Tensile strength, ductility and fracture of magnesium–silicon alloys

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Tensile tests were performed between 293–573 K in order to investigate the mechanical properties of cast and extruded Mg–Si alloys. For the cast materials, Mg–high Si ($\geqslant$10 wt %) alloys showed lower values of the highest tensile strength at temperatures up to 373 K, as compared to pure Mg and Mg–low Si ($<$10 wt %) alloys, whereas the strength at 573 K increased with increasing Si content. The addition of aluminum and zinc to the alloys was effective in increasing the strength. The fact that the Mg–high Si alloys showed lower strength than the Mg–low Si alloys was because a high volume of Mg_2Si embrittled the Mg–Si alloys. Microstructural investigations revealed that the particles of Mg_2Si were coarse for the cast materials and fracture of the particles was caused by deformation. The mechanical properties of the cast materials were improved by hot extrusion. Microstructural refinement by hot extrusion was responsible for the improvement of the mechanical properties.

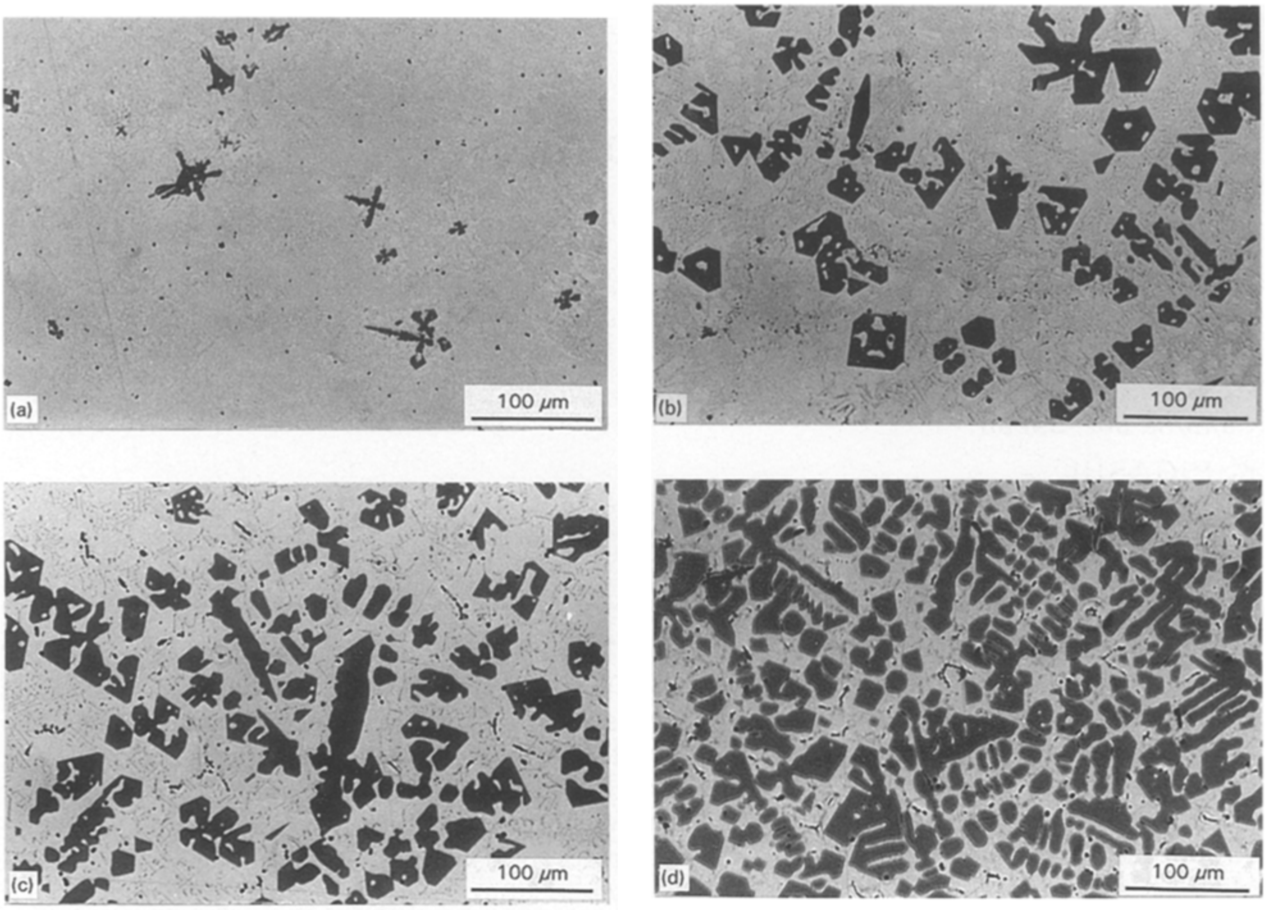
1. Introduction

Magnesium alloys have great potential as structural materials because of their low density. Recently, there have been significant advances in the development of magnesium alloys [1]. For example, magnesium alloys containing rare earth metals such as gadolinium or terbium show high elevated temperature strength [2]. However the alloys containing rare earth metals are considered to be expensive due to the cost of the rare earth metals. Recently Beer *et al.* [3] discussed thermophysical and mechanical properties of cast Mg–Si alloys. Light metals containing the intermetallic compound Mg_2Si have a great potential as a heat resisting light alloy since Mg_2Si exhibits a high melting temperature, low density, high hardness and a low thermal expansion coefficient [3, 4]. In addition since Si is much cheaper than rare earth metals, Mg–Si alloys are commercially interesting.

