RESEARCH PAPER

Microstructure-Property Relationships in an Erbium-Modified Al-Si-Mg Alloy

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Abstract: *The effect of erbium (Er) addition at various weight percentages (0-0.6 wt.% at an interval of 0.2) on the microstructural features, tensile properties and wear behavior of as-cast Al-7.5Si-0.5Mg alloy were evaluated. The microstructure of the specimens was examined by X-ray diffraction (XRD), optical microscopy (OM) and scanning electron microscopy (SEM). The obtained results clearly demonstrated that the incorporation of erbium decreased the α-Al grain size and eutectic Si, and altered the Si morphology from plate to semi-globular. Further addition of erbium (> 0.2 wt.%) did not alter the eutectic morphology and size. Moreover, the Al3Er phase was also observed in the eutectic region after modification. Out of the erbium contents used, 0.2 wt.% erbium showed the best influence on the tensile and wear properties. Compared with those of unmodified specimen, the values of ultimate tensile strength and elongation were enhanced by 31 and 39%, respectively through 0.2 wt. % erbium addition. Additionally, a remarkable enhancement in the wear properties was observed with the addition of 0.2 wt.% erbium.*

Keywords: *Al-Si-Mg alloy, Erbium, Eutectic Si, Microstructure, Tensile properties, Wear.*

1. INTRODUCTION

Al-Si alloys are commonly used in various industries such as automotive and aerospace owing to their specific characteristics such as high mechanical properties, desirable corrosion resistance, good fluidity and low density. It is generally accepted that the microstructural features can remarkably affect the mechanical properties of a specimen [1,2]. Many researchers have reported the deleterious effects of coarse and acicular eutectic Si on the strength and ductility. In this regard, the Si morphology change to fibrous or laminar forms plays a key role [3,4]. Till now, many research work have been conducted to modify the eutectic Si phase. Modification can be obtained via various techniques such as chemical modification, quench modification, and heat-treatment. Among these techniques, chemical modification is known as an effective and simple route to modify the microstructure. Various elements are used for chemical modification such as Ti [5], Sr [6,7], B [8], Na [9], Sb [10] and rare earth elements (Y [11,12], Nd [13], Ce [14], La [15], Sc [16], Sr [17], Eu [18], Yb [19], Sm [20], Er [21], and Gd [22]). For example, Li et al. [11] explored the influence of Y addition on the microstructure and mechanical behavior of Al-20Si and reported that the tensile strength increased by 47.9% with the addition of 0.8% Y. The microstructural characteristics of Yb-modified Al-Si-Mg was evaluated by Li et al. [19]. They found that the introduction of Yb led to Si morphology change from plate to flake. In the work of Razaghian et al. [7] the optimum content of Sr as a modifier for Al-A357 alloy was found to be 0.03%. Prukkanon et al. [16] evaluated the effects of Sc on the modification of Al6Si0.25Mg alloy and demonstrated that the incorporation of only 0.2 wt.% Sc effectively modified eutectic Si. Hu et al. [13] found that the mechanical properties of as-cast Al-12Si alloy was increased after 0.3 wt.% Nd incorporation. Colombo et al. [21] reported that the 0.22 wt.% Er-modifed Al-Si-Mg can be effectively employed at room and high temperatures. Microstructure features of Eu-modified Al-A356 alloy was evaluated by Mao et al. [18] and found that the introduction of 0.1 wt.% Eu modified the morphology of

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eutectic Si. Pourbahari et al. [15] showed that the incorporation of only 0.1 wt.% La enhanced the elongation of A357 by about 78%.

The detailed work on the influence of erbium addition on the microstructure, tensile, and wear properties of Al-Si-Mg alloy are still limited. This point was the main reason for the selection of the present work. Herein, the alloys were prepared with the addition of various erbium weight percentages and the effect of erbium on the microstructure, tensile response and wear properties were investigated. Finally, the relationship between the microstructure and mechanical properties was also discussed.

