg_2Si particles during the solidification of the composite has been thought to deteriorate the expecting mechanical properties preserving by the in-situ composite. Hence, controlling the size and morphology of primary Mg_2Si is crucial in order to enhance the mechanical properties.

According to the literature, there are numerous approaches that introduced to refine and modify the undesired primary Mg_2Si structure in hypereutectic $Al - Mg_2Si$ composite. The refinement/modification of Mg_2Si particles by addition of alloying elements is one of the applicable approaches to modify the structure of Mg_2Si particles. Several alloying elements such as Strontium [6], Boron [7], Yttrium [8], Gadolinium [9] has been utilized to induce adequate refinement/modification effect on Mg_2Si particles structure. In addition, it has been showed that by conducting heat treatment on $Al - Mg_2Si$ composite homogenization of microstructure and better alloying elements

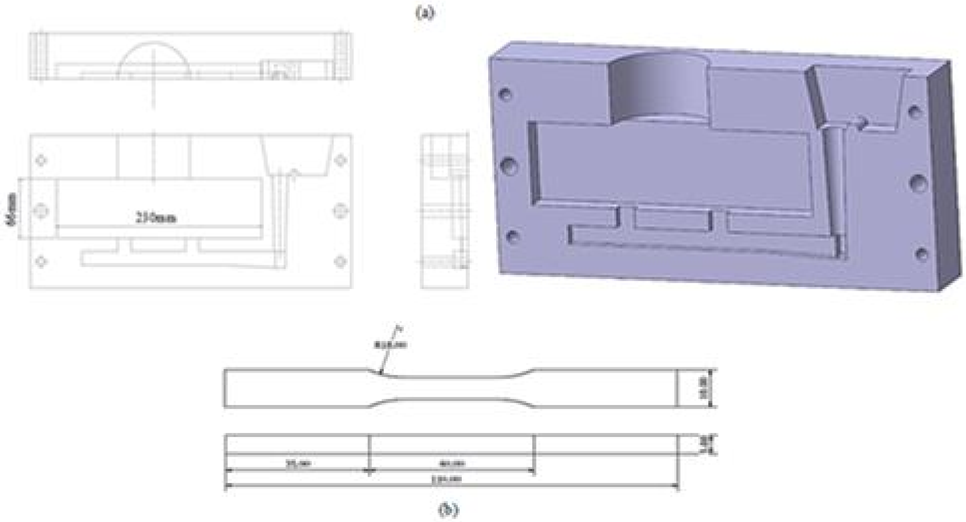

Fig. 1. Drawing presentation of (a) cast iron mould and (b) dimensions of tensile sample

distribution is achieved; the soluble phases contain Mg and Si are dissolved and eutectic phases are spheroidized [10]. Although the behaviour of Al and Mg alloys is studied during solution heat treatment [11]; however, less research has been conducted on $Al - Mg_2Si$ composites. Hence, the purpose of the present study is to examine the microstructure alteration and consequently tensile properties analysis of Al-15% Mg_2Si composite after addition Gd and conducting solution heat treatment.

2. Experimental setup

Ingot of Al-15%Mg_2Si composite was prepared using pure Al (99.9%), pure Mg (99.8%) and pure Si (99.8%) in a maffle furnace, in which its chemical composition is shown in Table 1. Around 200 g of the parent composite was re-melted (with a small SiC crucible) in an induction furnace in 750 $^\circ C$ and then pure Gd (0.5 wt. %) was introduced into the melt. Dry tablets containing C_2Cl_6 were used to conduct the degassing. After removing of the slag, composite melt was poured into a cast iron mold which was preheated to 200 $^\circ C$ (Fig. 1 (a)). The samples were then solution treated at 500 °C for 4 h in an air circulated furnace and water quenched at room temperature. The procedure was followed to prepare the composites with 0, 1.0, 2.0 and 5.0 wt. % Gd additions. The microstructure samples were cut from the as-cast material with size of 15×15×10mm. Metallographic preparation was conducted on the samples through standard routine by grinding and polishing procedures followed with etching for 5s using 2% HF acid at ambient temperature. Furthermore, in order to eliminate the Al coating from the primary Mg_2Si crystals and hence revealing their 3D morphologies, deep eating was conducted on some of the samples for 6 h using 5% HCl acid and 95% ethanol solution. To observe microstructural features of the Mg_2Si phase, SEM (XL-40) was utilized. Sub-sized specimens (Fig. 2 (b)) were made by machining of tensile samples based on ASTM B557M-02a sub-size specimen standard. The tensile tests were conducted on at least three samples for each condition using Instron testing machine at 0.1 mm/min strain rate at ambient temperature. The fracture surface of tensile sample was captured using SEM.

