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Study on fracture behaviour of Al–15%Mg_2Si metal matrix composite with and without beryllium additions

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Abstract In this study, the influence of Beryllium (Be) content on the fracture behaviour of Al–15%Mg_2Si composite was investigated. The results showed an increase in mechanical properties with increasing of Be content. The stress–strain curves of samples showed a same category of serrations reflecting non-uniform deformation. Scanning electron microscopy was employed to examine the crack nucleation and fracture model. The results indicate that Al–15%Mg_2Si composite shows different behaviours of crack initiation and fracture for samples with and without Be. Differences observed in the fracture behaviour were attributed to microstructural changes as well as morphological aspects of primary Mg_2Si particles.

Introduction

In today's modern engineering, particulate metal matrix composites (PMMC's) play a crucial part in many applications especially in the aerospace, automobile as well as in other industries because of their excellent properties [1–3]. They exhibit higher ductility and lower anisotropy than fibre-reinforced MMCs, better dimensional stability over the corresponding unreinforced alloys and are economically cheaper by way of raw materials and fabrication process [4]. Recently, in situ techniques have been developed to fabricate Aluminium-based metal matrix composites which can lead to better adhesion at the interface and hence better mechanical properties [5]. In situ composites are materials where the reinforcing phase is formed within the matrix during composite fabrication [6]. Al-based composites reinforced with particulates of Mg_2Si have been introduced as a new group of composites that offer attractive advantages such as improved high temperature properties, reduced density and good corrosion resistance [7, 8]. However, the mechanical properties of the Al/Mg_2Si composites are not *suitable for most applications* due to the large size of Mg_2Si particles. Therefore, coarse primary Mg_2Si particles need to be refined to obtain *improved* mechanical properties. In the past years, many researches have enveloped around the modification of primary Mg_2Si particles [9–15]. In contrast, research efforts on the effects of modifiers on the fracture mechanisms of the composites have been rather limited. It was reported that Be, unfortunately a toxic metal, improves the mechanical properties of aluminium alloys [16]. In this study, the influence of Be on the fracture mechanism of the Al–15%Mg_2Si composites was investigated.

Experimental procedures

Commercial pure elemental Al, Mg and Si were used as starting materials to prepare a composition of Al–15%Mg_2Si. The parent ingots were remelted to prepare alloys with 0, 0.3 and 0.5%Be. Al–5%Be master alloy was added at 1023 °C. The melt was kept for 5 min for homogenisation. Degassing was accompanied by submerging dry C_2Cl_6. *After skimming the dross*, alloys were poured into a permanent mould, Fig. 1a, prepared according to B108-03a ASTM standard, preheated at 200 °C. The microstructural characteristics of the specimens were examined using an optical microscope. Tensile tests were carried out at a

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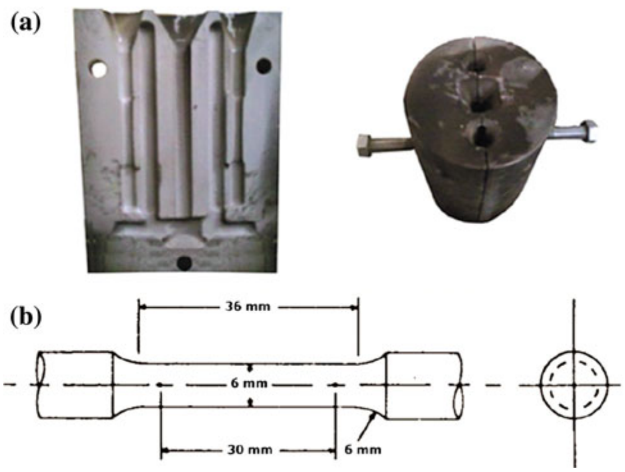

Fig. 1 **a** Cast iron mould used for in situ casting and **b** ASTM B557M-02a sub-size specimens used for tensile tests

constant cross-head speed of 1 mm/min at room temperature. The fracture surfaces of tensile test specimens were also examined with SEM.