2. EXPERIMENTAL PROCEDURES

About 500 g Al-7.5Si-0.5Mg alloy was melted at 750±5°C. After degassing using 0.3 wt.% C2Cl6 tablets, Al-30 wt.% erbium master alloy was added to the molten alloy. Different weight percentages of erbium (0, 0.2, 0.4 and 0.6) were employed. Subsequently, the melt was poured into a preheated mold at 750°C (Fig. 1).

The metallographic specimens were etched using a 0.5%-HF solution after polishing. The microstructural features were evaluated by an optical microscope (OLYMPUS). The chemical composition of observed phases was determined by scanning electron microscopy (SEM) (TESCAN/VEGA) equipped with energy dispersive spectroscopy (EDS).

Tensile test was conducted on an INSTRON machine based on ASTM B557M, and a cross-speed of 1 mm/min. The values of mechanical parameters were presented as a function of erbium weight percent.

Wear test was done by a pin-on-disc machine (ARIANA Modern Industry (AMI) Company, Iran). The specimens in the form of pins were slid against a steel disk (64 HRC). The sliding velocity and applied load were kept constant at 1 m/s and 20 N, respectively. The tests were carried out for a total distance of 200 m.

The fractured and worn surfaces of samples were analyzed by a KYKY-EM3900M SEM.

3. RESULTS AND DISCUSSION

3.1. Microstructural Features

The optical micrographs of specimens with various erbium contents are depicted in Fig. 2. It is seen that the microstructure of base alloy changed significantly with the introduction of

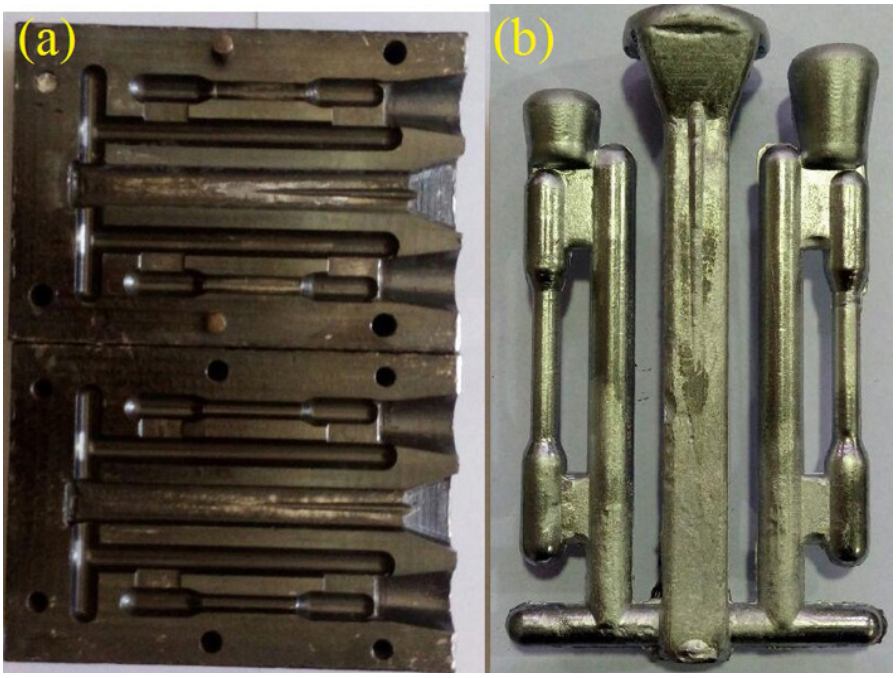

Fig. 1. The representation of a) fabricated steel mold, and b) cast specimen.

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erbium. Variation of equivalent α-Al grain size versus erbium content is depicted in Fig. 3. For unmodified alloy without erbium addition, the value of equivalent α-Al grain size is about 94 µm. It decreased to 25.1 µm when 0.2 wt. % erbium was added, and afterward enhanced to 36.1 µm and 50.2 µm with the addition of 0.4 and 0.6 wt.% erbium, respectively. In summary, the equivalent size of α-Al grains in the specimens modified with erbium is smaller than that of the base alloy. The main reason for the grain refinement in the erbium-modified specimens is probably attributed to the constitutional undercooling due to the segregation of solute ahead of the solid-liquid interface. This is because; erbium has a larger atomic radius compared to the Al, and its solid solubility in Al is extremely low. Another refining mechanism may be because the introduction of erbium creates some Al3Er compound at the grain boundaries [13,24]. The participated Al3Er with a crystal structure of FCC is considered as heterogeneous nuclei for the α-Al (Al/Al3Er lattice parameter mismatch is 4%). It seems that the formation of lager Al3Er at higher contents of erbium is the main reason for the observed trend (see Fig. 4b). This is in line with the published report in the literature [25].

