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The tensile behaviour of rapidly solidified magnesium alloys

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In this paper, the microstructure and tensile behaviour of three rapidly solidified magnesium alloys is reported. The alloy's composition, i.e. neodymium content, is observed to have an influence on tensile properties and fracture behaviour. The elastic modulus, yield strength and ultimate tensile strength of the alloy increase with an increase in neodymium content. The ductility of the alloys decreased marginally with an increase in neodymium content. The tensile fracture characteristics of the alloys is highlighted in the light of alloy composition and microstructural effects.

1. Introduction

The need for improved performance in the aerospace and ground transportation industries has resulted in materials engineers developing and examining new materials that satisfy the desired requirements. The requirement for lightweight structures to aid savings in operating costs, through decreased fuel consumption and enhanced performance, through speed, range and manoeuverability, led to the emergence and use of low density materials. Among the growing contenders for structural applications are aluminum, magnesium and titanium.

Magnesium is the lightest structural metal available. With a density of 1.74 $\mathrm{g\,cm^{-3}}$, magnesium is 35.6% lighter than aluminum and 61.3% lighter than titanium [1]. However, its atomic structure coupled with a low core potential and bivalency, arising from the 2*s* orbit electrons, restricts the physical characteristics of unalloyed magnesium and magnesium-base alloys. In particular, magnesium-base alloys suffer from high chemical reactivity, which results in inferior corrosion resistance, and a hexagonal close-packed structure, with a limited number of slip systems, which results in limitations to enhanced strengthening and degradation of ductility or deformability. Consequently, the widespread use of ingot metallurgy (IM) processed magnesium-base alloys has been restricted by competing and mutually interactive influences of poor oxidation and corrosion resistance, low thermal stability, poor formability and low strength levels. Furthermore, a number of alloying additions (such as molybdenum, titanium and chromium) have high melting points that far exceed the boiling point of magnesium and, consequently, alloying by traditional IM methods was difficult and had its limitations [2]. Also, the common alloying elements exhibit limited solid solubility in magnesium and tend to form intermetallic compounds as a result of the electropositive nature of magnesium [3]. The limitations were overcome by the application of powder metallurgy–rapid solidification processing (PM–RS).

Rapid solidification (RS) technology involved the promotion of extremely high cooling rates (10^3–10^9 $^\circ\mathrm{C\,s^{-1}}$) as the material solidified. Rapid solidification processing of these alloys facilitates departure from thermodynamic equilibrium and aids in the preparation of not only high purity alloys, but also alloys with great compositional flexibility [4]. Extended solid solubilities achievable by rapid solidification permit the preparation of alloy compositions that cannot be made using ingot metallurgy technology. Improved compositional flexibility aids in improving the corrosion behaviour by reducing galvanic coupling between microscopic inhomogeneities. Furthermore, the possibility of new non-equilibrium phases facilitates an improvement in corrosion behaviour. The conjoint influence of these effects results in improved mechanical and physical properties and the elimination of redundant working and finishing operations. The development and emergence of high strength, lightweight magnesium-base alloys would serve as an attractive alternative to aluminum alloys, with a concomitant saving in weight. Consequently, in recent years, intensive research activity involving rapid solidification magnesium alloys has been undertaken by many researchers.

The present study was undertaken with the objective of evaluating the influence of alloy composition on the tensile properties and fracture behaviour of three magnesium alloys, and is part of a larger study aimed at studying and characterizing the cyclic stress response characteristics and cyclic strain resistance of these alloys. In this paper, the tensile properties and fracture behaviour of the alloys are discussed in the

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light of alloy composition and intrinsic microstructural effects.

2. Experimental procedure

2.1. Material

The magnesium alloys used in this experimental study were provided by Allied Signal Corporation (Morristown, NJ). The chemical composition of the alloys (in weight per cent) is given in Table I. The material was manufactured using the powder metallurgy–rapid solidification (PM–RS) technique. Rapidly solidified ribbons of magnesium alloys were produced by planar flow casting. The processing of ribbons was conducted in a protective atmosphere to prevent:

1. any oxidation of the liquid metal surface, and
2. entrapment of air under the liquid film.

The ribbons were then reduced to powder using a series of high speed mechanical comminution processes [5–8]. The powder particles obtained following mechanical comminution have a uniform microstructure irrespective of the particulate size [9]. To make a consolidated body the powders were either outgassed in a can and then sealed under vacuum, or subsequently vacuum hot pressed for different time levels, depending upon the size of the billet. The cans were then extruded at an extrusion ratio of 18:1. Precise details of the processing technique and precautionary methods used can be found elsewhere [9].

