RESEARCH PAPER

Influence of Erbium Addition on the Microstructural Evolution and Tensile Properties of Al/Mg_2Si In-Situ Metal Matrix Composites

Zahra Rousta, Esmaeil Tohidlou* and Hamed Khosravi

* etohidlou@eng.usb.ac.ir

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Department of Materials Engineering, Faculty of Engineering, University of Sistan and Baluchestan, Zahedan, Iran

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Abstract: *This study deals with the effects of Erbium (Er) addition on the microstructural evolution and tensile properties of Al-Mg_2Si in-situ metal matrix composites. The morphology of primary Mg_2Si and eutectic phases were observed in detail using an optical microscope and scanning electron microscopy (SEM). The results showed that the increase of Er content has a slight effect on the size and morphology of primary Mg_2Si phases, but the eutectic structure evolves from the coarse structure into the fine one. Also, with Er addition, the eutectic mixtures of Al and Mg_2Si with fibrous morphology have been developed instead of the flake-like Al-Mg_2Si eutectic microstructure. Meanwhile, the Al_3Er phase was observed in the samples containing Er. The ultimate tensile strength (UTS) of the composite changes under the various contents of Er. The maximum strength was found at 0.6 wt.% Er with the fine eutectic microstructure. The study of SEM micrographs from the fracture surface of composites revealed that Er addition changes the fracture mode from brittle to ductile one with fine dimples. The mechanism of microstructural evolution was discussed in detail.*

Keywords: *In-situ composites, Al-Mg_2Si metal matrix composite, Erbium Microstructure, Tensile properties.*

1. INTRODUCTION

Particle reinforced aluminum matrix composites have been developed in recent years because of wide-spread applications in the automotive industries, as well as aerospace technology [1-3]. The mechanical properties of the particle reinforced metal matrix composites depend on the microstructural parameters, such as the size, volume fraction, and morphology of the second phase [4-6]. In recent years, more scientific research in aluminum matrix composites has been directed towards the development of Al-Mg_2Si in-situ composites with the addition of rare-earth elements. In such composites, the rare-earth elements have been used for the refinement of the microstructure and improving the mechanical behavior of the composites. In this regard, the minor additions of the rare-earth elements such as La [7,8], Gd [9], Ho [10], Y [11], Nd [12] were used to modify the microstructure and mechanical properties of Al-Mg_2Si composites. In addition, the effect of Er and Zr on the microstructure and mechanical properties of pure Al was investigated by Gao et al. [13].

The results of the Akhlaghi et al. [8] study showed that an increase of La-intermetallic compound contents in the Al-15 wt.% Mg_2Si composite will increase the ultimate tensile strength and elongation values of the produced composite. The research of Ghandvar et al. [9] revealed that the addition of Gd decreases the average size of primary Mg_2Si particles in the composite and the best modification effect was observed at 1.0 wt.% of Gd content. Also, the morphology of primary Mg_2Si was changed from a coarse dendritic shape to a fine truncated octahedral. Moreover, Liu et al. [10] investigated the effect of the Holmium (Ho) element on the microstructural evolution of Al-Mg_2Si composites. They reported that 0.4 wt.% Ho content improved the hardness behavior and microstructure of the composite. Furthermore, the study of Nodooshan et al. [11] indicated that the addition of Y did not affect the size of primary Mg_2Si particles, but the pseudo-eutectic Mg_2Si was changed from a flake-like morphology to the fine fibrous one. Also, with the addition of 0.3 wt.% of Y, the wear resistance of the in-situ composite was increased. Wu et al. [12] studied the microstructural evolution and tensile properties of Al-Mg_2Si metal matrix composites under the addition of Nd. Their results showed that at 0.5 wt.% Nd, the UTS and elongation were increased properly. Wu et al. [14] studied the effects of Er addition on the microstructure and mechanical properties of an as-extruded Al-Mg alloy.

To the best of the authors' knowledge, the effect of Erbium (Er) addition on the microstructural evolution and mechanical properties of the Al-Mg_2Si composites has not been investigated so far. Therefore, this work aims to perform the experimental study of the microstructural development and mechanical properties of the Al-15wt.% M_2Si composites with the addition of various contents of Er element.