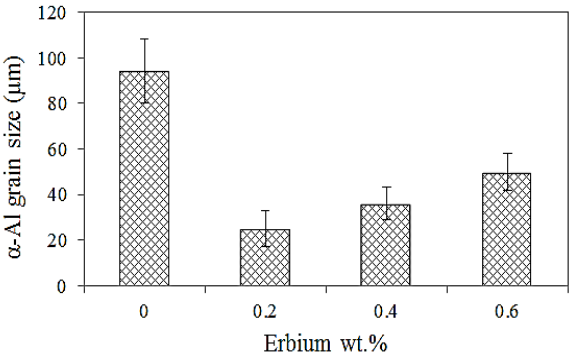

Fig. 3. Variation of equivalent α-Al grain size versus erbium loading.

Fig. 4 displays the SEM micrographs of Al-Si-Mg specimens containing 0.2 and 0.6 wt.% erbium. Besides, EDX analysis of the marked phase in the Fig. 4b is shown in Fig. 4c. In order to verify that the bright phases in SEM images are Al3Er, the X-ray diffraction pattern of the 0.6 wt.% erbium-modified alloy was also taken and the results are displayed in Fig. 5. According to the Fig. 5, α-Al, Si, and Al3Er are detected. This is in line with the experimental study conducted by Hu et al. [23].

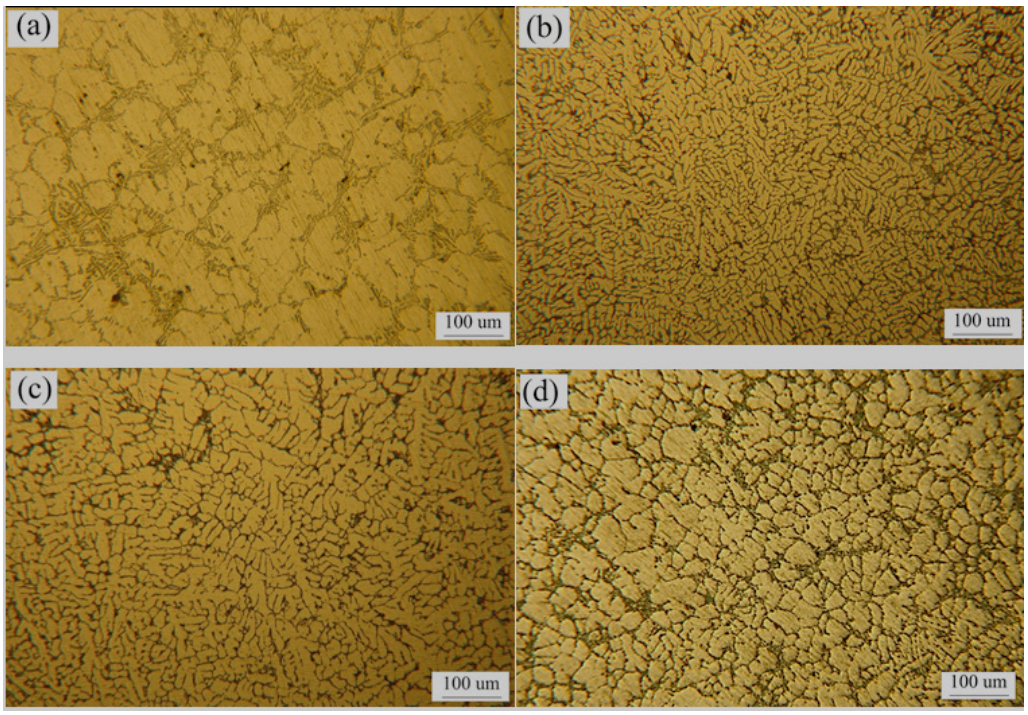

Fig. 2. Microstructures of Al-7.5Si-0.5Mg samples with various loadings of erbium: a) 0 wt.% Er, b) 0.2 wt.% Er, c) 0.4 wt.% Er, and d) 0.6 wt.% Er.