2.2. Experimental techniques

The initial microstructure of the as-received material, in the extruded condition, was characterized by optical microscopy after standard metallographic preparation techniques. The etched specimens were observed in an optical microscope and photographed using a standard bright field technique.

Tensile specimens were machined such that the longitudinal direction or major stress axis of each specimen was parallel to the extrusion direction. Thus, in each case, the gross fracture plane was perpendicular to the extrusion direction. The cylindrical tensile specimens, conformed to standards specified in ASTM E-8, with threaded ends and a gauge length which measured 26 mm in length and 6.25 mm in diameter. To minimize the effects of surface irregularities and finish, the gauge sections were ground using 600 grit silicon carbide paper in order to remove any and all circumferential scratches and surface machine marks. Uniaxial tensile tests were performed on a computer controlled servohydraulic test machine in a room temperature (25 °C), laboratory air (relative humidity of 55%) environment. Specimens of each magnesium alloy were deformed at a constant strain rate of $10^{-4}\,s^{-1}$. Stress and strain parallel to the load line were recorded on an X–Y recorder equipped with a pen plotter.

TABLE I Nominal chemical composition (wt %) of the magnesium alloys

Alloy	Element			
	Al	Zn	Nd	Mg
1	5.72	2.96	6.05	Balance
2	4.89	4.36	5.81	Balance
3	4.96	4.75	5.43	Balance

Fracture surfaces of the deformed tensile specimens were examined in a scanning electron microscope in order to characterize the predominant fracture mode and the fine scale features on the tensile fracture surface.

3. Results and discussion

3.1. Initial microstructure

Triplanar optical micrographs illustrating the grain structure of the extruded magnesium alloys are shown in Figs 1 and 2. The microstructure of the

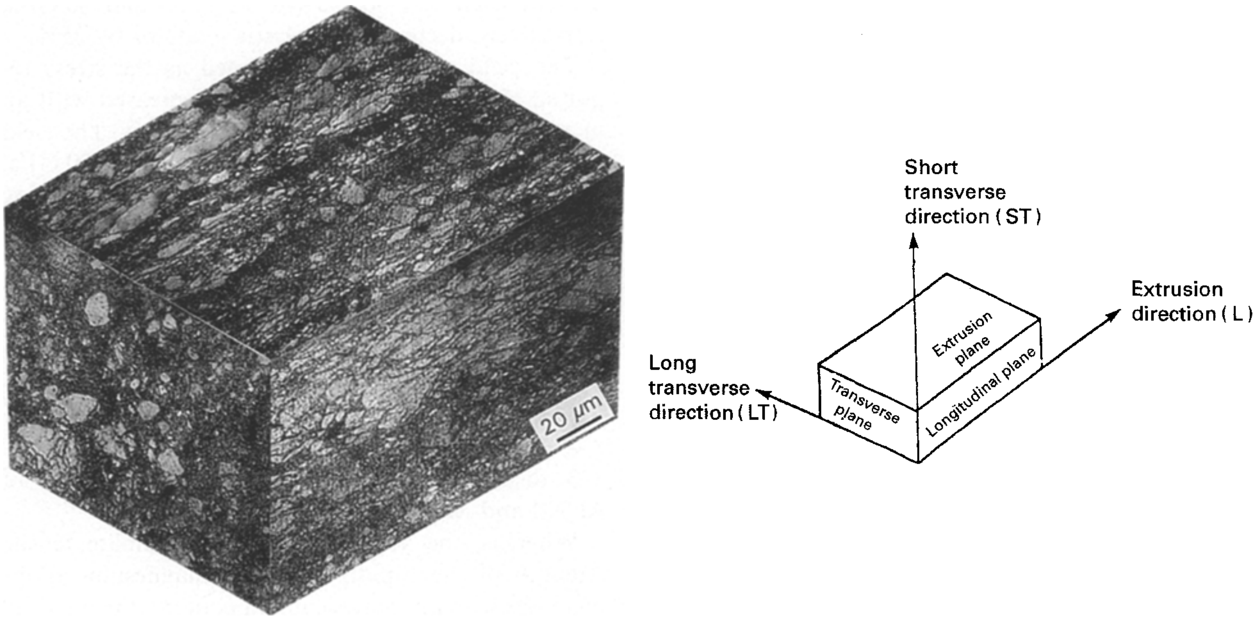


Figure 1 Triplanar optical micrograph illustrating the microstructure of the Mg–4.96Al–4.75Zn–5.43Nd alloy.