2. EXPERIMENTAL PROCEDURES

The Al-15wt.% Mg_2Si composite was fabricated by casting technique using the commercial pure Al (>99.8 % purity), Mg, and Si metals in an electric resistance furnace. After Al melting in a crucible and heating up to 750 °C, Si (5.5 wt.%) and Mg (9.5 wt.%) were added into the molten Al. To prepare the composite containing different Er values (0.0, 0.2, 0.4, 0.6, 1.0 wt.% Er), the parent alloy remelted in a standard graphite crucible. Then the balanced amount of Al-30wt% Er alloy (provided by Shanghai Xinglu Chemical Technology Co., Ltd) was added to the molten composite at 750 °C. Afterward, the obtained liquid composite was kept 10 min to homogenize, and subsequently, it poured into a steel mold which was preheated up to 200 ºC. Figs. 1(a) and (b) show the steel mold including the geometric shape of the casted composite and the dimensions of the tensile sample after the machining process, respectively.

To characterize the evolution of microstructure in the casting composites, all specimens were prepared from the same position. Thereafter, by applying the standard methods such as grinding, polishing, and etching, the surface of metallographic specimens were prepared. After preparation, a scanning electron microscope and an optical microscope equipped with an image analysis system were employed to characterize the microstructures and fracture surfaces of the composites with various contents of Er. To conduct the tensile test, the specimens were machined to dimensions mentioned in Fig. 1(b). A computerized Instron machine was used to carry out the tension tests at a constant cross-head speed of 1 mm per minute.

3. RESULTS AND DISCUSSION

3.1. Microstructural Evolution

The phase changes that occur during the solidification of Al-15%wt. Mg_2Si composites can be studied by a pseudo-binary Al-Mg_2Si phase diagram. Based on the Al-Mg_2Si phase diagram [15], it can be realized that under the liquidus line, the first nuclei of Mg_2Si form. As the temperature falls, the Mg_2Si particles continue to grow, which is known as the primary Mg_2Si phase (Mg_2Si_p). When the remaining liquid (L_1) reaches the eutectic line, it solidifies into the mixture of α-aluminum and secondary Mg_2Si particles, which is known as the eutectic reaction. The solidification process of Al-15%%wt. Mg_2Si can be written as:

$$L \Rightarrow L_1 + Mg_2Si_p \Rightarrow Mg_2Si_p + \{\alpha \quad \text{alu min um} + Mg_2Si\}_{\text{eutecticmi xture}}$$

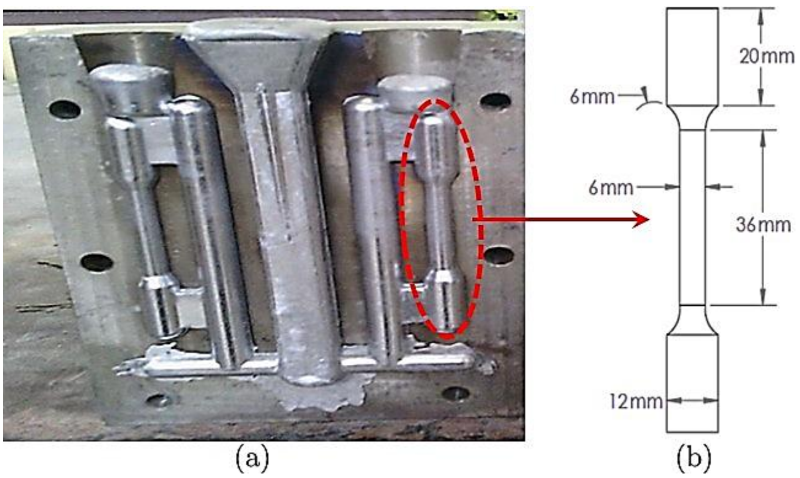

Fig. 1. (a) The steel mold which is used for the casting process, (b) Dimensions of the tensile sample.

Therefore, the microstructure of composites includes both primary and secondary Mg_2Si particles. The elemental X-ray mapping for the Al-Mg_2Si composite (Fig. 2) confirms the presence of primary Mg_2Si particles in the matrix.

The prepared samples of the hypereutectic Al-15wt.% Mg_2Si in-situ composites with various amounts of Er were examined under the OM microscope. The revealed structures (Figs. 3(a-e)) indicate that the composites are composed mainly of primary Mg_2Si particles and secondary Mg_2Si in the matrix of aluminum (eutectic structure).