Results and discussion

Microstructural observations

According to the Al–Mg_2Si equilibrium phase diagram (Fig. 2), Mg_2Si particles are the primary phase during solidification. Then α-Al and secondary Mg_2Si co-solidify from the liquid alloy in the narrow ternary phase area. The optical microstructures of Al–15%Mg_2Si with and without Be addition are shown in Fig. 3. It can be seen that the microstructure consists of Mg_2Si particles and bright α-Al phase in a matrix of Al–Mg_2Si eutectic cells. Because primary Mg_2Si acts as heterogeneous sites for the nucleation of α-Al to reduce the interfacial energy [14], and Mg_2Si particles, especially in samples with Be, were surrounded by a layer of α-Al phase.

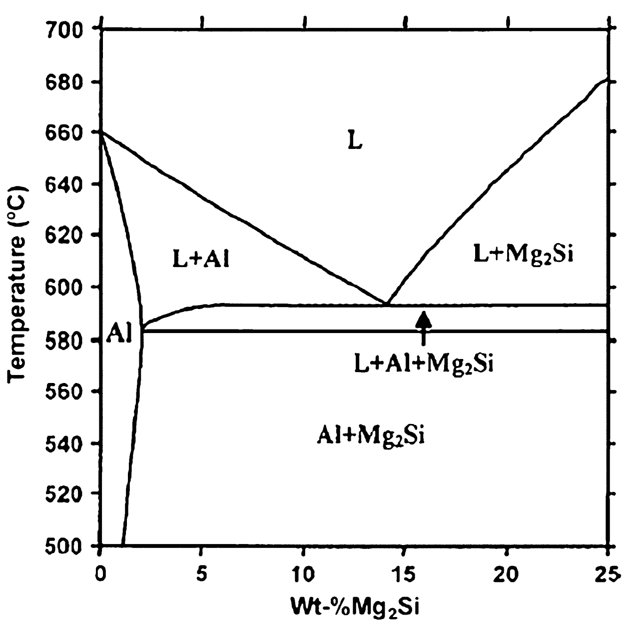

Fig. 2 Calculated equilibrium Al–Mg_2Si phase diagram: pseudoeutectic point at Al–13.9%Mg_2Si [9]

Figure 3 shows that in the presence of Be the morphology of primary Mg_2Si particles changes from irregular polygonal and starlike to a completely faceted and equiaxed shape. Also, it can be seen from Fig. 3 that Be decreases the size of primary Mg_2Si particles. Consequently, it can be inferred that Be limits the growth of nuclei of Mg_2Si particles. One possibility is that Be changes the surface energy of Mg_2Si crystals. It is clear from Fig. 3 that most of the coarse Mg_2Si primary crystals in an unmodified alloy have internal alpha phase, but the finer Mg_2Si particles in Be-modified alloys do not show this hopper morphology.

A decrease in the size and volume fraction of primary Mg_2Si (see Fig. 3) implies a shift of the eutectic point in the Al–Mg_2Si equilibrium diagram towards the higher Mg_2Si concentration. Further observations of Fig. 3 depict that the volume fraction of α-Al increased with increasing Be content but the eutectic cell area was appreciably reduced. This change could be achieved by intensifying the skewed coupled zone in the Al–Mg_2Si binary diagram [11]. Also, larger α-Al grains have been attributed to the wider ternary range in the phase diagram [11].

Stress–strain relationships and fracture toughness

For both specimens with and without Be, there is no softening and necking on the conventional stress–strain curve in Fig. 4. This type of failure indicates brittle behaviour of the alloys. The mechanical properties in percent of the respective properties of the reference material (Al–15%Mg_2Si base composite) are compiled in Fig. 5. The properties for the reference material are given in Table 1. It can be seen that increase of ultimate stress and elongation to fracture becomes appreciable with increasing Be content. However, increase of yield stress and energy density is more significant. To elucidate the data in Fig. 3 further, an assumption is made to calculate the toughness of the samples. The area under the stress–strain curve, UT, is approximated by the following equation [17]:

$$\mathrm{UT} \approx \frac{(\mathrm{YS} + \mathrm{UTS})\,\varepsilon_f}{2} \quad (1)$$

where YS is the yield stress, UTS the ultimate stress and ε_f is the strain to failure. It can be seen from Fig. 5, based on