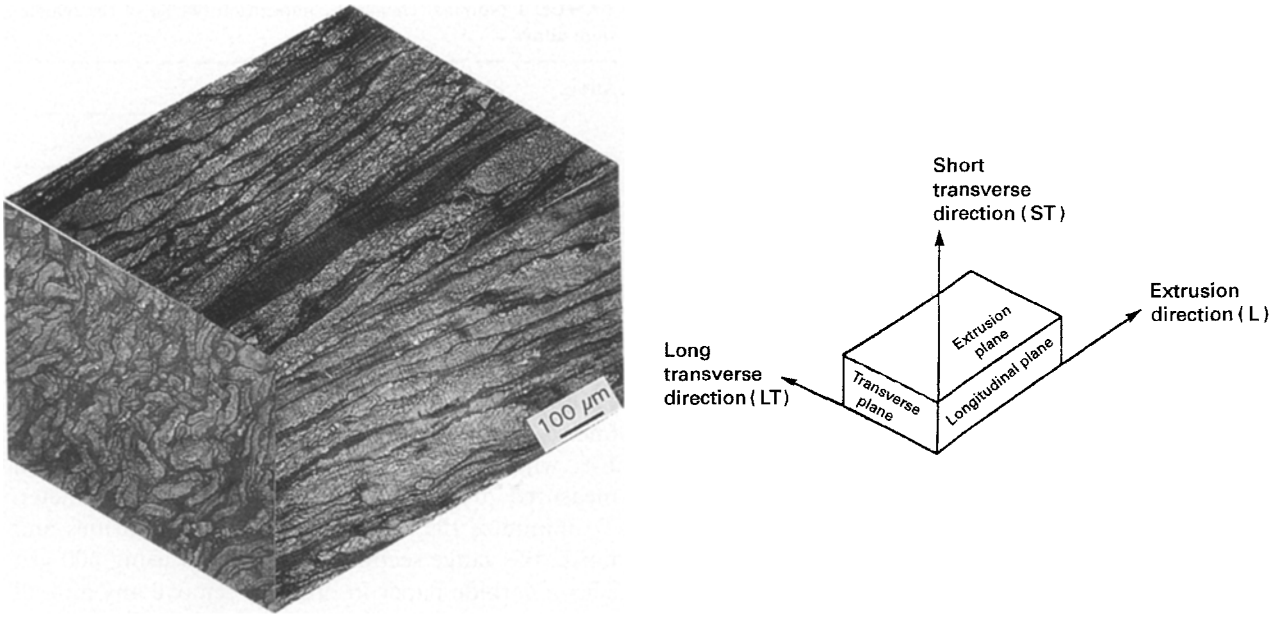


Figure 2 Triplanar optical micrograph illustrating the microstructure of the Mg–4.89Al–4.36Zn–5.81Nd alloy.

TABLE II Room temperature tensile properties of rapidly solidified magnesium alloys

Alloy	Elastic modulus[a]		0.2% yield strength		Ultimate tensile strength		True fracture stress		Elongation ($GL = 12.5$ mm)	True strain $\ln(A_o/A_f)$	Reduction in area
	Msi	GPa	ksi	MPa	ksi	MPa	ksi	MPa	(%)	(%)	(%)
1	6.20	42	57.0	400	66.0	450	70.0	480	4.50	3.50	5.50
2	8.00	55	61.0	420	71.0	490	71.0	490	2.00	3.50	4.00
3	5.80	40	50.0	340	64.0	440	68.0	470	4.00	7.20	7.00

[a] Tangency measurements based on extensometer trace.

Mg–4.89Al–4.36Zn–5.81Nd alloy reveals well defined pancake-shaped powder particles, elongated in the direction of deformation, i.e. the extrusion direction. The average grain size is about 2 μm. High magnification observation reveals that the powder particles are comprised of fairly well defined grains. The average grain size was 1–2 μm. Fine particles were distributed in the alloy matrix. In an earlier study, these particles were identified to be the dispersoids [9]. Microdiffraction studies, in an earlier study, have verified the dispersoid particles to contain a significant portion of aluminum and neodymium, the Al_2Nd [9]. The formation of Al_2Nd dispersoids (with a melting point temperature of 1733 K) instead of Mg–RE (rare earth) dispersoids, which have lower melting point temperatures, in rapidly solidified Mg–Zn–Al–RE alloys is interesting. The Al_2Nd dispersoids are thermally stable and help to pin the grain boundaries during hot extrusion. The microstructure of the Mg–4.96Al–4.75Zn–5.43Nd alloy also reveals a non-uniform grain size along the three orthogonal directions; with the grains elongated in the direction of extrusion.