From Fig. 3(a) it can be seen that the morphology of primary Mg_2Si particles is irregular with sharp corners. In this regard, the results of Zhang et al. [15] manifested that primary Mg_2Si particles act as heterogeneous sites in the formation of the α-Al phase. Also, the average size of unmodified primary particles is about 14 μm. A comparison between the unmodified composite (Fig. 3a) and the modified one (Figs. 3(c-e)) reveals that the addition of Er has no significant effects on the morphology of the primary Mg_2Si particles, but the size of pro-eutectic crystals are under the influence of Er contents. Fig. 4 demonstrates the variations of the primary Mg_2Si size as a function of Er contents in the Al-Mg_2Si-xEr in-situ composites. It can be seen that increasing Er content in the samples reduces the average size of the pro-eutectic particles, and the minimum particle size was about 8 μm which is observed in the Al-15%Mg_2Si-0.6%Er in-situ composite. Further, the addition of Er has a minor effect on the crystal size.

The results of previous research of Wu et al. [12] have revealed that the reason for the grain refinement of Mg_2Si crystals in Al-Mg_2Si composite might have resulted from increasing the constitutional supercooling at the front of the liquid/solid interface of Mg_2Si during solidification, which suppresses the intermetallic particles growth and thus the particle size, becomes finer. In addition, the heterogeneous nucleation is a well-known mechanism for the modification of Mg_2Si particles in the Al-Mg_2Si composites, where the modifier elements or their components act as nucleation sites, so increasing the density of nuclei for primary Mg_2Si particles at the first solidification process reduces the size of Mg_2Si particles [9].

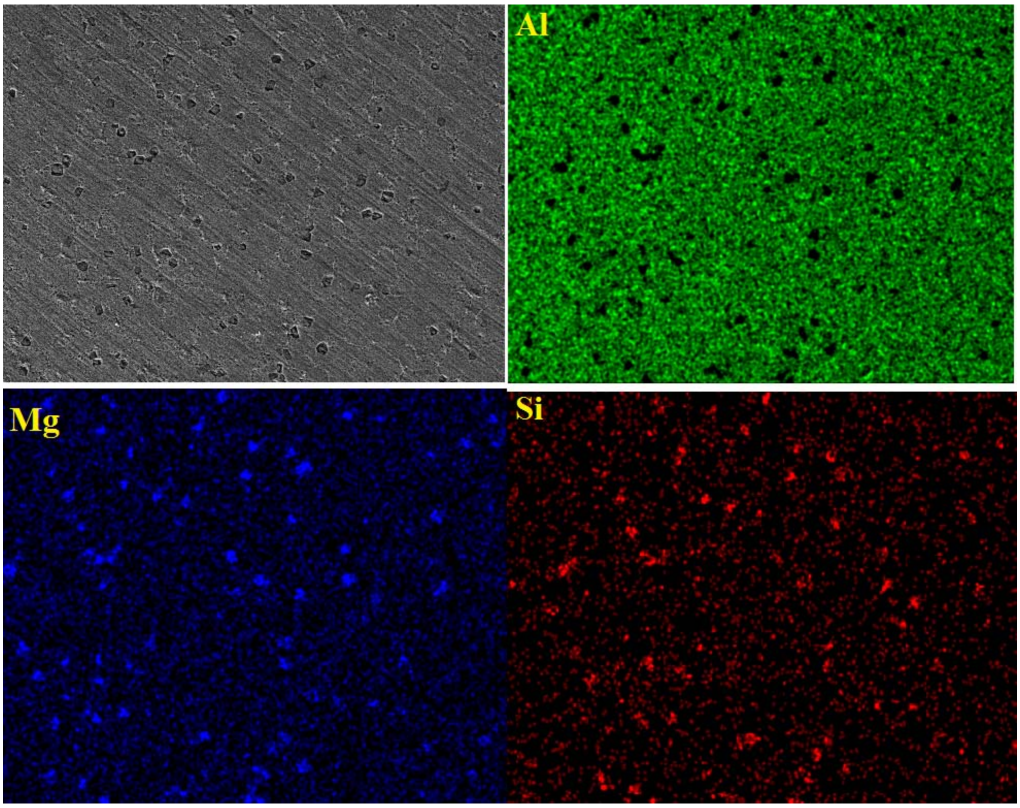

Fig. 2. Elemental X-ray mapping for the Al-Mg_2Si composite.