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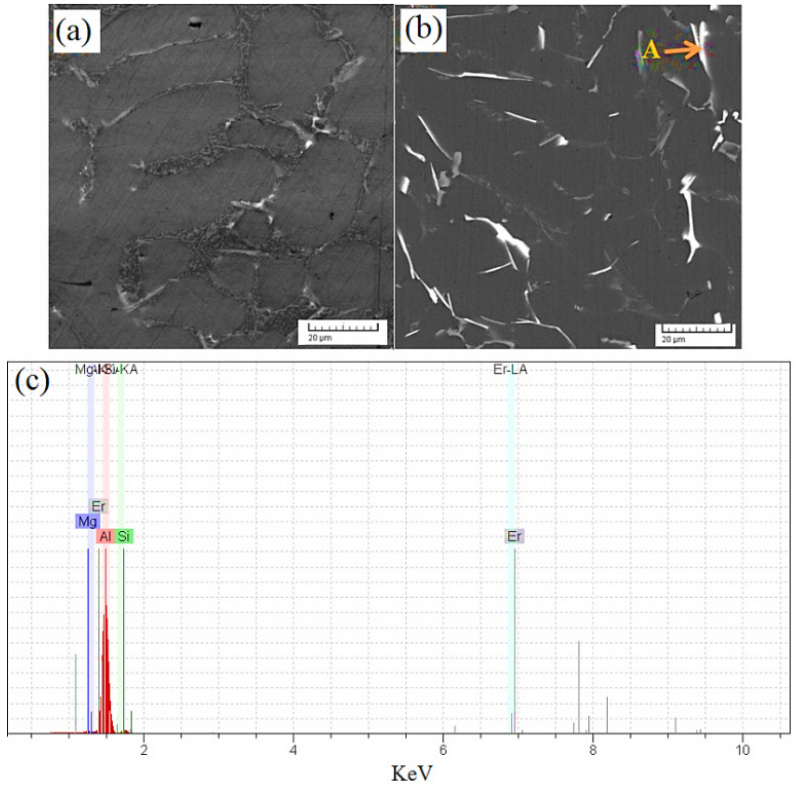

Fig. 4. SEM micrographs of a) 0.2 wt.% erbium-modified sample, b) 0.6 wt.% erbium-modified sample, and c) EDS analysis from the point "A".

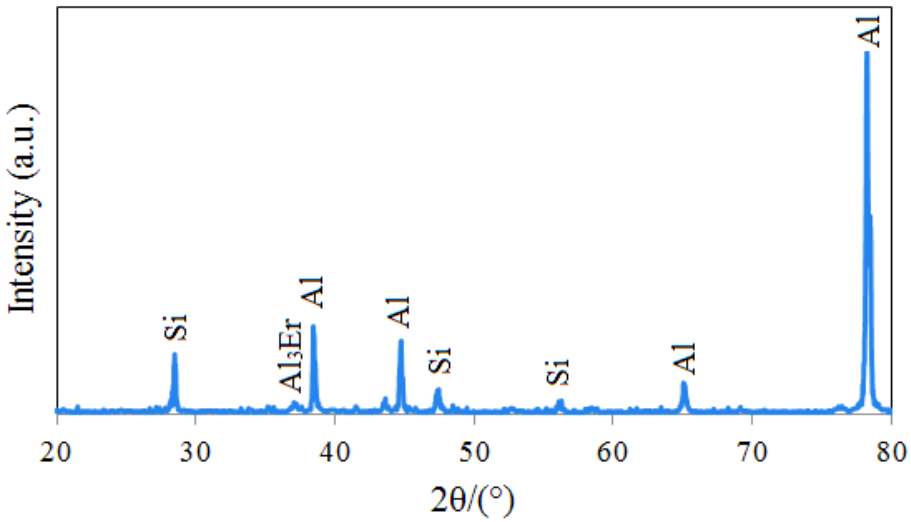

Fig. 5. XRD analysis of the 0.6 wt.% erbium-modified alloy.