3.2. Tensile properties

The ambient temperature tensile properties of the rapidly solidified magnesium alloys, in the as-extruded condition, are summarized in Table II. Duplicate samples were tested for each condition and no significant variation between the pairs of samples was observed.

The elastic modulus, E, obtained by extensometer trace, varied (showed no definite trend) with increasing Nd content in the matrix. However, increasing the Nd content from 5.81 to 6.05 wt %, at 55 and 40 GPa, respectively, decreased the elastic modulus by 25%.

The yield strength, $\sigma_{0.2}$, defined as the stress required at a plastic strain of 0.2%, increased with an increase in neodymium content in the alloy. The yield strength of the alloy with 6.05 wt % Nd is 400 GPa, which is 15% more than the yield strength of the alloy with 5.43 wt % Nd (340 GPa). The ultimate tensile strength, of all three RS magnesium alloys, is only marginally higher than the yield strength, indicating that the work hardening rate past yielding is low. The high yield strength of the alloys can be ascribed to the conjoint action of:

1. fine grin size,
2. solid solution strengthening, and
3. dispersion strengthening from the presence of Al_2Nd and MgZn particles.

Whereas, the yield strength and ultimate tensile strength of the rapidly solidified magnesium alloys increases with an increase in Nd content, the ductility measured by elongation over a 12.7 mm gauge length (GL) of the specimen, changes little with an increase in

Nd content. The reduction in area, another measure of tensile ductility, decreased 50% with an increase in Nd content from 5.43 to 6.05 wt %, i.e. from 7.0 to 3.5%, respectively. The observed degradation in reduction in area is consistent with the improvement in strength with increased neodymium content. A comparison of the engineering stress–engineering strain curves of the three alloys is shown in Fig. 3.

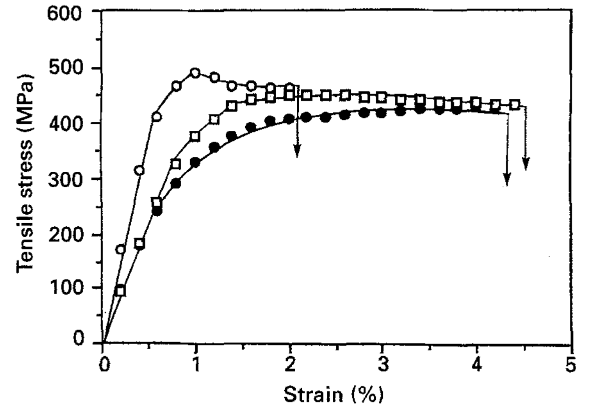


Figure 3 A comparison of the engineering stress–engineering strain of the three rapidly solidified magnesium alloys: (□) alloy 1, (○) alloy 2, and (●) alloy 3.

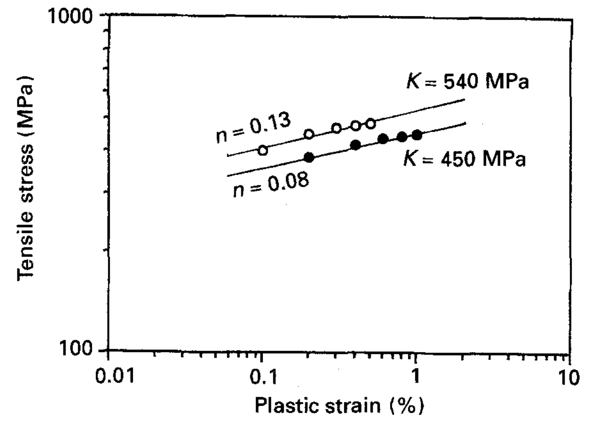


Figure 4 Monotonic stress–strain curves for the rapidly solidified magnesium alloys: (○) alloy 1, (●) alloy 3.

The strain hardening characteristics of the alloys was evaluated from examining the variation of stress with plastic strain plotted on a bilogarithmic scale Fig. 4. The variation of stress, σ, with plastic strain, ε_p obeyed the relationship of the form

$$\sigma = K(\varepsilon_p)^n$$

where K is the monotonic strength coefficient and n is the monotonic strain hardening exponent. A low degree of strain hardening can be inferred from this figure and the strain hardening exponent. The strain hardening exponent increases with increasing neodymium content and conforms well with the improvement in strength. The monotonic parameters n and K are summarized in Table III.