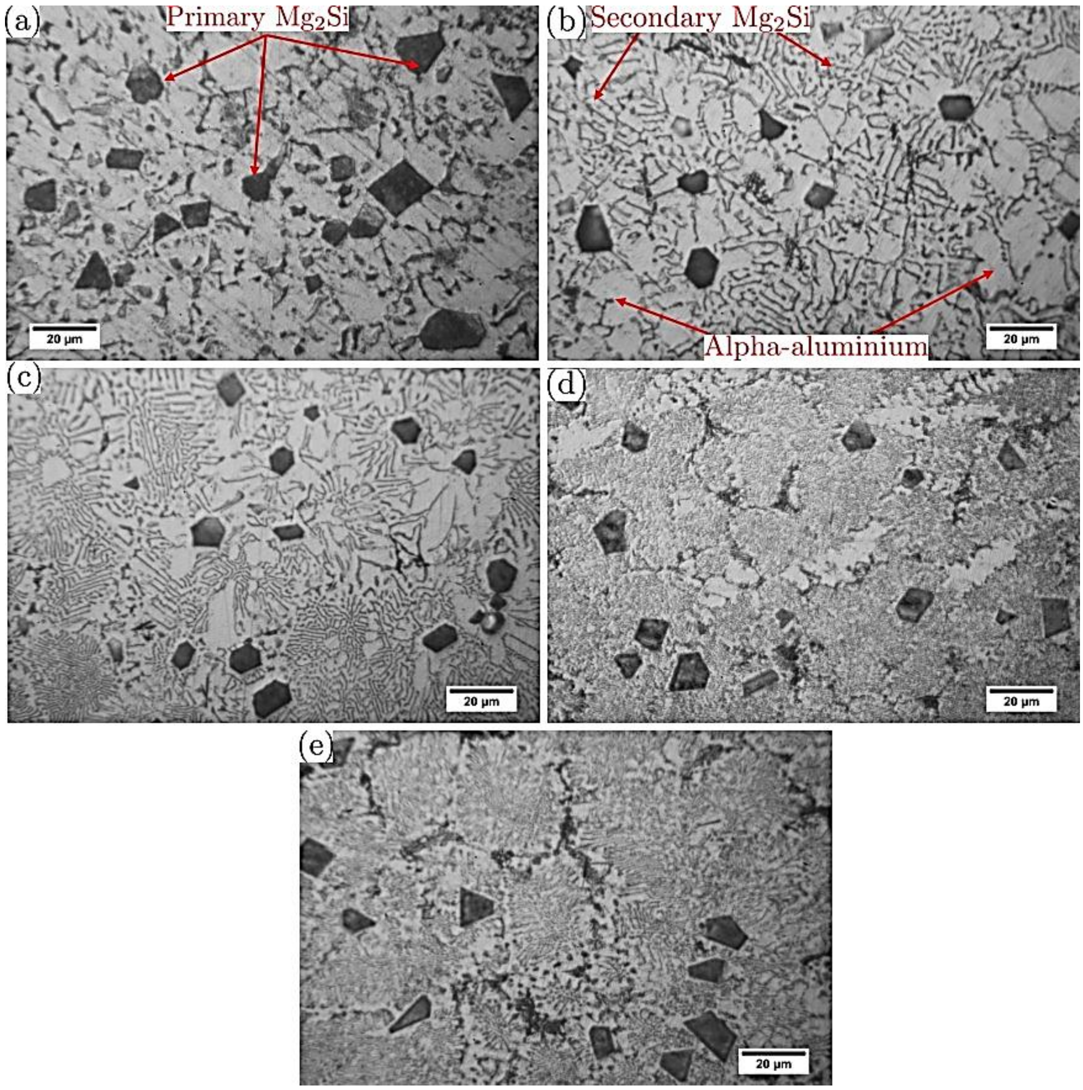

Fig. 3. Optical microscope of microstructural evolution in Al-15%Mg_2Si composites with various contents of Er: (a) 0 wt.%, (b) 0.1 wt.%, (c) 0.2 wt.%, (c) 0.4 wt.%, (d) 0.6 wt.%, (e) 1.0 wt.%.