3. Result discussions

3.1. Microstructure evolution of Al-15% Mg_2Si-xGd composites

Fig. 2 (a-e) illustrates the BSE images of the final casting microstructures of Al-15%Mg_2Si composite in untreated and treated with various contents of Gd additions. Fig. 2(a) presents the primary Mg_2Si particles with a coarse and polyhedral structure in untreated composite. As it was stated before this kind of morphology induces high concentration of stress at the sharp tips of the particles which in turn increase the structure fracture surface and hence, lessen the composite performance [7–9]. With addition of 0.5 wt. % Gd, the particles altered into a polygonal morphology with a reduction in size as depicted in Fig. 2(b). Similarly, when the Gd concentration increased to 1.0 wt. %, the Mg_2Si particle was undergone the adequate refinement, as they illustrates a regular polygonal morphology with the smallest size (Fig. 2 (c)). Nevertheless, once the Gd concentration increased to 2.0 wt. % and 5.0 wt. %, the primary Mg_2Si morphology lost its regular shape and their size increased in which this trend is owing to over-

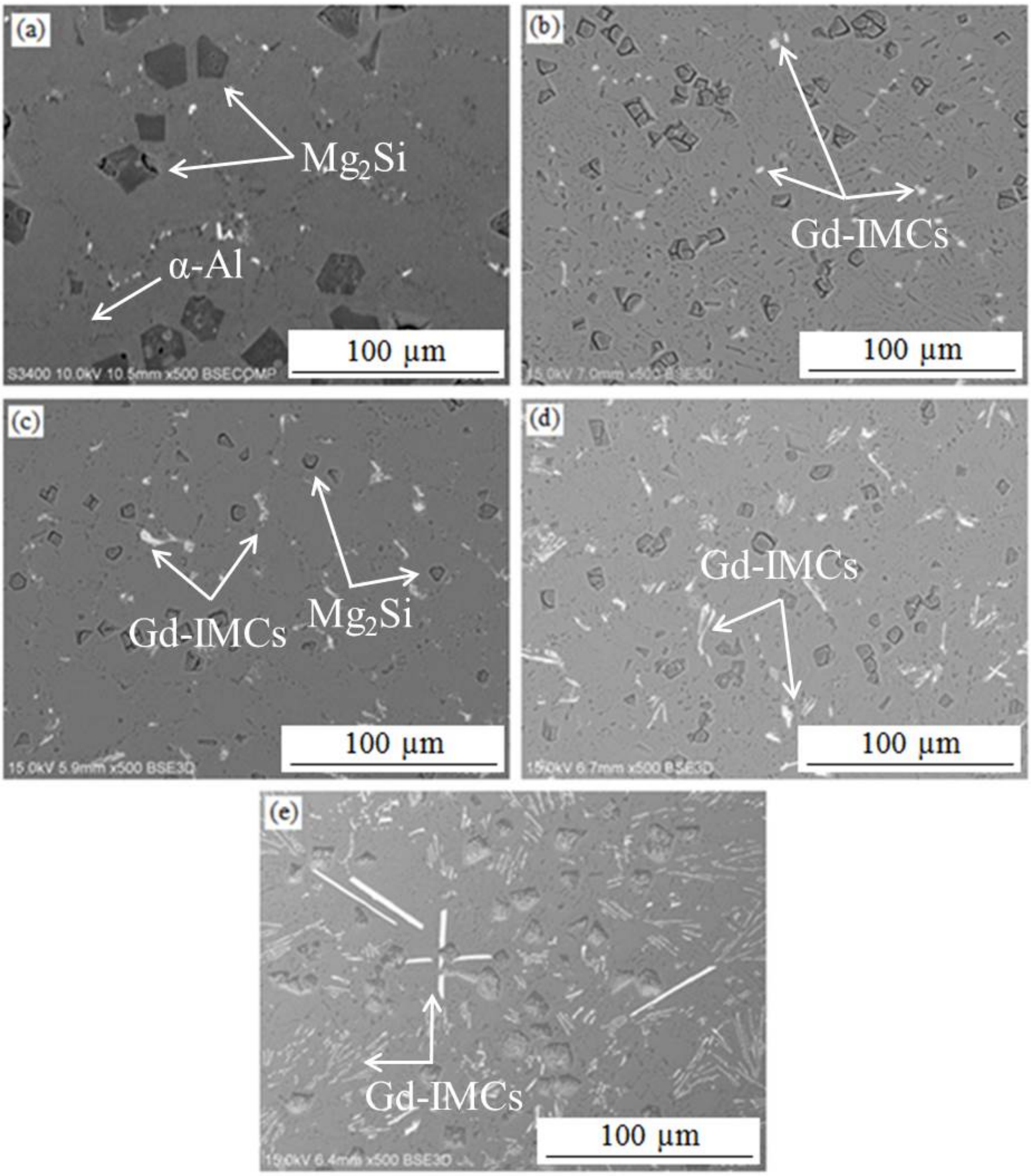

Fig. 2. SEM micrographs of Al–15% Mg_2Si composites with different Gd concentrations: (a) 0 wt. %, (b) 0.5 wt. % (c) 1.0 wt. %, (d) 2.0wt% and (e) 5.0 wt. %

Table 1. Chemical compositions of Al-15%Mg_2Si ingot (wt. %)

Material	**Mg**	**Si**	**Gd**	**Fe**	**Cr**	**V**	**Mn**	**Ti**	**Al**
MMC	9.71	5.09	0.00	0.18	0.02	0.01	0.01	0.01	Bal.

modification phenomenon as seen in Figs. 2 (d) and (e) respectively.

3.2. 3.2 Influence of heat treatment on composite microstructure

Fig. 3 (a-d) illustrates the SEM micrographs of primary Mg_2Si particles in Al-15%Mg_2Si composite in unmodified and 1.0 wt. % Gd modified conditions before and after heat treatment. From Fig. 3 (a, b) it can be observed that after heat treatment the Mg2Si particles in unmodified composite are still in dendritic morphology which designate that the heat treatment owns a minor influence on size and morphology of the particles; however, Fig. 3 (c, d) clearly shows that in the Gd-modified composite, heat treatment considerably changes the of primary Mg_2Si morphology, in which the sharp edges of the particles alters to round shape. This is because primary Mg_2Si particles in as-cast