The mechanical properties of Mg–Al–Zn alloys have been improved by ageing treatments [5, 6]. The improved properties were attributed to a refinement in the precipitate dispersion [7]. However, since Mg_2Si shows little solubility in the temperature range around the melting point of magnesium, it is difficult to achieve a refinement in the precipitate dispersion by an ageing treatment. Recently, it was reported that the mechanical properties were improved by hot extrusion in a Mg–Si–Al alloy [8]. This was attributed to microstructural refinement caused by the hot extrusion. Currently however there are few reports on the mechanical properties of Mg–Si alloys. In this work, tensile tests were carried out between 293–573 K and mechanical properties were investigated in cast Mg–Si alloys with a wide range of Si content (0 $\sim$ 21 wt % Si). Furthermore the Mg–Si alloys were extruded and mechanical properties of the extruded materials were compared with those of the cast materials.

2. Experimental procedures

A pure Mg, Mg–Si (Si wt % = 2.4, 6.3, 10.1, 17.9, 20.8) alloys, a Mg–Si–Al (Si wt % = 12.6, Al wt % = 4.2) and a Mg–Si–Zn (Si wt % = 4.3, Zn wt % = 4.0) alloy were cast in a green sand mould. The Mg–Si–Al and the Mg–Si–Zn were prepared in order to investigate the effects of alloying with aluminium and zinc on the mechanical properties. Bars of 40 mm diameter of the pure Mg, the Mg–Si (Si wt % = 10.1 and 2.08) and the Mg–Si–Al alloys were machined from the cast ingots and then the bars were extruded at 823 K with a reduction ratio of 100:1.



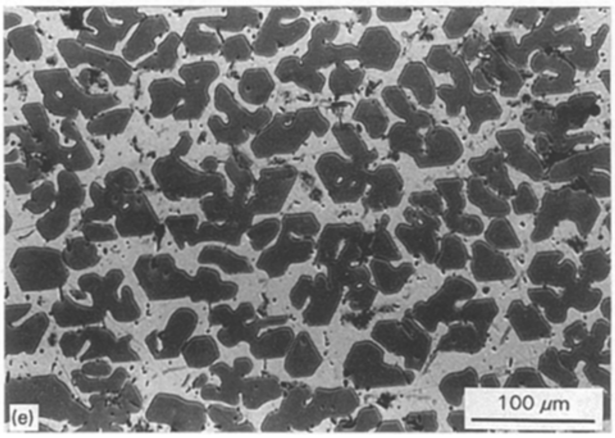


Figure 1 Microstructures of (a) the cast Mg–2 wt % Si, (b) the cast Mg–6 wt % Si, (c) the cast Mg–10 wt % Si, (d) the cast Mg–18 wt % Si and (e) the cast Mg–21 wt % Si.

The Vickers hardness at room temperature was examined using an average of about 10 measurements. Tensile specimens were cut from the cast ingots and the extruded bars. The specimens had a gauge length of 15 mm and a gauge diameter of 2.5 mm for room temperature tension tests and a gauge length of 5 mm and a gauge diameter of 2.5 mm, respectively, for elevated temperature tension tests. The tensile tests were carried out between 293–573 K. Room temperature (293 K) tension tests were carried out at a strain rate of $1.1 \times 10^{-3}\ s^{-1}$. The elevated temperature tension tests were carried out at a strain rate of $3.3 \times 10^{-3}\ s^{-1}$. The tensile axis was selected to be parallel to the extrusion direction for the extruded materials. Optical light microscopy and a scanning electron microscope (SEM) were used to investigate microstructures.

3. Results and discussion

3.1. Cast Mg–Si alloys

The microstructures of (a) the cast Mg–2 wt % Si, (b) the cast Mg–6 wt % Si, (c) the cast Mg–10 wt % Si, (d) the cast Mg–18 wt % Si and (e) the cast Mg–21 wt % Si are shown in Fig. 1. The Mg_2Si particles were coarse and were not granular in shape because of dendritic solidification. There were pores for the cast materials. The volume fraction of pores appears to increase with the Si content.

The variation in Vickers hardness at room temperature as a function of the Si content for the cast Mg–Si is shown in Fig. 2, where the data are obtained using an average of about 10 measurements. The hardness increased from 37 to 139 Hv with increasing Si content in the range investigated.