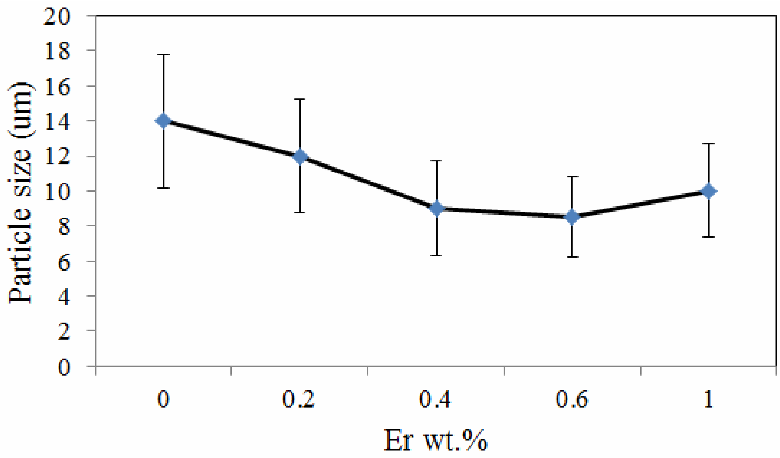

Fig. 4. The size of pro-eutectic Mg_2Si particles as a function of Er contents.

Because of the noticeable difference between the atomic radius of Er (0.245 nm) with that of Mg (0.145 nm) and Si (0.118 nm), it is evident that Er atoms cannot dissolve into Mg and Si melts. The previous study of Wang et al. (2012) indicated that due to a minor difference between the crystal lattice parameter of Er and Al, intermetallic compounds form as a result of the Er addition to the Al melt. The SEM micrograph of the Al-15%Mg_2Si-1%Er composite (Fig. 5a) demonstrates a second phase (white area) that is developed in the composite matrix with increasing Er contents. Energy-dispersive x-ray (EDX) analysis was used to characterize the elemental composition of the second phase at point B. Fig. 5b shows the EDX pattern of withe phases where the atomic percentage of aluminum and erbium are 70.56 and 25.13, respectively. Based on the atomic percentage and Al-Er phase diagram, the white particles in Al-15%Mg_2Si-Er composites are detected as Al_3Er phase and the amount of particles is depending on the Er content in the in-situ composites. In the XRD pattern (Fig. 6), the Al_3Er inter-metallic is not observable probably due to the very low content of the phase. The Al-Er phase diagram [16] confirms that when the Er content is below 25% in Al, the Al_3Er inter-metallic compound will develop in the matrix. Also, the results reported by Colombo et al. [17]. Pandee et al. [18] indicated that by increasing Er contents, Al_3Er particles precipitated in Al-Mg-Si alloys affect the mechanical behavior of the casting alloys. This inter-metallic compound (Al_3Er) might assist the nucleation of primary Mg_2Si crystals during the solidification process.

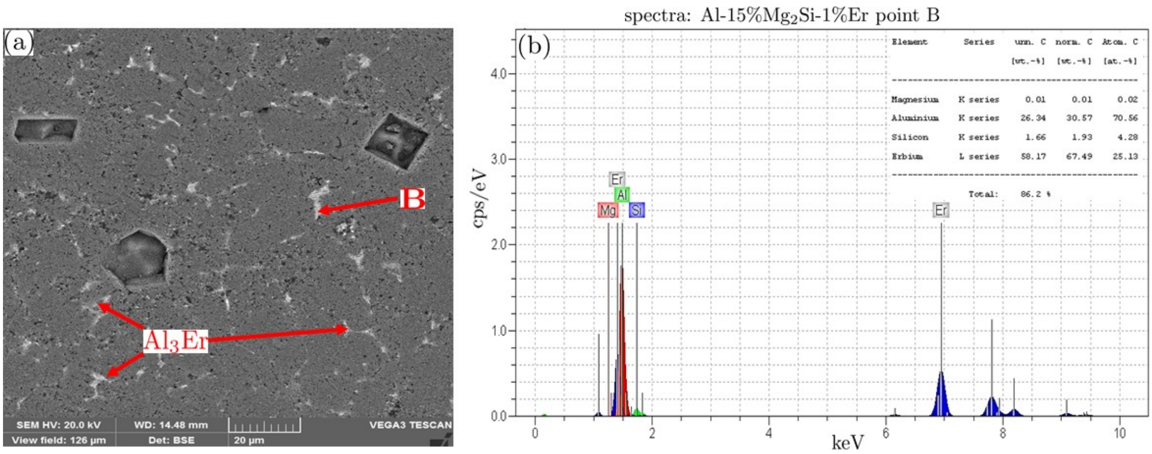

Fig. 5. (a) SEM micrograph and (b) EDX characterization of the Al-15%Mg_2Si-1%Er composite.