modified Al-15%Mg_2Si composite are near-spherical truncated octahedron (Fig. 3 (c)), consisting of more planes; meanwhile, the area of 111 planes, which are considered as stable faces, is decreased. It suggests that truncated octahedron has a strong potential to transform into spherical shapes. During the subsequent heat treatment, Mg or Si atoms will diffuse from positions having large curvatures to positions having flat interfaces, causing dissolution of the tips and hence formation of spherical primary Mg_2Si particles.

3.3. Tensile properties

Fig. 4 (a) and (b) depicts the ultimate tensile strength (UTS) and elongation percentage El% of the specimens as a result of heat treatment respectively, as a function of gadolinium (Gd) concentration in the Al-15%Mg_2Si. The considerable tensile properties enhancement of the composite with addition of Gd is attributed to the role of Gd as an efficient refiner and modifier for primary Mg_2Si particles, in which with 1.0 wt. % Gd addition to the Al-15%Mg_2Si composite, the size of primary Mg_2Si particles decreased and its morphology transformed to truncated octahedral morphology (Fig. 2 (c)) compared to unmodified composite (Fig. 2 (a)). Furthermore, presence of Gd intermetallic compounds with regular morphologies in the composites up to 1.0 wt. % Gd (Fig. 2) is another reason for strength enhancement. As a result, the UTS values increased from 204.79 to 224.62 MPa. These results are consistent with findings reported in the previous published papers [9–12].

Another feature of Fig. 4 is that solution heat treatment affected all the specimens. The tensile properties enhancement of the composite after heat treatment owns to the formation of primary Mg_2Si particles with fine and round morphology in the composite microstructure as illustrated in Fig. 3 (d). The existence of the crystal in the structure results in less initiation of crack and stress concentration areas caused positive influence on the mechanical properties of the fabricated materials. For a particle reinforced alloy, damage in metallic alloys containing particles falls into two broad categories: particle fracture and particle matrix interface debonding [13]. According to Griffith's theory, a particle breaks when its fracture stress exceeds the Griffith criterion given by [14, 15].