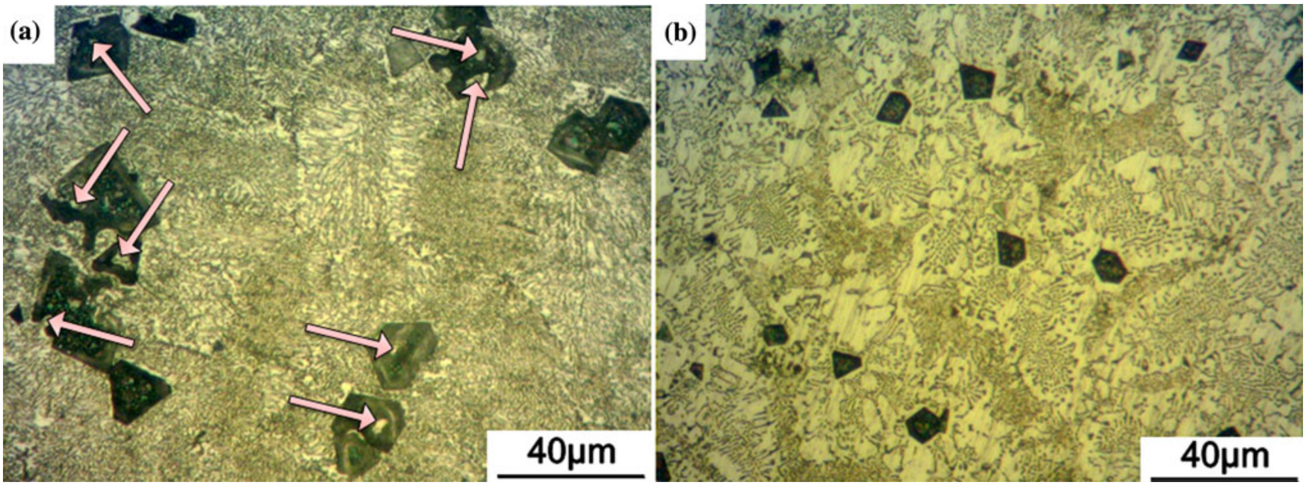

Fig. 3 The general microstructures of Al–15%Mg_2Si composites with different Be additions: **a** 0.0 wt% and **b** 0.5 wt% Be

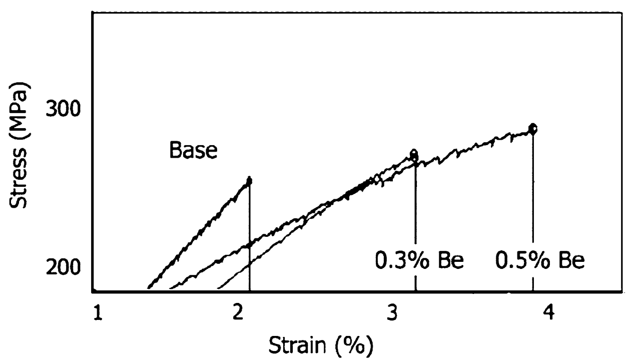

Fig. 4 Partial stress–strain curve of Al–15%Mg_2Si composite as a function of Be content

the approximate values of the area under the stress–strain curves that the toughness of samples with 0.5%Be is about 2.2 times that of base alloys.

As it can be seen, the specimens containing Be have superior mechanical properties in comparison with the base composite. The higher strength and higher fracture toughness of the composites with Be can be related to the distribution of refined Mg_2Si particles; According to Griffith's theory, a particle breaks when its fracture stress exceeds the Griffith criterion given by

$$\sigma_c = \frac{k_c}{\sqrt{d}} \quad (2)$$

where k_c is the fracture toughness of the particles and d is the diameter of the particle. Thus, the refined structure has a higher strength.

The stress–strain curves of the both unmodified and Be-modified alloys exhibit a serrated yielding behaviour (Fig. 4). This plastic instability in Al–Mg_2Si composites has been also reported by Hadian et al. [11] and interpreted