3.3. Tensile fracture

The tensile fracture surfaces are helpful in elucidating microstructural effects on the ductility and fracture properties of the magnesium alloy. Scanning electron microscopy (SEM) examination of the interparticle

TABLE III Monotonic parameters of rapidly solidified magnesium alloys

Alloy	n[a]	K[b]	
		MPa	ksi
1	0.13	540	77
2	0.08	450	62
3	0.08	450	62

[a] n, monotonic strain hardening exponent.
[b] K, monotonic strength coefficient.

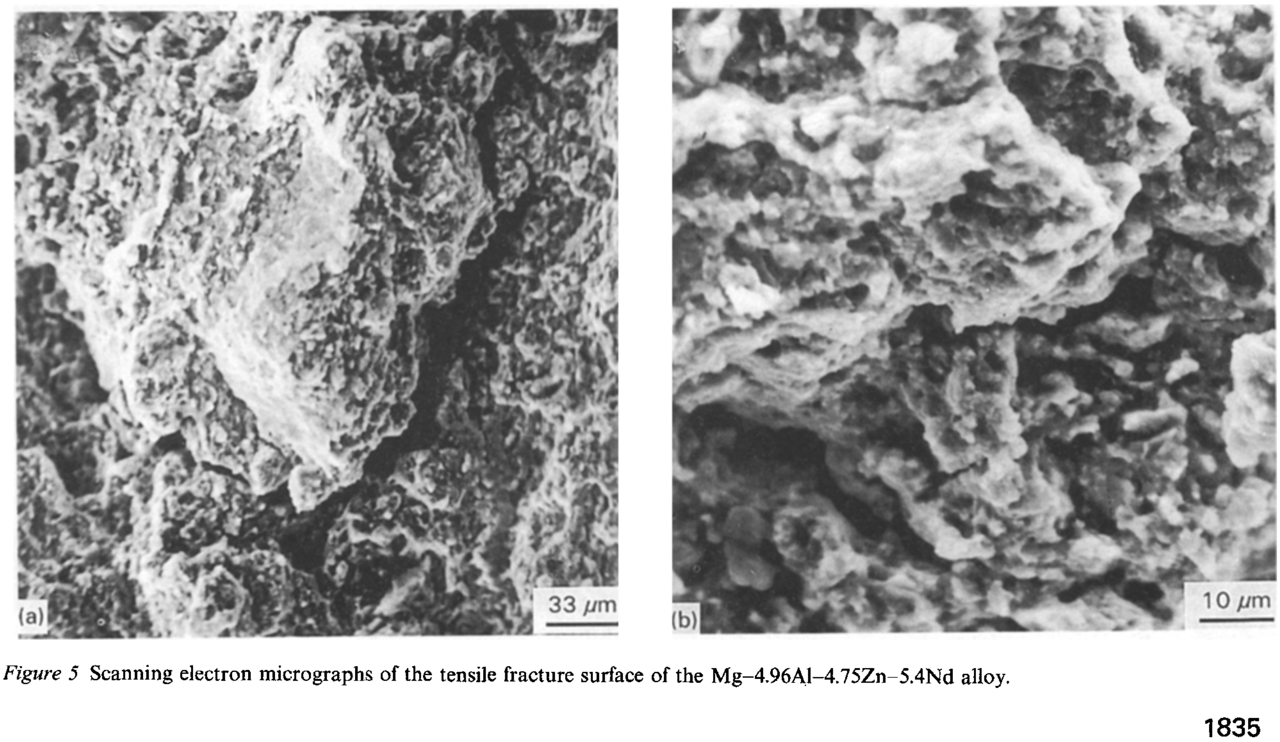
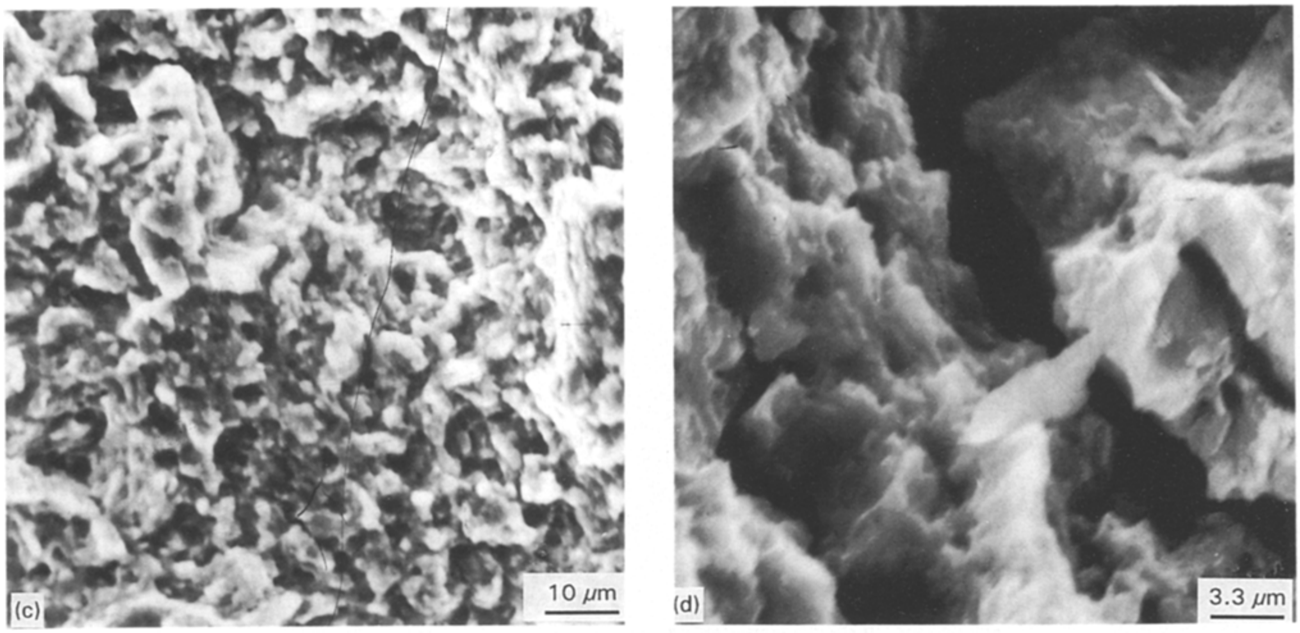