$$\sigma \times c = k \times \ c \times \ d^{-0.5} \qquad (1)$$

where kc is the fracture toughness of the particle and d is the diameter of the particle. Thus, the refined Mg_2Si particle size corresponds to a higher fracture stress. After heat treatment, formation of fine spherical primary Mg_2Si not only leads to a higher fracture stress but also increases the strength of the matrix/particle interface, both of which account for improved mechanical properties in the modified alloy. The enhancement of the elongation values of the composite after heat treatment (Fig. 4 (b)) is associated to the role of heat treatment in transformation of fibre eutectic Mg_2Si crystals to dot-like morphology. However, at high levels of 2.0 and 5.0 wt.% Gd the elongation values decreased. It is because in high levels of Gd (> 1.0 wt.%) the structure of the Gd phases changed to twin needle-like and flake-like respectively which results in decreasing the elongation. In fact, hardness and brittleness feature of these intermetallic compounds can negatively affects the elongation results. During the solidification, these intermetallic compounds are pushed into inter cellular regions by advance of the freezing front [16] and may cause cracks initiation and fast propagation of inter-granular crack [7–12]. Thus, based on the findings, the best tensile property is obtained by addition of 1.0 wt.% Gd to Al-15%Mg_2Si composite.

Fig. 5 (a-d) exhibits the typical fracture surface of the untreated and 1.0 wt.% Gd treated Al-15%Mg_2Si composite as a result of heat treatment. As observed in Fig. 5 (a) the fracture surface depicts observed cleavage caused a quick fracture generating from their pre-cracked structure and