The high-magnification optical micrographs of specimens with various erbium contents are depicted in Fig. 6. For the unmodified alloy, a coarse lamellar-like eutectic Si is observable (Fig. 6a). It can be observed that the addition of erbium has a significant influence on the Si morphology and its size. Additionally, there is no noticeable difference in the size and morphology of eutectic Si in the erbium-modified specimens (Figs. 6b-6d). Due to small atomic radius of erbium and also its difficulty in diffusion, erbium atoms can easily absorb on the {111}Si planes and poison

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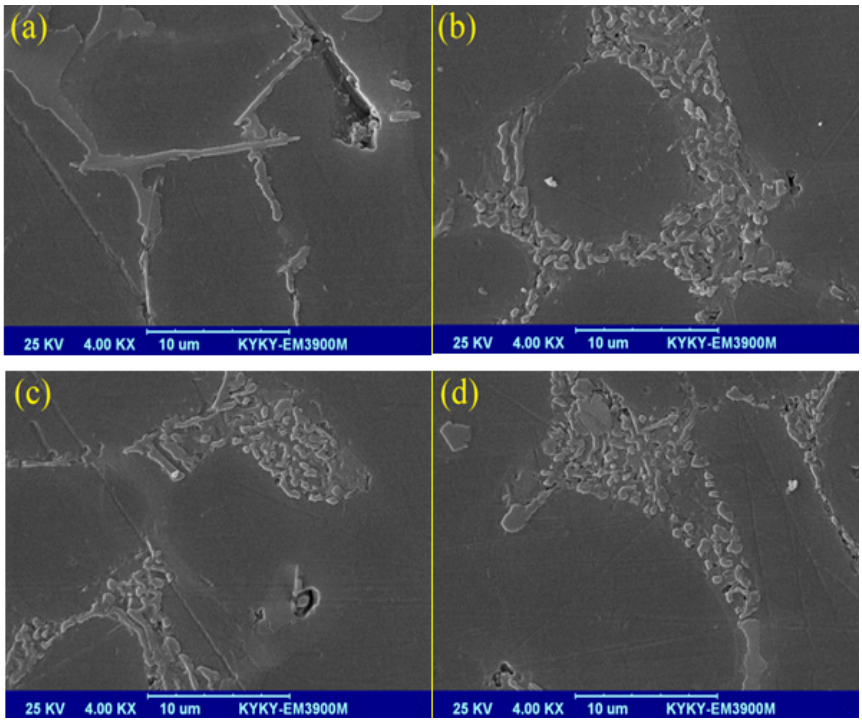

Fig. 6. High-magnification SEM micrographs of the Al-7.5Si-0.5Mg samples having various loadings of erbium: a) 0 wt.% Er, b) 0.2 wt.% Er, c) 0.4 wt.% Er, and d) 0.6 wt.% Er.

the orientation growth of the Si particles. On the other hand, similar to La and Ce, the addition of erbium can create undercooling in the melt and as a result, the eutectic Si is refined.

3.2. Tensile Behavior

Fig. 7 illustrates the stress-strain curves of the Al-7.5Si-0.5Mg specimens with various contents of erbium. The variation of strength and elongation versus erbium loading is seen in Fig. 8. It can be observed that the addition of 0.2 wt.% erbium enhances the tensile strength of the sample from 126 MPa to 165 MPa (i.e. 31% increase). Moreover, the addition of 0.2 wt.% erbium increases elongation from 8.96 to 12.52% (i.e. 39% increase). These improvements in UTS and elongation are mainly attributed to the microstructural features in the modified alloys. As discussed earlier, the addition of erbium led to formation of a refined microstructure with modified morphology of α-Al and Si. Besides, adding erbium beyond 0.2 wt.% leads to a remarkable decrease of strength and elongation, probably due to the presence of lager Al3Er at higher contents of erbium. The quality parameter (Q = UTS + 150×log (elongation)) [19] was employed to study the efficiency of erbium addition. Table 1 summarizes the values of quality index as a function of erbium content. It is evident that among the elongation loading used, 0.2 wt.% erbium has resulted in the best tensile property efficiency. Based on the above findings, it can be observed that there is a good consistency between the results of tensile testing with microstructural features.