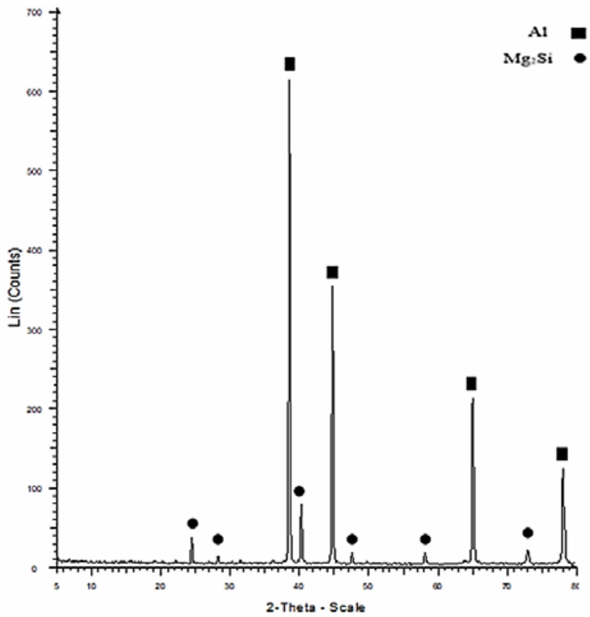

Fig. 6. XRD pattern of the Al-15%Mg_2Si-1%Er composite.

Also, precipitated fine Al3Er particles act as an impediment to dislocation motion and will increase the strength of the material (Wang et al. [19]). It was reported that the formation of intermetallic compounds is one of the effective mechanism for the modification of Mg_2Si particles in the Al-Mg_2Si in-situ composites [9].

The morphology of eutectic structures is shown in Figs. 3(a-e). It can be seen that with increasing the Er concentration in the composite, eutectic mixtures become finer and the finest eutectic structure is developed in the Al-15%Mg_2Si-0.6%Er. In Fig. 7, to observe the effect of Er addition on the morphology of the eutectic mixture, the high magnification of the eutectic structure of Al-15%Mg_2Si modified with 0.2% and 0.6% Er is presented. It can be noticed that the morphology of Mg_2Si crystals in the eutectic mixture of Al-15%Mg2-0.2%Er is mainly flake-like. However, the microstructure of the modified Al-Mg_2Si composites with 0.6% Er consists primarily of rod-like or dot-like Mg_2Si particles. The results of Ghandvar et al. [9] showed that the morphology of Mg_2Si crystals depends mainly on the interface energy between aluminum and the eutectic Mg_2Si particles, moreover, rare-earth contents in the composite have an influence on the interface energy between two phases.

3.2. Mechanical Properties

The stress-strain curves were employed to investigate the effect of Er additions on the mechanical properties of Al-Mg_2Si composites. Fig. 8 and table 1 demonstrate the influence of Er contents on the tensile properties. It is evident from Fig. 7 that all composites suffer from a lack of ductility. However, the Er addition has resulted in the improvement of the mechanical properties of Al-15Mg_2Si composites in terms of ultimate tensile strength and elongation. When the amount of Er reaches 0.4 wt.% and 0.6 wt.%, the tensile strength of the Al-Mg_2Si composites has been increased up to 220 and 250 MPa, respectively. The optimum level of the UTS and elongation values are around 250 MPa and 7 %, respectively, where the Er content is 0.6 % and at this stage, the tensile strength has improved about 32 %. It sounds that increasing the tensile behavior of the composites with Er additions resulted from the modification of morphology of both eutectic and proeutectic Mg_2Si particles.

The increasing of Er content changes the eutectic Mg_2Si from the flake-like morphology to the fibrous one. It has a significant effect on the increase of ductility of the modified composites. Also, the size of primary Mg_2Si decreases during the modification process which will influence both strength and ductility of in-situ composites. In the Al-15%Mg_2Si-1%Er composite, both the tensile strength and elongation slightly decreased. It seems that the formation of coarse Al_3Er phase at the higher Er concentrations has a negative impact on the mechanical properties. Besides, it has been confirmed that the precipitation of the intermetallic compounds will decrease the tensile and mechanical properties of the in-situ metal matrix composites [12].