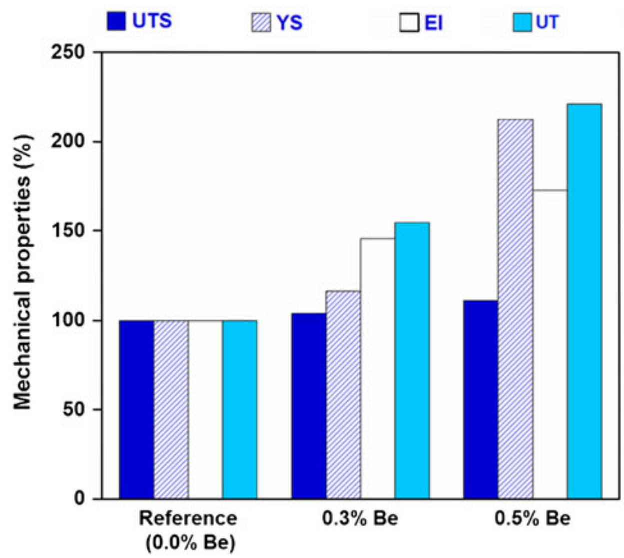

Fig. 5 Mechanical properties of Al–15%Mg_2Si composite as a function of Be content. *UTS* ultimate stress; *YS* yield stress; *El* elongation; and *UT* area under the stress–strain curve

Table 1 Mechanical properties for the reference material (Al–15%Mg_2Si base composite)

Ultimate tensile stress UTS (MPa)	Yield stress YS (MPa)	Elongation to failure El (%)	Calculated toughness, UT (MPa)
252.0	49.3	2.2	3.31

as Portevin–LeChateliers effect. Portevin–LeChateliers's observations of this behaviour in Al–Mg alloys have been attributed to solute atoms or vacancy interactions with lattice dislocations [18].

SEM fractography

Low magnified fracture surfaces of different castings are shown in Fig. 6. As it is clear, fracture of the alloys has been occurred in a brittle manor. Figure 6a and c shows an irregular and extremely inhomogeneous fracture surface of the unrefined alloy, whilst the fracture of Be-refined alloy shows a more uniform pattern, Fig. 6b and d. This pattern stands for appropriate function (e.g. more homogeneous distribution, more refined and uniform primary Mg_2Si particles) of Be in Al–15%Mg_2Si composite. Figure 7 shows the fracture surfaces of the unmodified and Be-modified specimens at higher magnifications. The fracture features exhibited by the samples containing Be confirm to the ductility results obtained from tensile testing. Lesser number of cleavage fractures of Mg_2Si particles suggests a decrease in the degree of brittle nature of fracture. In the base alloy, coarsened primary Mg_2Si particles caused high levels of stress concentration and consequently the reduction of tensile properties. However, Be decreases the size of Mg_2Si particles as well as *eliminates the formation of* alpha phase inside them. Formation of α-Al inside primary particles, indicated with arrows in Fig. 3, *produces the sites* that act as *stress concentrators promoting crack nucleation.* Therefore, the tensile properties of the base alloy are lower than that of the Be-modified specimens.

The reinforcement particles exposed on the fracture surface of unmodified samples were generally broken (see Fig. 7a and b). Fracture of Mg_2Si particles causes the formation of cleavage facets and lots of secondary cracks in the fracture surface, clearly implying a brittle fracture mode. However, in samples modified by Be, cracks take place preferentially along the interface of Mg_2Si particles and matrix, and propagate by shearing. Particle–matrix interface debonding thus acted as a preferential mechanism of fracture nucleation, Fig. 7c and d.

It is well known that under tensile straining condition, the ductility of discontinuously reinforced MMCs is heavily affected by the progression of reinforcement damage [19]. From current knowledge it is, therefore, supposed that the increase in ductility as well as the improvement in strength are brought about by a lower damage sensitivity induced by Be additions. From concurrent analysis of fracture surfaces, it was elucidated that