Figure 5 Scanning electron micrographs of the tensile fracture surface of the Mg–4.96Al–4.75Zn–5.4Nd alloy.



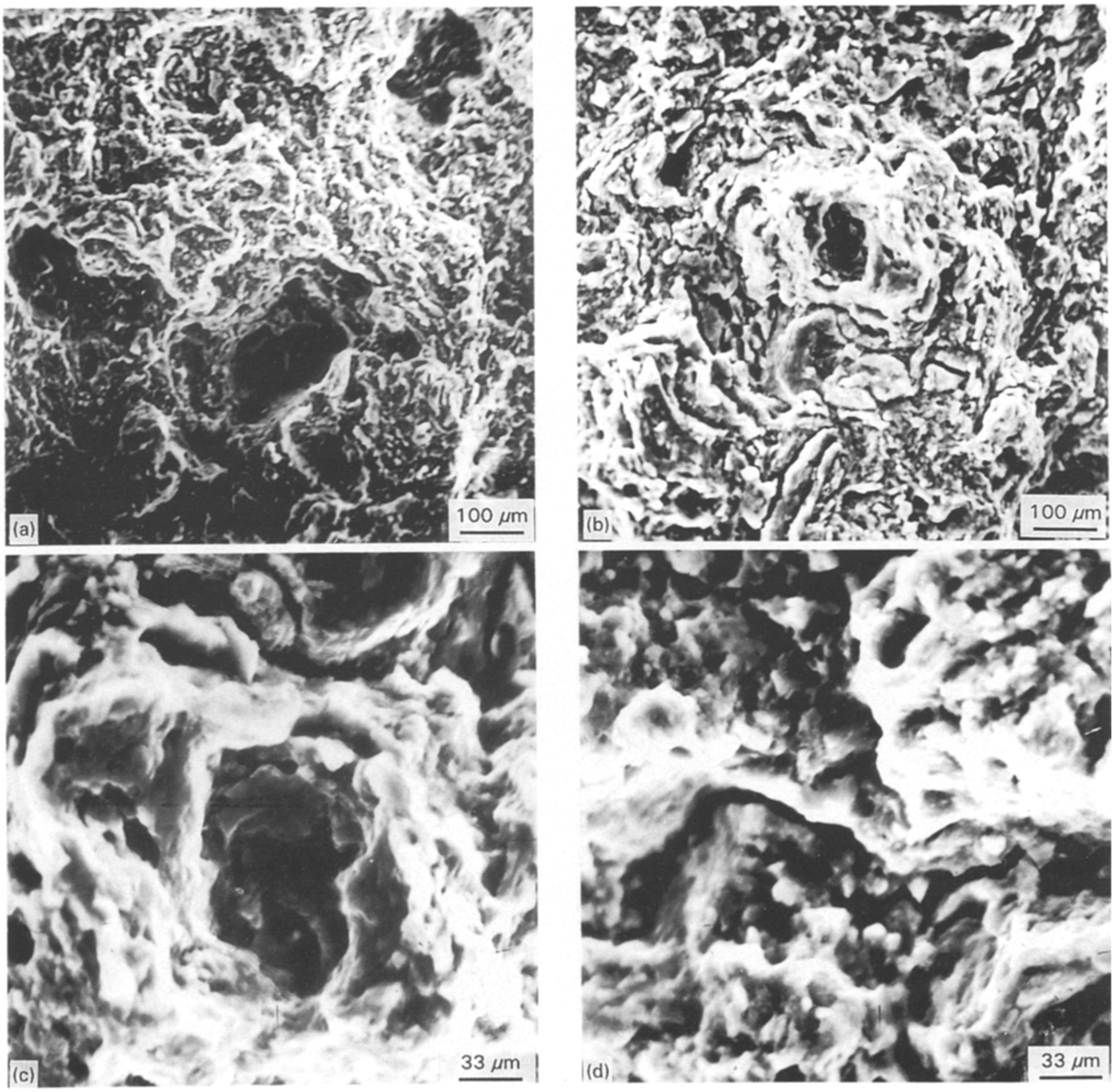


Figure 6 Scanning electron micrographs of the tensile fracture surface of the Mg–4.89Al–4.36Zn–5.81Nd alloy.

fracture surface features of the deformed tensile specimens was done at low magnification to identify the overall fracture morphology, and at higher magnifications to identify the fine-scale fracture features. Fractography of the tensile samples revealed near similar features for the three alloys. Representative fracture features, for the three alloys, are shown in Figs 5–7.

On a macroscopic scale, tensile fracture was predominantly delamination of powder particles coupled with the formation of cracks and voids of varying sizes. Examination of the tensile fracture surfaces, at high magnifications, essentially revealed features reminiscent of brittle failure:

1. cracking along the powder particle boundaries, and
2. fine microscopic cracking along the grain boundaries.

Under the influence of a far-field tensile load, triaxial stresses are generated in the matrix and the