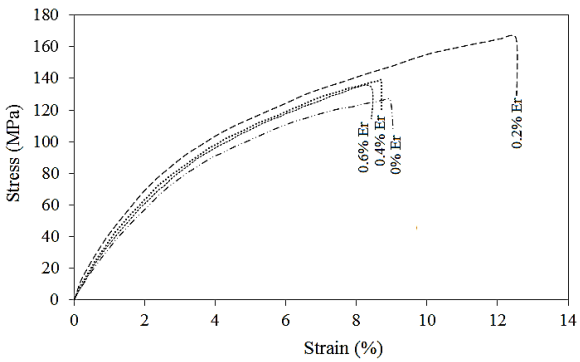

Fig. 7. The stress-strain curves of the Al-7.5Si-0.5Mg specimens with various loadings of erbium.

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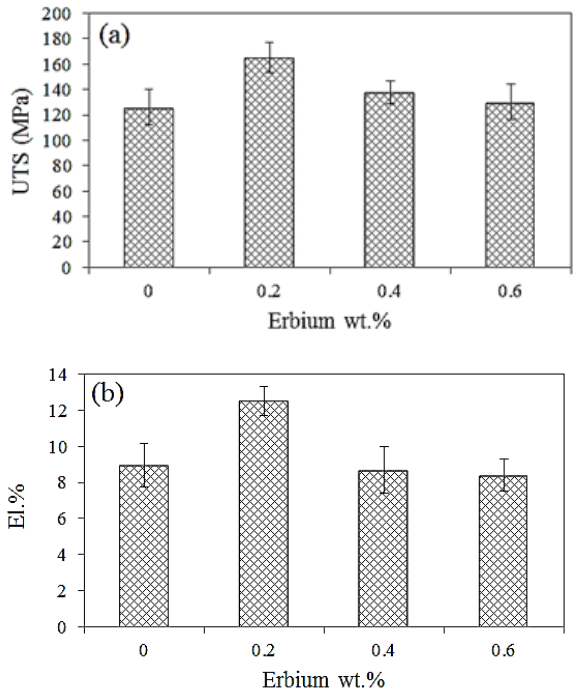

Fig. 8. a) Tensile strength and b) elongation of the Al-7.5Si-0.5Mg samples versus erbium contents.

Table 1. The values of quality index (Q) for specimens with various erbium contents

Erbium wt.%	Q
0	268.85
0.2	329.65
0.4	279.00
0.6	268.80

Fig. 9 displays the SEM images of the fractured surface of the unmodified and erbium-modified specimens. It is evident that the surface of the unmodified alloy after tensile testing (Fig. 9a) demonstrates the presence of irregular facets (cleavage planes) as well as some tearing ridges. The introduction of 0.2 wt.% and 0.4 wt.% erbium, as indicated in Figs. 9b and 9c, decreases the facet area and size due to the Si modification. Besides, the fracture surfaces for these specimens are covered by more tearing ridges, especially for the alloy with 0.2 wt.%