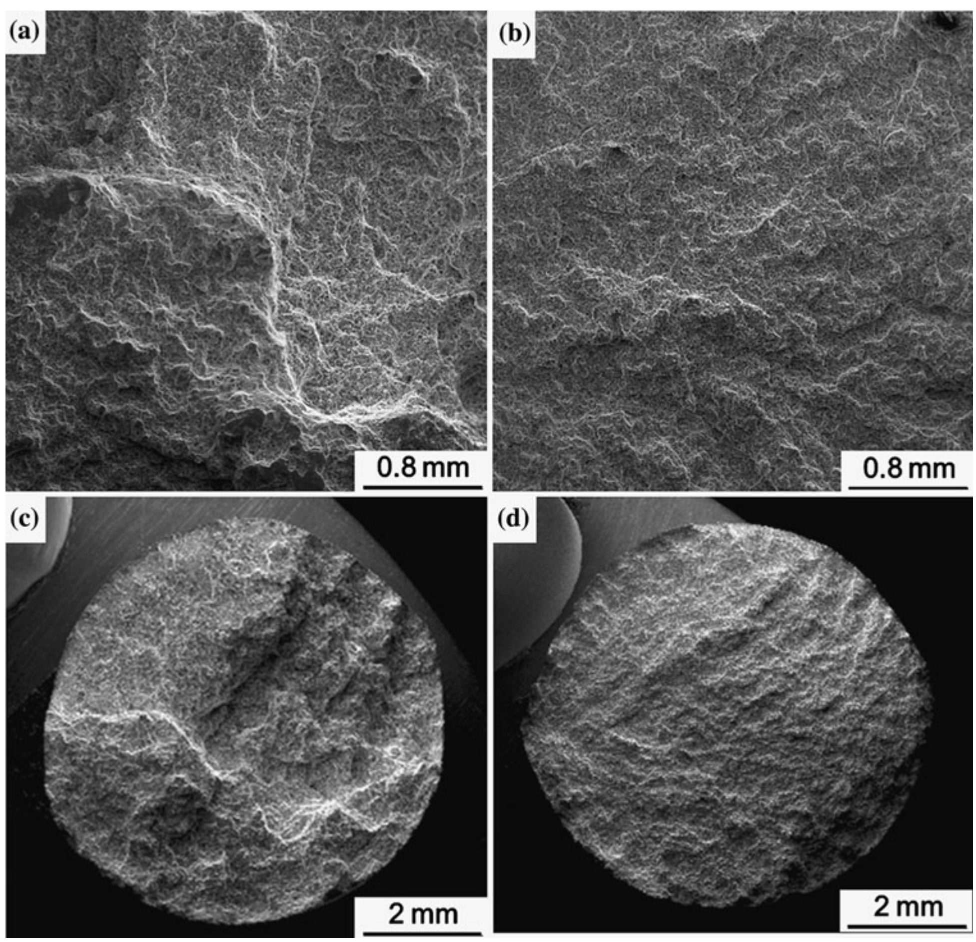

Fig. 6 Low magnified fracture surfaces of Al–15%Mg_2Si composite with: **a**, **c** 0.0 wt%; and **b**, **d** 0.5 wt% Be