The variation in the maximum tensile strength as a function of the Si content for the cast Mg–Si alloys is shown in Fig. 3. The alloys with high Si contents ($\geqslant$ 10 wt %) showed lower values of the ultimate tensile strength between 293–373 K, compared with the alloys with low Si contents ($<$10 wt %). For example, the Mg–6 wt % Si showed an ultimate tensile strength of 110 MPa at room temperature, whilst the ultimate tensile strength at room temperature of the Mg–21 wt % Si was only 88 MPa. On the other hand, the ultimate tensile strength at

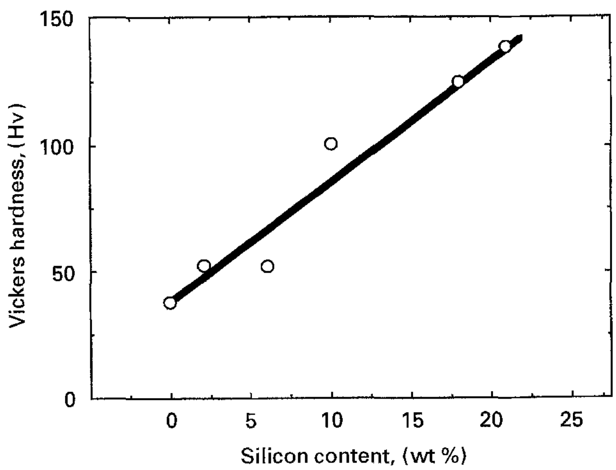


Figure 2 The variation in Vickers hardness at room temperature as a function of the Si content for the cast Mg–Si.

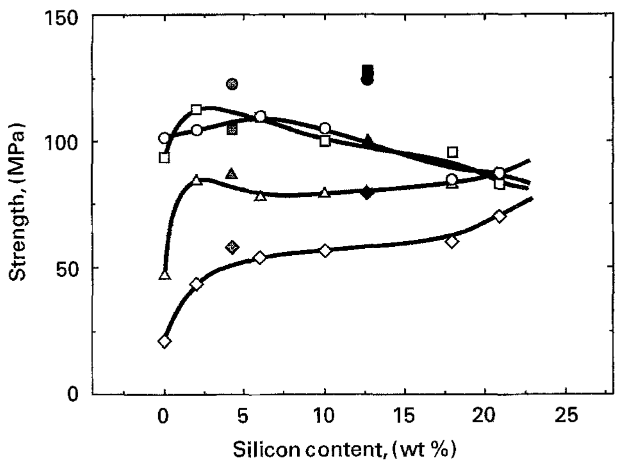


Figure 3 The variation in the maximum tensile strength as a function of the Si content for the cast (a) Mg–Si alloy at (○) room temperature, (□) 373 K, (△) 473 K and (◇) 573 K; (b) the Mg–Si–Zn alloy at (◎) room temperature (⊞) 373 K, (△) 473 K and (◇) 573 K; (c) the Mg–Si–Al alloy at (●) room temperature, (■) 373 K, (▲) 473 K and (◆) 573 K.

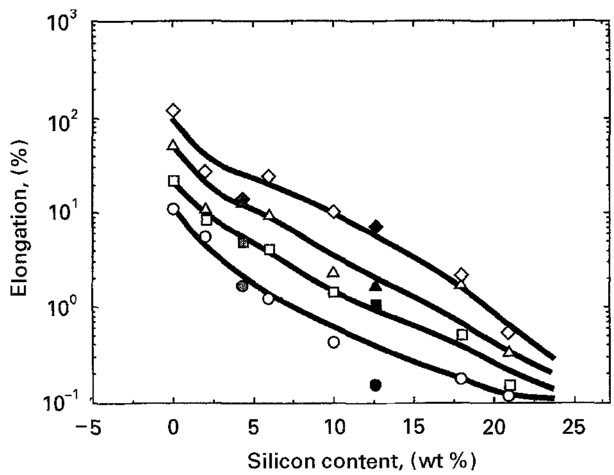


Figure 4 The variation in the elongation to failure as a function of the Si content for the cast (a) Mg–Si alloy at (○) room temperature, (□) 373 K, (△) 473 K and (◇) 573 K; (b) Mg–Si–Zn alloy at (◎) room temperature, (⊞) 373 K, (△) 473 K and (◇) 573 K; (c) Mg–Si–Al alloy at (●) room temperature, (■) 373 K, (▲) 473 K and (◆) 573 K.

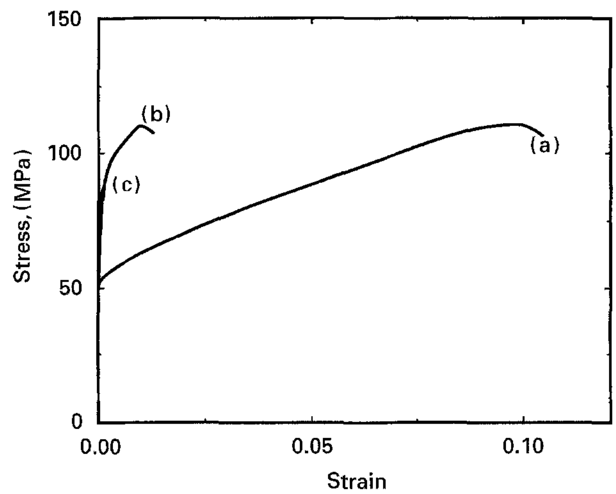


Figure 5 The stress–strain curves at room temperature for (a) the cast pure Mg, (b) the cast Mg–6 wt % Si and (c) the cast Mg–21 wt % Si.