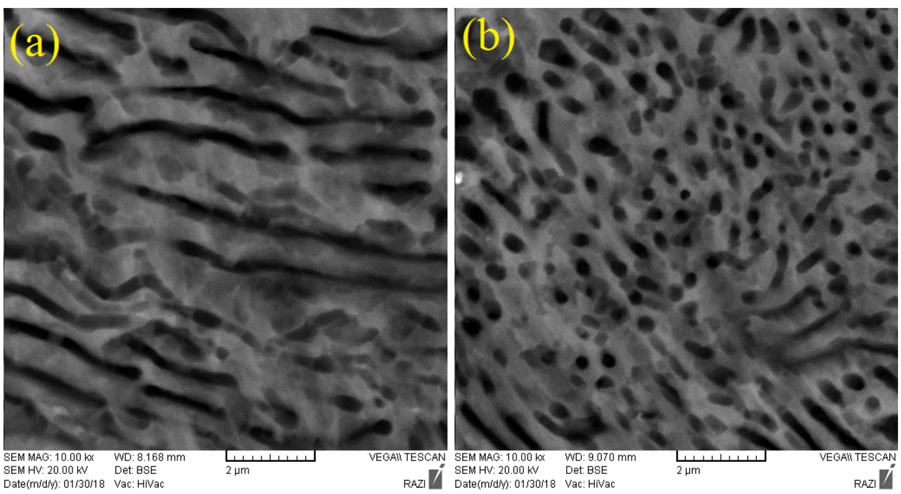

Fig. 7. SEM micrographs of the morphology of Mg_2Si particles in the eutectic mixture of Al-15%Mg_2Si composite (a) un-modified, and (b) modified with 0.6 wt.% Er.

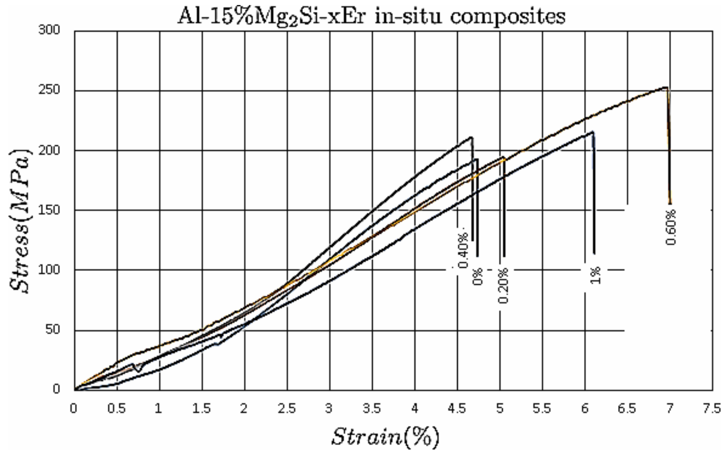

Fig. 8. Stress-strain curves as a function of various Er contents.

Table 1. The values of tensile properties as a function of Er content.

Er wt.%	UTS (MPa)	El. (%)
0	193.4	4.73
0.2	194.6	5.04
0.4	204.8	4.66
0.6	248.5	6.96
1	215.4	6.09

Fig. 9 shows the unmodified and modified fracture surfaces of Al-15%Mg_2Si composite after the tensile test. It can be seen that the cleavage fracture takes place in the unmodified state. Meanwhile, the cracked particles and large facets of the broken primary Mg_2Si particles can be seen on the fracture surface of the unmodified composite. Because of the intrinsic brittleness of Mg_2Si particles, the cracks appear in the coarse Mg_2Si particles. It has been indicated that the primary Mg_2Si particles act as preferred crack initiation sites [20].