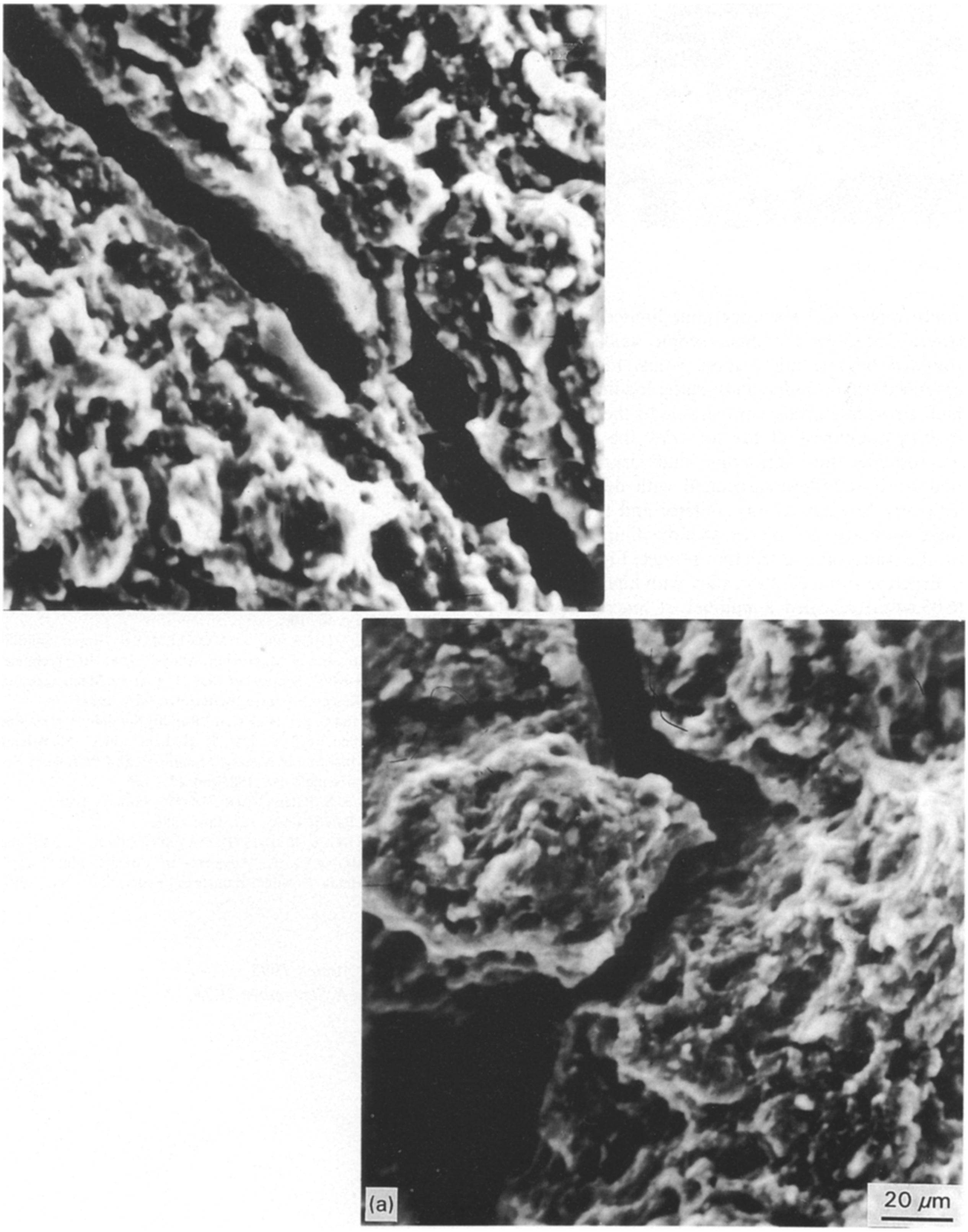


Figure 7 Scanning electron micrographs of the tensile fracture surface of the Mg–5.72Al–2.96Zn–6.05Nd alloy.

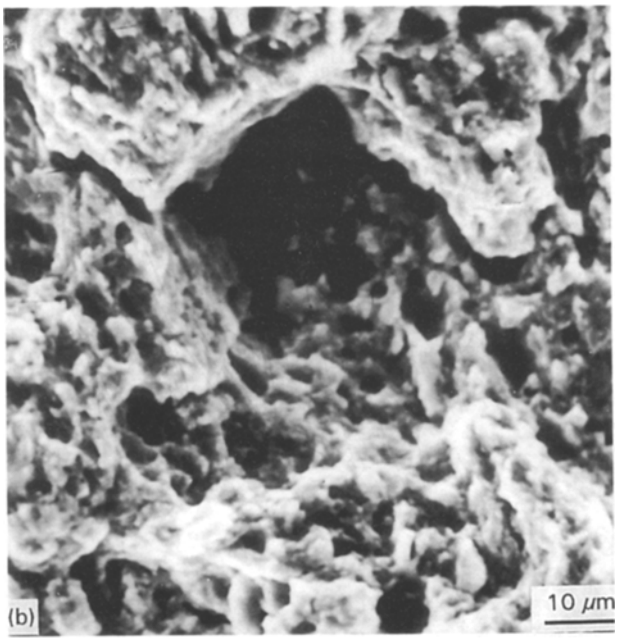


Figure 7 Continued

voids appear to have undergone limited growth. At several locations the macroscopic voids were surrounded by fine microscopic voids, Fig. 6c. Since crack extension under quasi-static loading occurs at high stress intensities, comparable to the quasi-static fracture toughness of the material, the presence of macroscopic and microscopic voids degrades the actual strain-to-failure associated with ductile failure. The very fine microvoids coalesce and the halves of these voids are the isolated, shallow dimples observed on the transgranular fracture surface, Fig. 5d.

Fracture surfaces of the alloy with high Nd content (6.05 wt %) revealed a number of macroscopic and microscopic cracks. However, fracture surfaces of the alloys with lower Nd content, i.e. 5.81 and 5.43 wt % Nd, revealed isolated microcracking, and macrocracking along the powder particle boundaries. For all three magnesium alloys orientation of failure was predominantly at and along the powder particle boundaries and grain boundaries.

4. Conclusions

Based on a study of the tensile behaviour of the rapidly solidified magnesium alloys, the following are the key observations:

1. The microstructure of the alloys consisted of well defined powder particles. The grains were small in size (1–2 μm) and elongated in the direction of deformation (extrusion). The dispersoids (Al_2Nd) were distributed uniformly in the matrix.
2. The elastic modulus of the alloys decreased with an increase in neodymium content.
3. The strength (yield strength and ultimate tensile strength) of the rapidly solidified magnesium alloys increased with an increase in neodymium content. The strain hardening capability of the alloys was low and increased with an increase in neodymium content.
4. Tensile elongation was marginally influenced with an increase in neodymium content. The improvement in reduction-in-area was consistent with degradation in strength, resulting from increased neodymium content.
5. Tensile fracture of the alloys revealed features reminiscent of brittle failure, with cracking along the grain boundaries.

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