573 K continuously increased with the Si content in the range investigated.

The variation in the elongation to failure as a function of the Si content for the cast Mg–Si alloys is shown in Fig. 4. The elongation to failure decreased with increasing Si content, independent of temperature in the range investigated. In particular, the Mg–21 wt % Si showed lower elongations of less than 1% between 293–573 K. The stress–strain curves at room temperature are shown in Fig. 5 for (a) the cast pure Mg, (b) the cast Mg–6 wt % Si and (c) the cast Mg–21 wt % Si. It is found from Fig. 5 that the lower strength of the Mg–high Si alloy is attributed to very low ductility. A high volume of Mg_2Si embrittled the Mg–Si alloys, so that the alloys with high Si contents showed the poor tensile properties. Therefore an improvement of the poor ductility is required for the Mg–Si alloys.

Fracture surfaces of specimens deformed to failure at room temperature are shown in Fig. 6 for (a) the cast pure Mg, (b) the cast Mg–6 wt % Si and (c) the cast Mg–21 wt % Si. Mg_2Si was observed on the fracture surfaces for the Mg–Si alloys. In particular, many Mg_2Si particles were found on the fracture surface which was relatively flat for the cast Mg–21 wt % Si. It is suggested that the Mg_2Si particles provide the sites for fracture initiation. Relatively coarse Mg_2Si particles were fractured by deformation (Fig. 7). The fracture of the particles is because of stress–strain concentrations around the particles [9]. The propagation of the cracks from the sites of the fracture of the particles results in a low ductility for the alloys. Very low ductility of the high Si alloys appears to be caused by early formation and propagation of the cracks due to the smaller gaps between particles.

Beer *et al.* [3] showed that an improvement in the strength of Mg–Si alloys could be produced by alloying with aluminium. It is found from Fig. 3 that additions of zinc as well as aluminium to the alloys are effective for creating high strength in the temperature range investigated. This is due to either solid solution strengthening and/or precipitation strengthening [3].

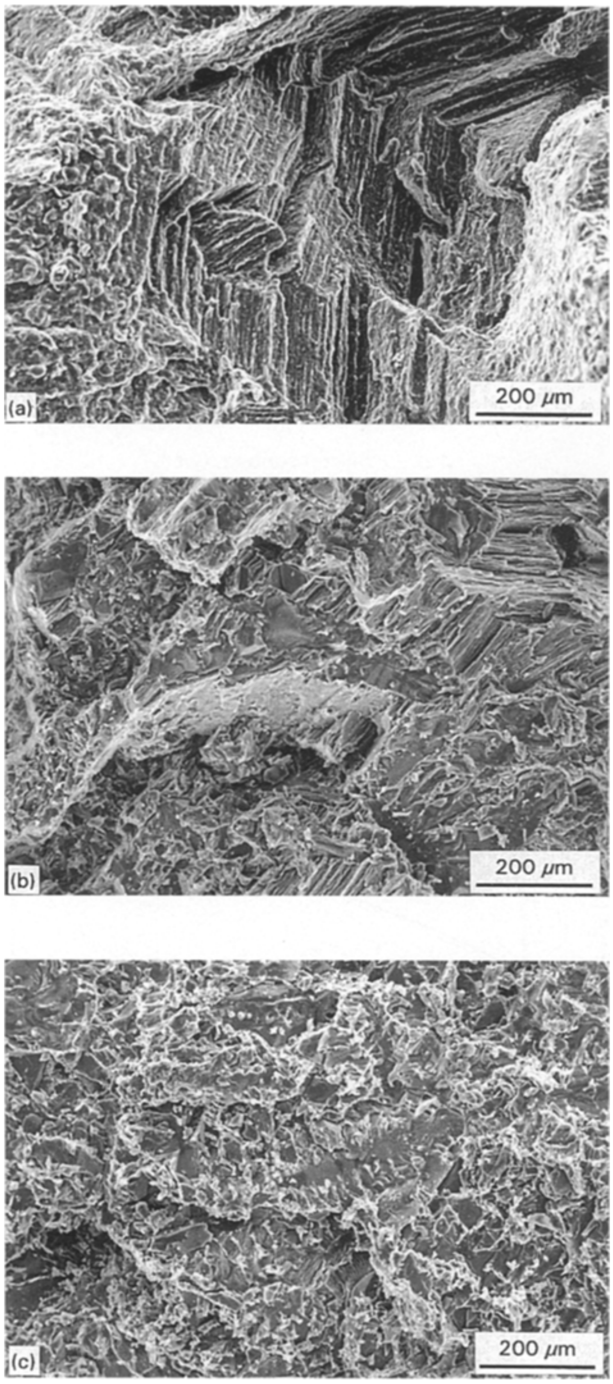


Figure 6 Fracture surfaces of specimens deformed to failure at room temperature for (a) the cast pure Mg, (b) the cast Mg–6 wt % Si and (c) the cast Mg–21 wt % Si.