The results of Azarbarmas et al. [21] research showed that under the tensile loading, both of inside of Mg_2Si particles and sharp corners of particles are prone to initiate the local cracks, and the increase of strain causes to break the Mg_2Si particles. The main fracture mode in the unmodified composites is brittle. Therefore, the abovementioned observations suggest that the coarse primary Mg_2Si phase deteriorates the mechanical properties of Al-15%Mg_2Si composites. From Fig. 9(b), it can be observed that after 0.6 wt.% Er addition, very fine and uniformly distributed dimples are formed on the fracture surface. In the modified composites the sharp corners of primary Mg_2Si particles act as the micro-crack sources due to the stress concentration. So, cracks initiate at the corners of the second phases and propagate along with the interface between primary particles and the composite matrix, therefore, the primary Mg_2Si phases decohere from the composite matrix. Previous studies on the Al-Mg_2Si composites also verified this kind of micro-cracks initiation and propagation along with the interface between the primary particles and the matrix [21].

A comparison between fractured surfaces of Al-15%Mg_2Si composites in unmodified and modified with 0.6 % Er demonstrates that by increasing Er content, the number of fine dimples increases on the fracture surface, which is fairly consistent with that of tensile test results, as shown in Fig. 8. Fine dimples on the fractured features indicate that in contrast to the unmodified composite with brittle fracture behavior, the ductile fracture mechanism takes place at the Er-modified composites. Moreover, fine dimples are attributed to the increase in the elongation behavior of the modified composites.

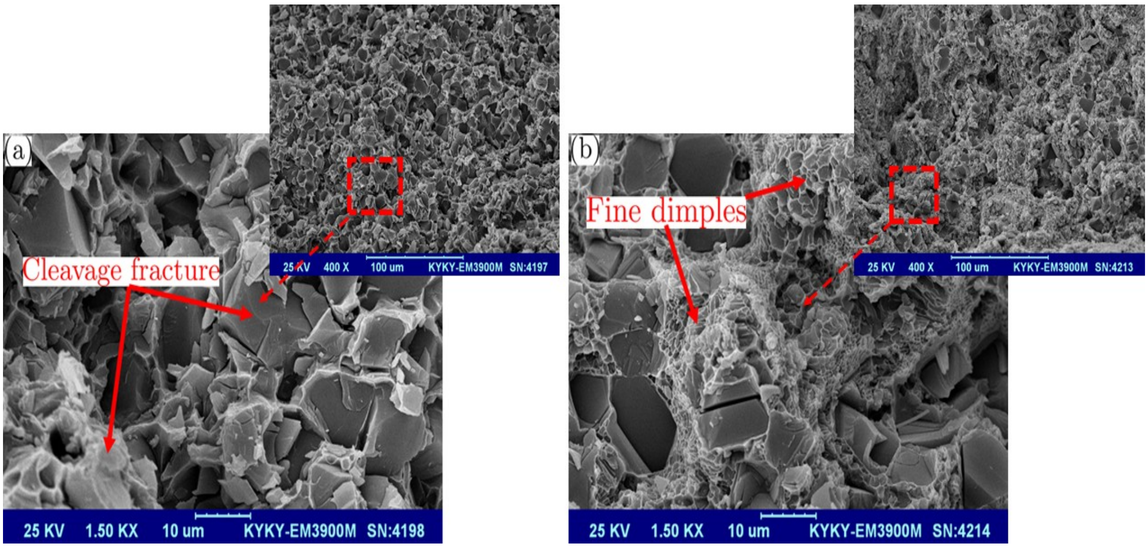

Fig. 9. Fracture surfaces of Al-15%Mg_2Si composites: (a) unmodified, (b) modified with 0.6% Er.

4. CONCLUSION

In the present study, the effect of various contents of erbium on the microstructural evolution and tensile properties of Al-Mg_2Si composites was investigated. The following conclusions can be drawn:

- Increasing Er contents in the Al-Mg_2Si reduces the average size of pro-eutectic Mg_2Si particles, and the minimum particle size was about 8μm which is observed in the Al-15%Mg_2Si-0.6%Er composite. Further addition of Er has a minor effect on the crystal size.
- Er addition to the composite has a slight effect on the morphology of proeutectic Mg_2Si particles. However, the morphology of Mg_2Si crystals in the eutectic mixture changes mainly from the flake-like structure to the rod-like or dot-like one.
- Er addition improved the tensile properties of the composites. The optimum level of the UTS is around 250 MPa where Er content is 0.6 % and at this state, the tensile strength has improved about 34 %.
- In contrast to the unmodified composite with brittle fracture behavior, fine dimples are increased and ductile fracture mechanism takes place at the Er-modified composites.

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