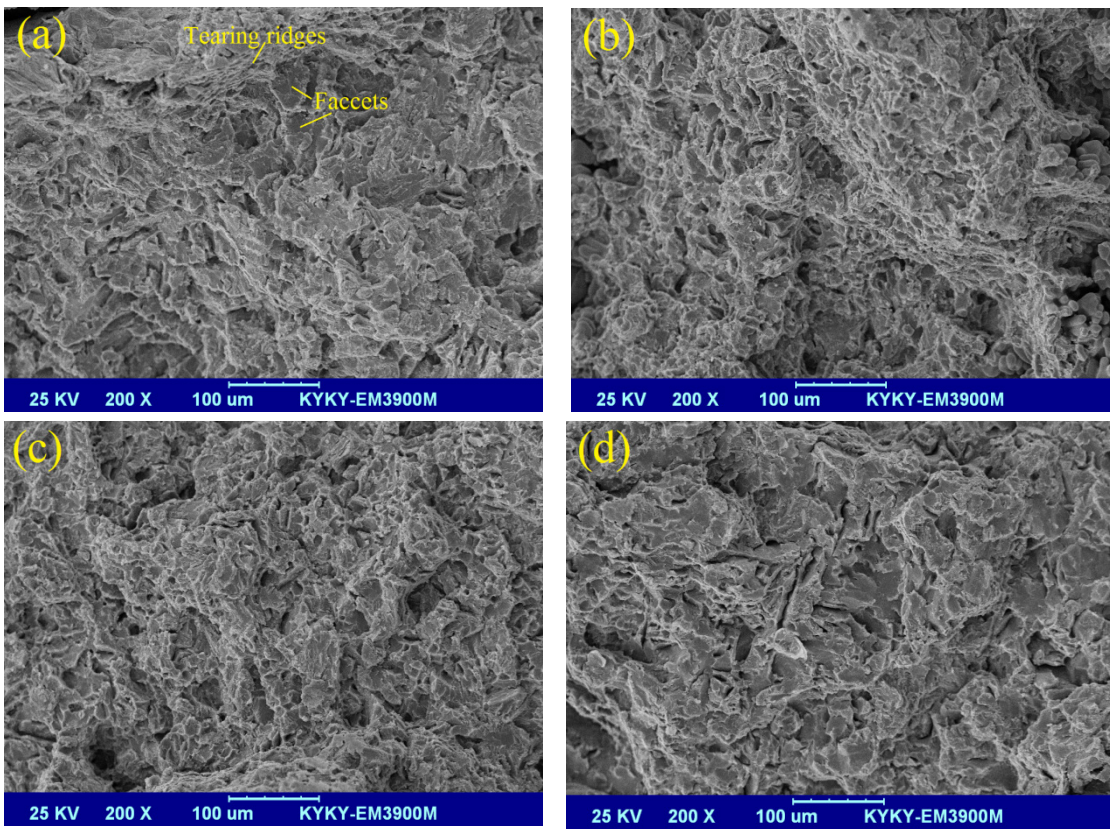

Fig. 9. SEM images of the fractured surface of the samples having various weight percentages of erbium a) 0, b) 2 wt.%., c) 4 wt.%., and d) 6 wt.%.

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erbium. On the other hand, at higher erbium contents (Figs. 9d), the surface is covered mostly by cleavage planes probably due to the presence of brittle Al3Er phase at a high level.

3.3. Wear Test Results

Fig. 10 shows the values of weight loss of specimens with various concentrations of erbium. It is obviously observed that 0.2 wt.% erbium-loaded specimen has the lowest weight loss. With the addition of 0.2 wt.% erbium, weight loss is reduced from 2.7 mg to 1.7 mg corresponding to a 58% enhancement in the wear resistance. This improvement can be described in terms of combined effects of α-Al refinement and Si modification. SEM micrographs of worn surfaces of unmodified and 0.2 wt.% erbium-modified alloys are depicted in Fig. 11. A mild wear regime is observable for both the unmodified and modified alloys. From these Figs, the grooves parallel to the sliding direction are observable, indicating the abrasive wear mechanism [26]. Also, plastic deformation regions can be found on the worn surface of specimens. In fact, two different zones are seen on the worn surfaces: smooth zones (marked as A), and craters or cavities (marked as B). In the A and B zones, the abrasive and adhesive wears are the prevailing mechanisms, respectively. Comparing the worn surfaces of base and modified alloys clearly indicates that the modified specimen is subjected to less severe damage than that of the unmodified alloy. This behavior can be explained by the microstructural changes due to the erbium addition as a microstructure modifier.