On the other hand, alloying with aluminium and zinc had little effect on ductility (Fig. 4).

3.2. Effects of hot extrusion

The microstructures of (a) the extruded pure Mg, (b) the extruded Mg–10 wt % Si and (c) the extruded Mg–21 wt % Si are shown in Fig. 8, where the samples are etched. The particles of Mg_2Si were dispersed more finely for the extruded materials, when compared with the cast materials. The increased fine dispersion of the particles is attributed to breakdown of the particles by hot extrusion. In addition an inspection of Fig. 8 reveals that the grain refinement was achieved by hot extrusion for the Mg–Si alloys,

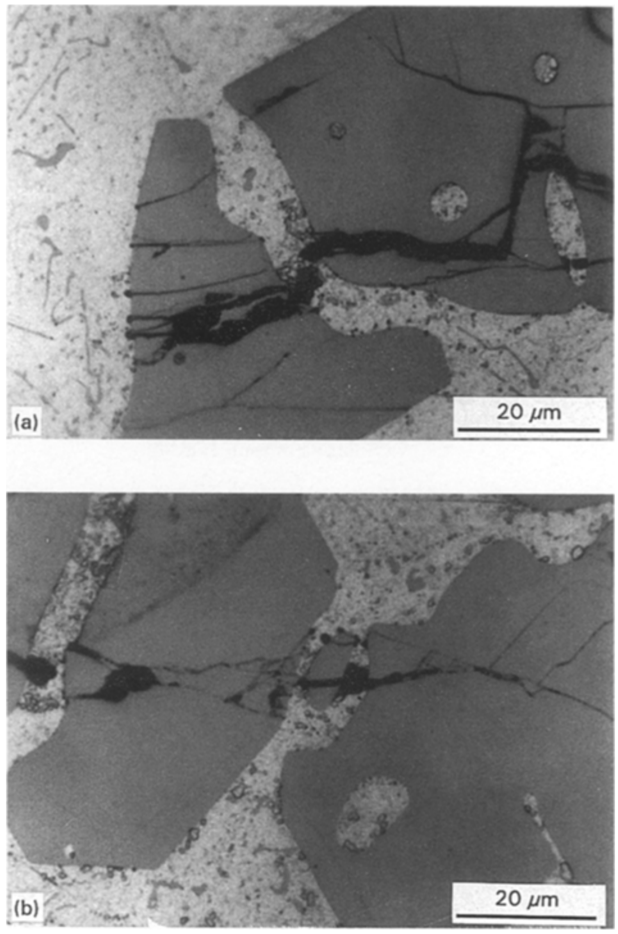


Figure 7 Micrographs of the specimens deformed to failure at room temperature in the (a) Mg–18 wt % Si and (b) the Mg–21 wt % Si, showing fracture of the Mg_2Si particles.

compared with the pure Mg. It is well known that large particles (> about 1 μm) stimulate nucleation for recrystallization [10, 11]. In this work, since the Mg_2Si particles very much larger than 1 μm, the particles likely stimulated nucleation for recrystallization. Furthermore the particles appear to restrict grain growth. Therefore stimulation of recrystallization and restriction are grain growth by the presence of the particles are probably responsible for the grain refinement in the Mg–Si alloys.

The variation in the ultimate tensile strength between 293–573 K of the cast materials and the extruded materials as a function of temperature is shown in Fig. 9 for the pure Mg, the Mg–10 wt % Si, the Mg–21 wt % Si and the Mg–13 wt % Si–4 wt % Al. It is found that in general the strength was improved by hot extrusion, the exception being the data at 573 K of the Mg–10 wt % Si. The refinement in structure likely caused the improvement in strength by hot extrusion. Not surprisingly, a higher strength at 573 K was not obtained for the extruded Mg–10 wt % Si, compared with the cast material. This is likely associated with grain boundary sliding because grain refinement was achieved for the extruded Mg–10 wt % Si.