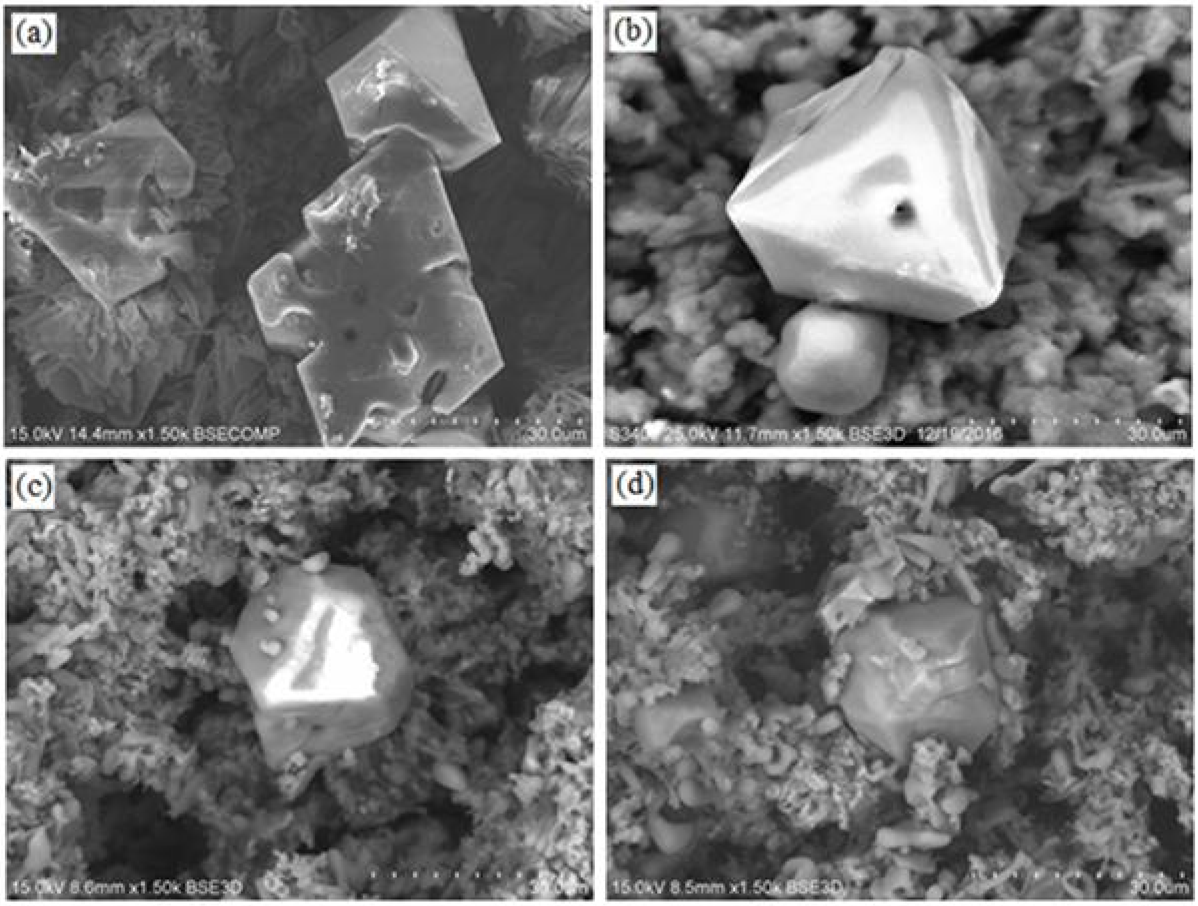

Fig. 3. 3D morphologies of primary Mg_2Si crystals before (a and c) and after (b and d) solution heat treatment with Gd concentration of: (a, b) 0 wt. %, (c, d) 1.0wt. %

intrinsic brittleness which called cellular fracture [8]. On a cellular fracture surface, both features of brittle and ductile fracture are at the same time existed. The fracture surface of untreated and solution heat treated composite is illustrated in Fig. 5 (b). As observed, tips are present on the coarse primary Mg_2Si surface indicative of intergranular fracture which demonstrates the minor influence of heat treatment on structure of untreated primary Mg2Si in Al-15%Mg_2Si composite. Fig. 5 (c) and (d) illustrates the fracture surfaces of Gd treated Al-15%Mg_2Si composite as a result of heat treatment respectively. As seen, the fracture surface of modified composite consists of fine dimples with honeycomb shape, which reveal a ductile fracture mode (Fig. 5(c)). Similarly, Fig. 5 (d) depicts the composite fracture surface after solution heat treatment with further fine dimples representing more homogeneous and deeper dimples which results in ductile mode of fracture, in which these results is consistent with elongation percentage values in Fig. 4(b) which approve the efficiency of solution heat treatment process on the ductility enhancement of the fabricated composites. Indeed, materials with fine structure own lower tendency to brittle cracking. Spheroidization of the primary Mg_2Si and eutectic Mg_2Si breakage decreased the influence of stress-concentration intensity on the Mg_2Si crystals; thereby, the micro regions of prospective crack initiation areas are eliminated.

4. Conclusions

In this research microstructure alteration and consequent tensile properties of Al-15%Mg_2Si composite as a result of gadolinium addition and solution heat treatment is examined. The following conclusion is drawn:

- Size and morphology of primary Mg_2Si particles alter considerably with Gd addition.

- The primary Mg_2Si size does not altered significantly by solution heat treatment; however, its morphology alters from truncated octahedral to round shape in Gd-treated composite.

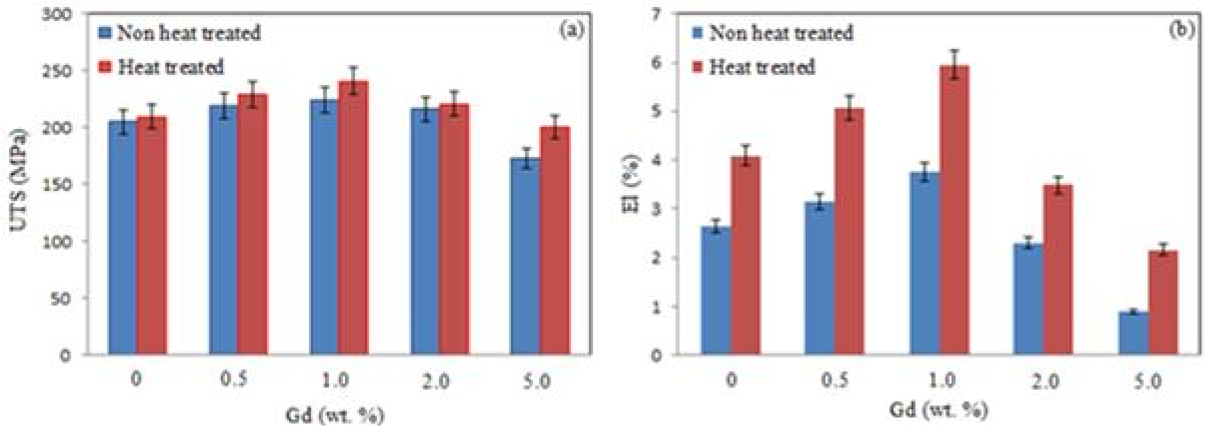

Fig. 4. The UTS (a) and elongation percentage (b) values of Al–15%Mg_2Si composite as a result of heat treatment, with respect to Gd concentration