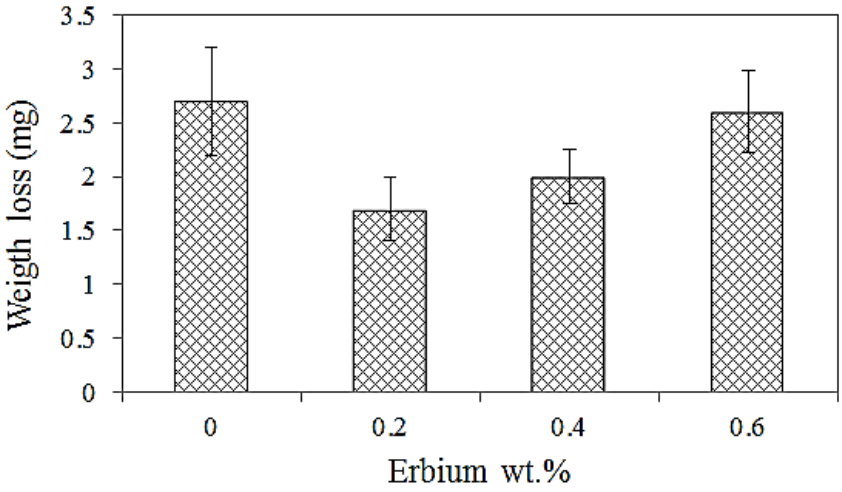

Fig. 10. The values of weight loss of samples with different concentrations of erbium.

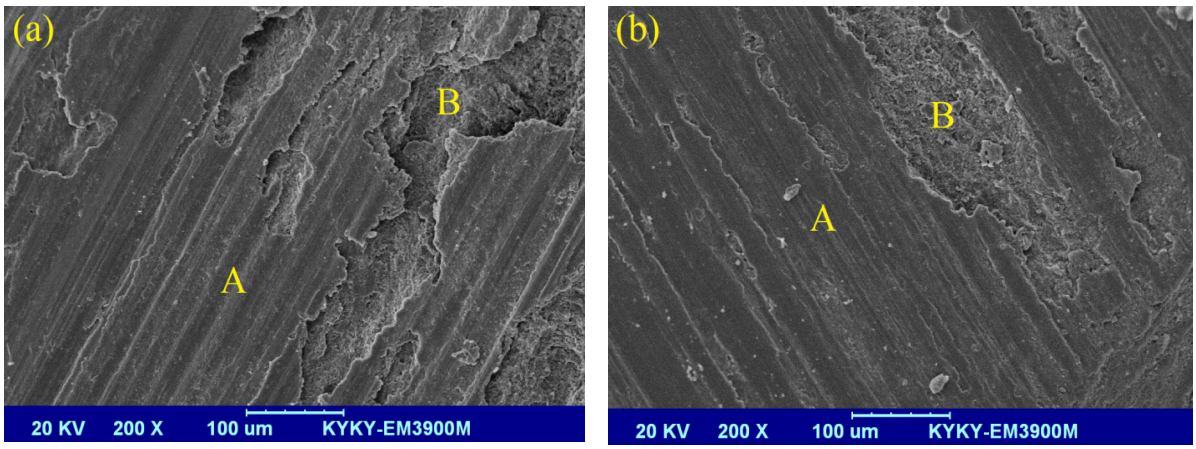

Fig. 11. SEM micrographs of worn surfaces of a) unmodified, and b) 0.2 wt.% erbium modified alloys.

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4. CONCLUSIONS

Herein, the effects of erbium at different weight percentages on the microstructural characteristics, tensile behavior and wear resistance of Al-7.5%Si-0.5%Mg were evaluated. The obtained results are as follows:

1. The introduction of erbium significantly modified the morphology of Si and reduced the size of α-Al and Si.
2. The tensile properties of the modified alloy were enhanced by adding a certain level of erbium. After modification with 0.2 wt.% erbium, the tensile strength enhanced about 31% from 126 to 165 MPa and elongation enhanced about 39% from 8.96% to 12.52%.
3. The wear resistance of alloy showed a significant improvement with the modification of microstructure. The wear resistance increased by 58% when the content of erbium was 0.2 wt.%.
4. This work showed that the addition of a minor addition of erbium is an effective method in achieving enhanced tensile and wear properties for the Al-Si-Mg alloys.

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