It is noted that the extruded Mg–10 wt % Si showed higher strength than the extruded pure Mg at any given testing temperature. For the cast material, the room temperature strength of the Mg–10 wt % Si was almost the same as that of the pure Mg. It is therefore

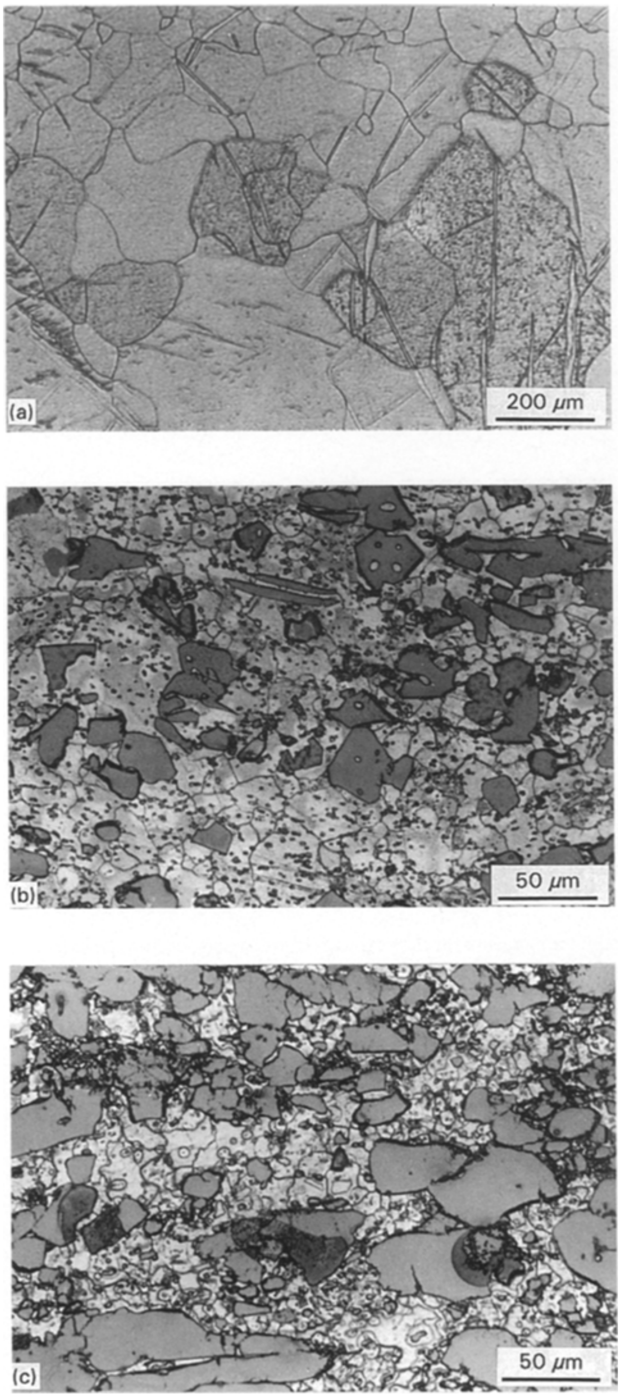


Figure 8 Microstructures of (a) the extruded pure Mg, (b) the extruded Mg–10 wt % Si and (c) the extruded Mg–21 wt % Si, where the samples are etched.

seen that any effect Mg_2Si has on the strength is enhanced by hot extrusion. The extruded Mg–21 wt % Si showed higher strength than the extruded pure Mg between 473–573 K, however, the extruded Mg–21 wt % Si showed lower strength than the extruded pure Mg between 293–373 K. More refinement in the structure appears to be required to achieve high strength for the Mg–21 wt % Si. The extruded Mg–13 wt % Si–4 wt % Al showed the highest strength in the temperature range investigated. It is seen that alloying with aluminium is effective for high strength.

The variation in the elongation to failure between 293–573 K of the cast materials and the extruded materials is shown in Fig. 10 for (a) the pure Mg,

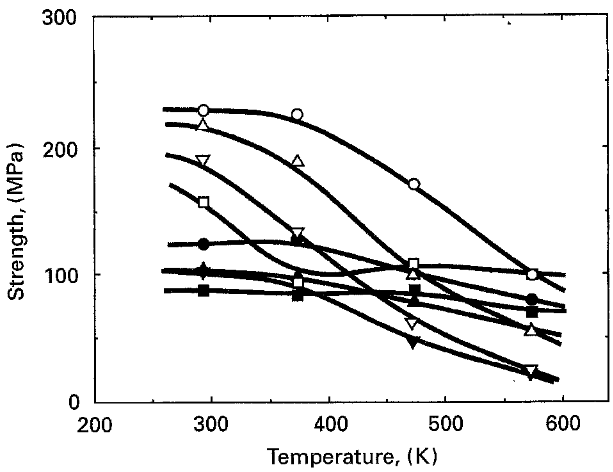


Figure 9 The variation in the ultimate tensile strength between room temperature and 573 K of the cast materials and the extruded materials as a function of temperature. The extrusion data are: (▽) Mg, (△) Mg–10 wt % Si, (□) Mg–21 wt % Si and (○) Mg–13 wt % Si–4 wt % Al. The cast data are: (▼) Mg, (▲) Mg–10 wt % Si, (■) Mg–21 wt % Si and (●) Mg–13 wt % Si–4 wt % Al.