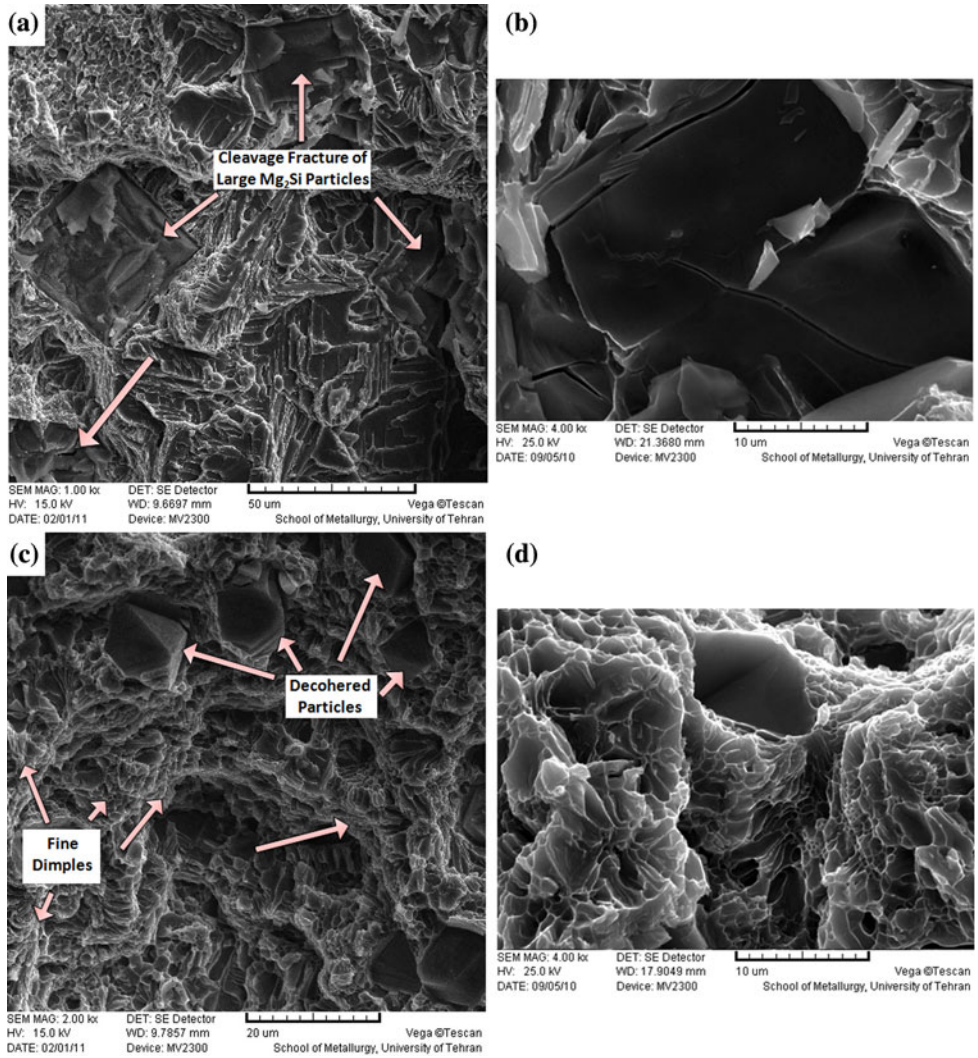

Fig. 7 Fracture surfaces of Al–15%Mg_2Si composite with: **a**, **b** 0.0 wt%; and **c**, **d** 0.5 wt% Be

the rise in ductility corresponded to a shift in damage behaviour from crack nucleation induced by particle cracking towards formation of voids due to preferential decohesion of reinforcement particles from the matrix at interface sites. Growth and eventual coalescence of the fine microscopic voids result in dimple formation (Fig. 7c and d). Overall, the SEM observations on the fractured surfaces show a good agreement with the ductility data given in Fig. 5.

Based on the microstructure changes observed in the process of deformation, the following model of fracture mechanism is proposed for unmodified composite (Fig. 8a–d).

(a) The microstructure in the initial state is characterized by large Mg_2Si particles, mainly with the internal alpha phase.
(b) With increasing tensile load, local cracks initiate inside Mg_2Si particles and at sharp corners of particles.
(c) In further increasing deformation of materials, some of the Mg_2Si particles break.
(d) Finally, specimens ruptured by cracks propagating in the matrix.

Also, There are four stages of fracture in Be-modified composites (Fig. 9a–d):

(a) The general microstructure of the Be-modified composite has refined Mg_2Si particles without any central alpha phase.
(b) Applying the *tensile stress*, local cracks form at *edges and corners* of particles.
(c) With progressively *increasing deformation*, cracks propagate along the interface of Mg_2Si particles and matrix, so some of the Mg_2Si particles decohere from the matrix.
(d) The final fracture results from the growth and coalescence of the cracks.