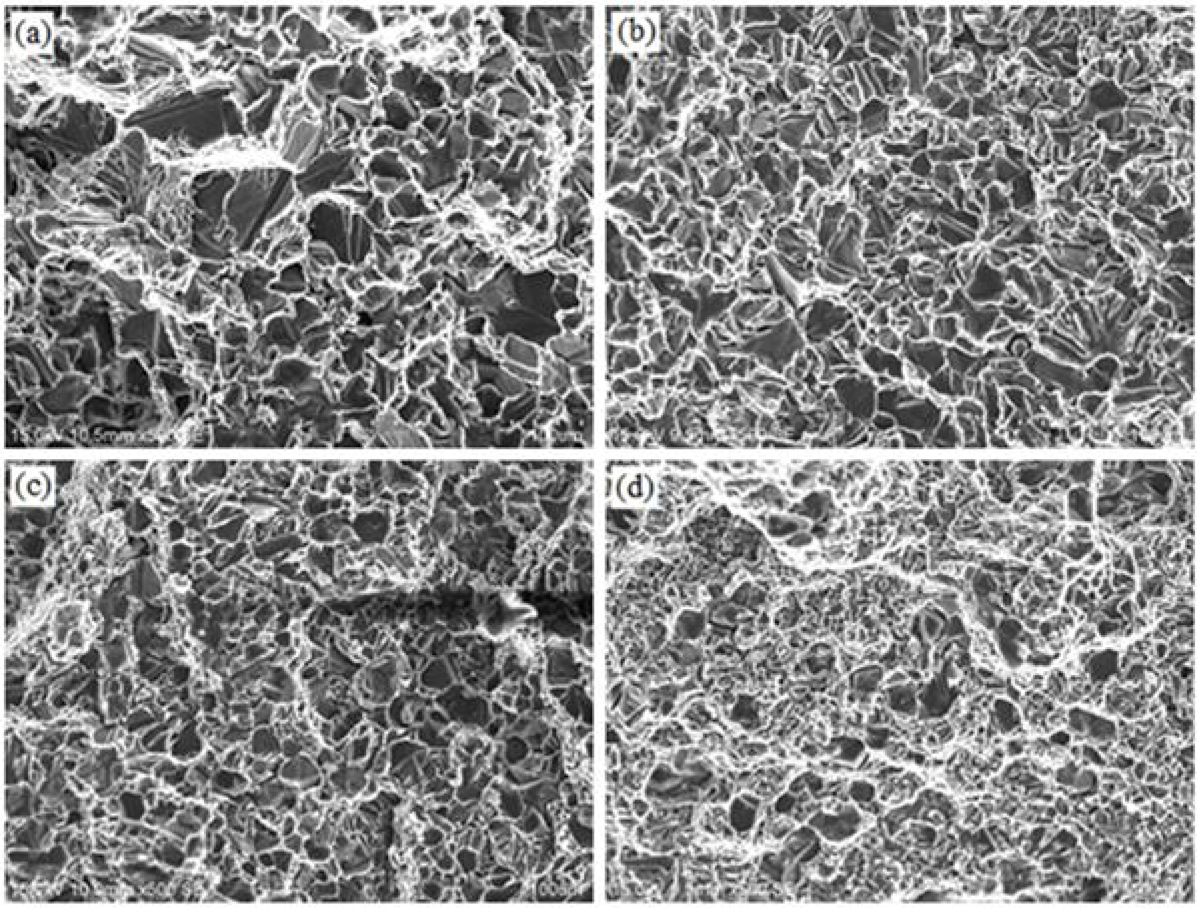

Fig. 5. SEM micrographs, illustrating the Al–15%Mg_2Si composites fracture surfaces before (a and c) and after (b and d) heat treatment with Gd concentration of: (a) and (b) 0wt%, (c) and (d) 1.0wt%

- The addition of Gd up to 1.0 wt% increases UTS values from 204.79 MPa to 224.62 MPa and this value increased to about 240.54 MPa after heat treatment.

- The tensile fracture surface of unmodified Al-15%Mg_2Si composite exposed a cellular fracture containing large facets of Mg_2Si particles. Nevertheless, the fracture surface of the composite after Gd addition and heat treatment illustrates the existence of dimples on the fracture surface, which indicated ductile mode of fracture.

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