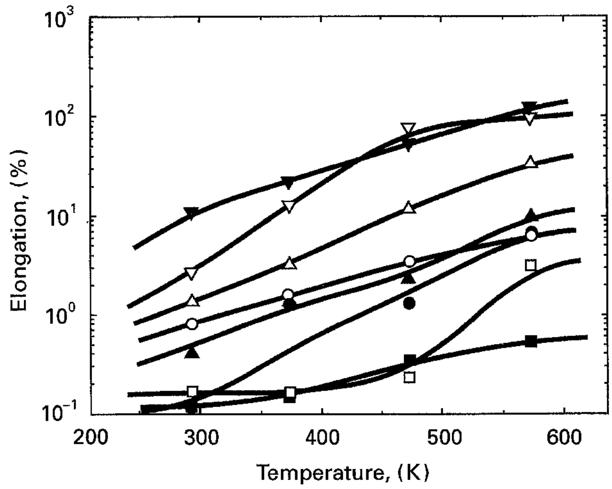


Figure 10 The variation in the elongation to failure between room temperature and 573 K of the cast materials and the extruded materials as a function of temperature. The extrusion data are: (▽) Mg, (△) Mg–10 wt % Si, (□) Mg–21 wt % Si and (○) Mg–13 wt % Si–4 wt % Al. The cast data are: (▼) Mg, (▲) Mg–10 wt % Si, (■) Mg–21 wt % Si and (●) Mg–13 wt % Si–4 wt % Al.

(b) the Mg–10 wt % Si, (c) the Mg–21 wt % Si and (d) the Mg–13 wt % Si–4 wt % Al. It is seen that the poor ductility was improved by hot extrusion for the Mg–Si alloys, in particular, for the Mg–10 wt % Si. The fracture surfaces of the specimens deformed to failure at room temperature are shown in Fig. 11(a, c) for the cast Mg–10 wt % Si and Fig. 11(b, d) for the extruded Mg–10 wt % Si, where (a) and (b) are low magnification micrographs and (c) and (d) are high magnification micrographs. It was observed that Mg_2Si appears on both fracture surfaces. The fracture mechanism created by the Mg_2Si particles providing the sites for fracture initiation appears to be the same for both the cast material and the extruded material. However, there was evidence of microstructural refinement for the extruded material. A reduction in the grain size has been shown to enhance the ductility at