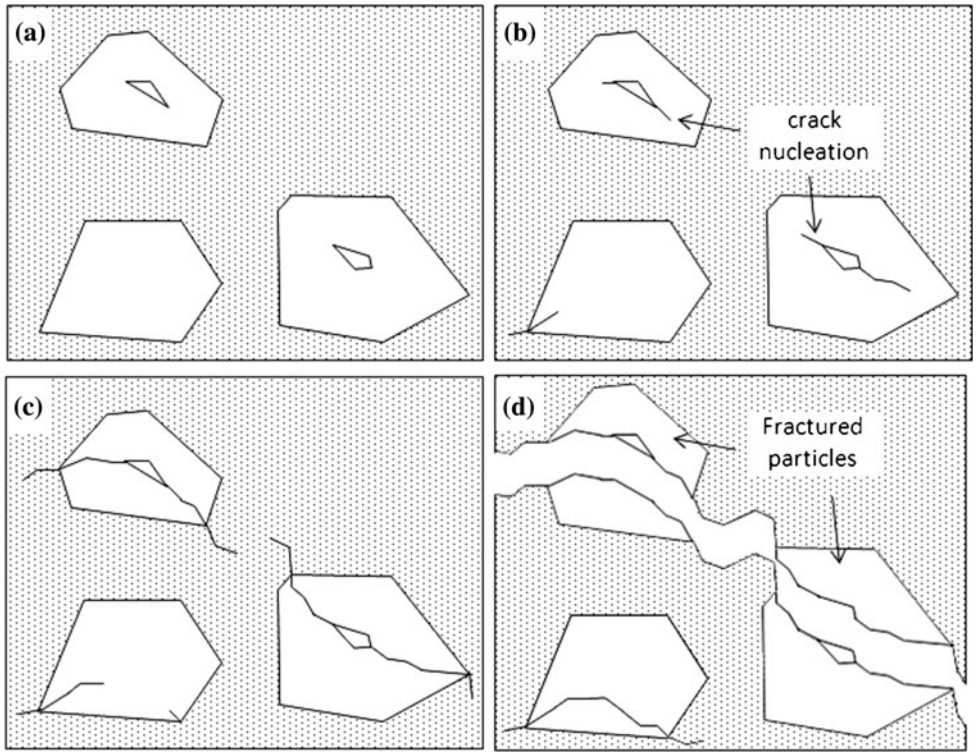

Fig. 8 **a–d** Schematic showing the fracture mechanism for the composite with unmodified particles

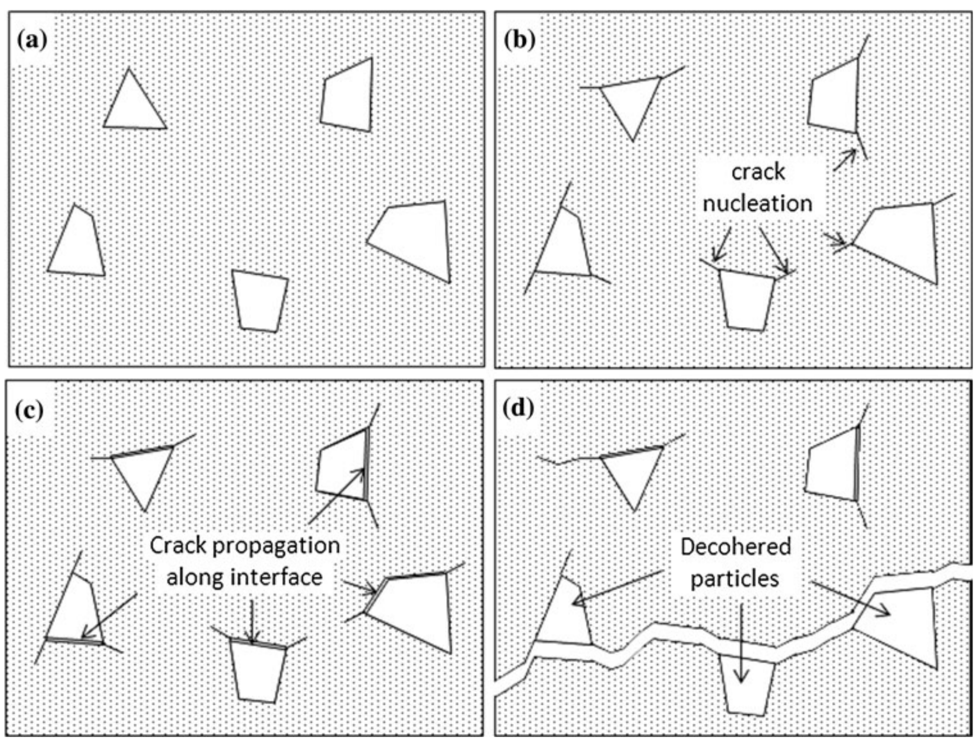

Fig. 9 **a–d** Schematic showing the fracture mechanism for the composite with modified particles

Conclusion

The effects of Be on the fracture behaviour of Al–15%Mg_2Si composite were investigated. The following conclusions can be drawn:

1. Be improved UTS and elongation values of the composite. However, increase of yield stress and energy density was more dramatic.
2. The stress–strain curves of the both unmodified and Be-modified composites showed a serrated yielding behaviour.

3. Be changes the irregular and extremely inhomogeneous fracture surface of the unrefined alloy to the more uniform pattern.
4. High levels of stress concentration induced by coarsened Mg_2Si particles caused the reduction of tensile properties in unmodified samples.
5. In the Be-modified alloys, α-Al phase did not form inside primary particles thereby the stress concentrators sites decreased.
6. In the unmodified composite, with increasing tensile stress, local cracks initiate inside Mg_2Si particles and at sharp corners of particles but in modified samples they form at edges and corners of the particles.
7. In the base alloys, cracks propagate by breaking of large Mg_2Si particles but in specimens containing Be by decohesion of particles.

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