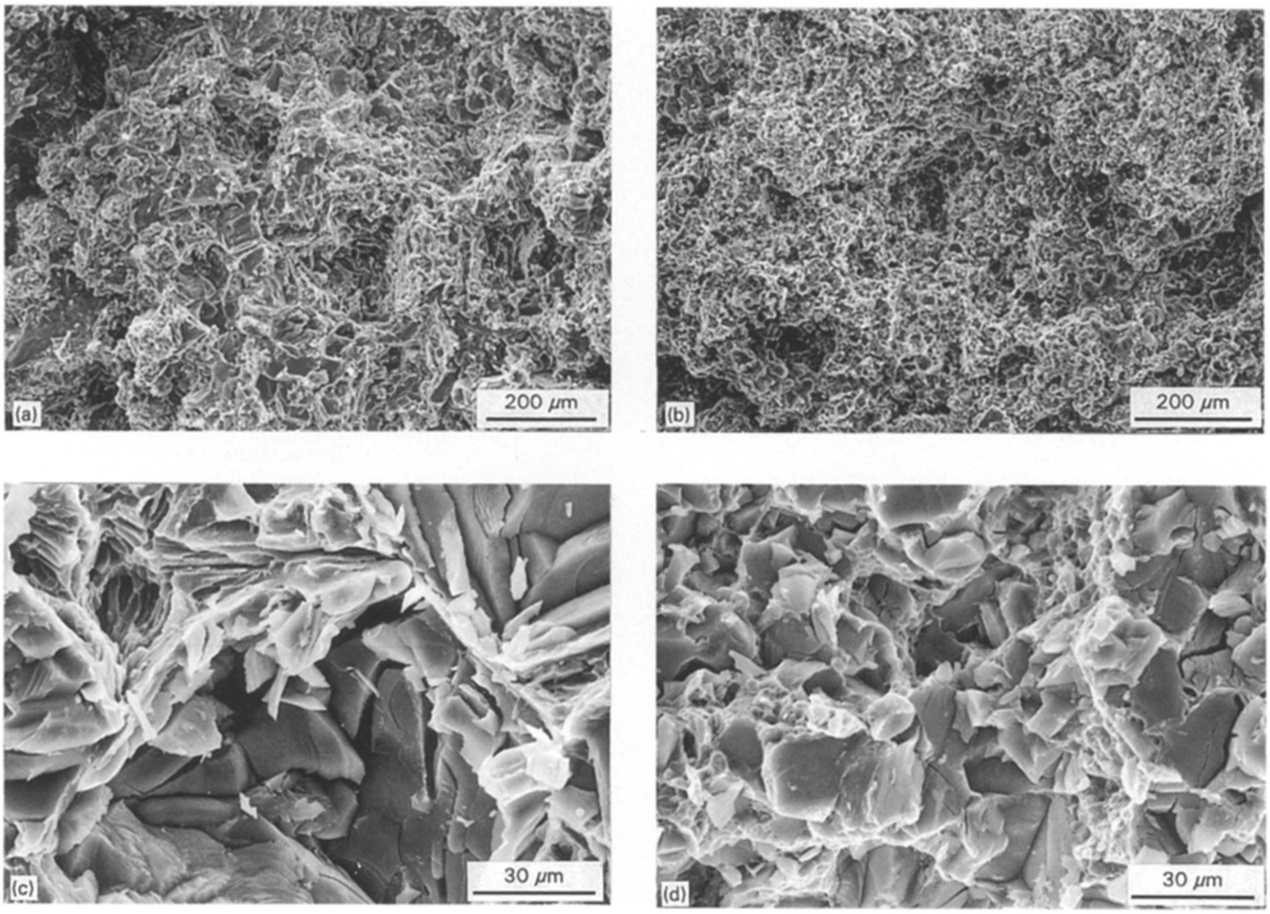


Figure 11 The fracture surfaces of the specimens deformed to failure at room temperature for the cast Mg–10 wt % Si (a, c), and the extruded Mg–10 wt % Si (b, d), where (a) and (b) are low magnification micrographs, (c) and (d) are high magnification micrographs.

room temperature for magnesium [12]. It is possible therefore that in our case the grain refinement contributed to the improvement of ductility. In addition, the Mg_2Si particles were dispersed more finely by hot extrusion. Fine dispersion of the particles reduces local stress concentrations, which results in the restriction of the particle fracture. Therefore the refinement in structure is responsible for the improvement of ductility by hot extrusion.

There are a few reported studies on the mechanical properties of Mg–Si alloys [3, 13]. For example, Beer *et al.* [3] processed Mg–Si alloys by ingot metallurgy method and measured the elevated temperature mechanical properties of the cast Mg alloys containing large volume fractions of Mg_2Si. Raghunathan and Sheppard [13] prepared rapidly solidified Mg–Si powders and then fabricated a Mg–1.5 wt % Si alloy by the powder metallurgy method. These reported values are compared to our measurements in Fig. 12. It is seen that the extruded Mg–Si–Al showed a higher elevated temperature strength when compared with cast materials containing large volume fractions of Mg_2Si. The fact that the P/M Mg–Si alloy showed a lower strength is attributed to its lower Si content.

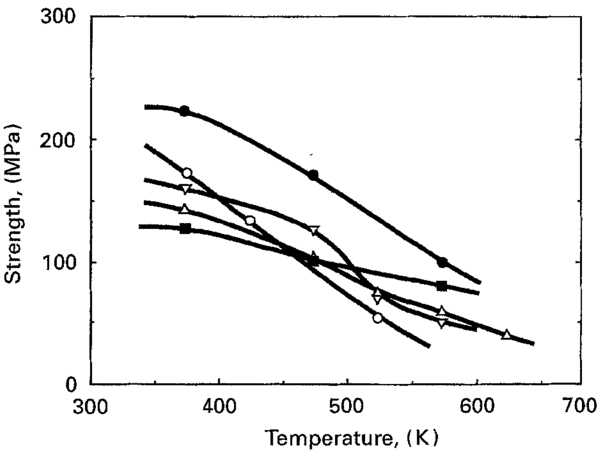


Figure 12 The variation in the ultimate tensile strength of Mg–Si alloys at elevated temperatures. The data from this investigation are: (●) Mg–13 wt % Si–4 wt % Al (extrusion) and (■) for the same composition but cast. The other data are: (○) Mg–1.5 wt % Si from Ref. [13], (▽) $(Mg_2Si)_{30}Mg_{64}Al_6$ and (△) $(Mg_2Si)_{50}Mg_{50}$ from Ref. [3].

In general, matrix–particle decohesion reduces mechanical properties in metals containing particles. For example, Dutta *et al.* [14] showed that the strengthening effect due to microstructural refinement could not be fully exploited for an aluminium matrix composite containing SiC particles because of the degradation of matrix–particle interfaces produced by hot working. In the present work, the Mg_2Si particles were fractured by hot extrusion, however, there was little interface degradation in the extruded Mg–Si alloys. Therefore microstructural refinement without the interface degradation is responsible for the improvement of mechanical properties by hot extrusion.

4. Summary

(i) For the cast materials, the Mg–high Si ($\geqslant 10$ wt%) alloys showed lower values of the ultimate tensile strength up to 373 K, as compared to the pure Mg and the Mg–low Si (< 10 wt%) alloys. This is because a high volume of Mg_2Si embrittled the Mg–Si alloys.

(ii) Addition of aluminium and zinc to the alloys was effective for the production of a high strength, although the alloying had little effect on ductility.

(iii) The mechanical properties of the cast materials were improved by hot extrusion. Refinement in the structure of the grains and fine dispersion of the Mg_2Si particles by hot extrusion is responsible for the improvement of the mechanical properties.

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