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Mechanical properties of rapidly solidified ribbons of some Al–Si based alloys

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Continuous uniform ribbons of Al–16 Si, Al–12.5 Si–1 Ni and Al–12.5 Si–1 Mg were prepared by melt spinning. Microhardness was measured. The as-melt spun values were 1280, 1370 and 1500 MN m^{-2} which relax on thermal ageing to 700, 700 and 800 MN m^{-2} for Al–16 Si, Al–Si–Ni and Al–Si–Mg, respectively. The hardness values of the melt spun ribbons are higher than the as-cast rods from which the ribbons were produced by a factor ranging from 1.8–2.2 times. Tensile testing at room temperature shows that the load–elongation curves are linear with a change of slope occurring in some of the specimens. These curves also show serrations in the case of as-melt spun and the intermediately annealed Al–Si specimens, while no serration was observed in the fully annealed samples. No serration was observed in the Al–Si–Ni and Al–Si–Mg alloys. UTS values were 420, 270 and 100 MN m^{-2} for Al–16 Si, Al–Si–Ni and Al–Si–Mg, respectively. These values show that the rapid solidification process improved the tensile properties significantly in Al–16 Si and Al–Si–Ni alloys while no significant improvement can be detected for Al–Si–Mg alloy. A discussion is given on hardness relaxation and tensile testing results in terms of silicon precipitation.

1. Introduction
The mechanical properties of metallic materials can be improved by grain refinement which can cause an increase in both strength and ductility [1, 2]. Rapid quenching from the melt of aluminium based alloys, for example, as achieved by melt spinning, produces very fine grains as a result of the high cooling rate on solidification [3, 4]. Van Rooyen and co-workers [5, 6] prepared Al–20 at % Si alloy by rapid solidification; an increase of 50% in ultimate tensile stress (UTS) was obtained. Al–12 wt % Si binary alloys were prepared by Todeschini *et al.* [7] using a rapid solidification technique. Marked improvement in mechanical properties was observed, while the addition of Cu, Ni or Mg as ternary elements improve further the yield strength as well as UTS in addition to a decrease in the alloy ductility. In the present work, hardness and tensile properties of some rapidly solidified Al–Si based alloys were studied. Two alloys have the eutectic composition plus minor Ni or Mg addition and the third Al–16 Si has the composition of the commercial alloy Al-392.

2. Experimental details
Al–16 Si, Al–12.5 Si–1 Ni and Al–12.5 Si–1 Mg alloys were prepared by melt spinning using the apparatus described in [8]. Continuous uniform ribbons of thickness about 25 μm and width of 1 mm were obtained.

The microhardness was measured using a Vickers hardness tester, a Leitz Wetzlar Germany instrument, which uses loads as low as 25 g. Measurements were carried out on specimens placed against glass slides. The hardness was measured with loads ranging from 25–150 g. The hardness values, as measured with different loads, lie within experimental uncertainty estimated to be $\pm 7\%$.

The microhardness tests were performed on the as-melt spun and annealed ribbons without polishing, since the ribbon surfaces were polished as prepared.

The specimens were tensile tested on an Instron machine. The tests were performed on ribbons of gauge length 50 mm at room temperature and head speed of 0.1 mm min^{-1} which cause a strain rate of 1.66×10^{-5} s^{-1}. This strain rate was chosen to avoid fracture of the ribbons before the completion of the test.

3. Results
3.1. Microhardness
Microhardness measurements on the wheel side and air side did not show significant differences contrary to what was observed by Jones [9] in splat cooled Al–8 wt % Fe. Hence only measurements on the wheel side are presented in Fig. 1. Fig. 1 shows the decrease in hardness with time during isothermal annealing. The hardness relaxation occurs in two stages, an initial fast stage followed by a slower one.

The as-melt spun hardnesses are 1280, 1370 and 1500 MN m^{-2} for Al–Si, Al–Si–Ni and Al–Si–Mg, respectively. These values decrease on thermal ageing to reach values 700, 700 and 800 MN m^{-2} for Al–Si, Al–Si–Ni and Al–Si–Mg, respectively.

The as-cast rods with the same composition as the ribbons, give hardness values of 690, 740 and

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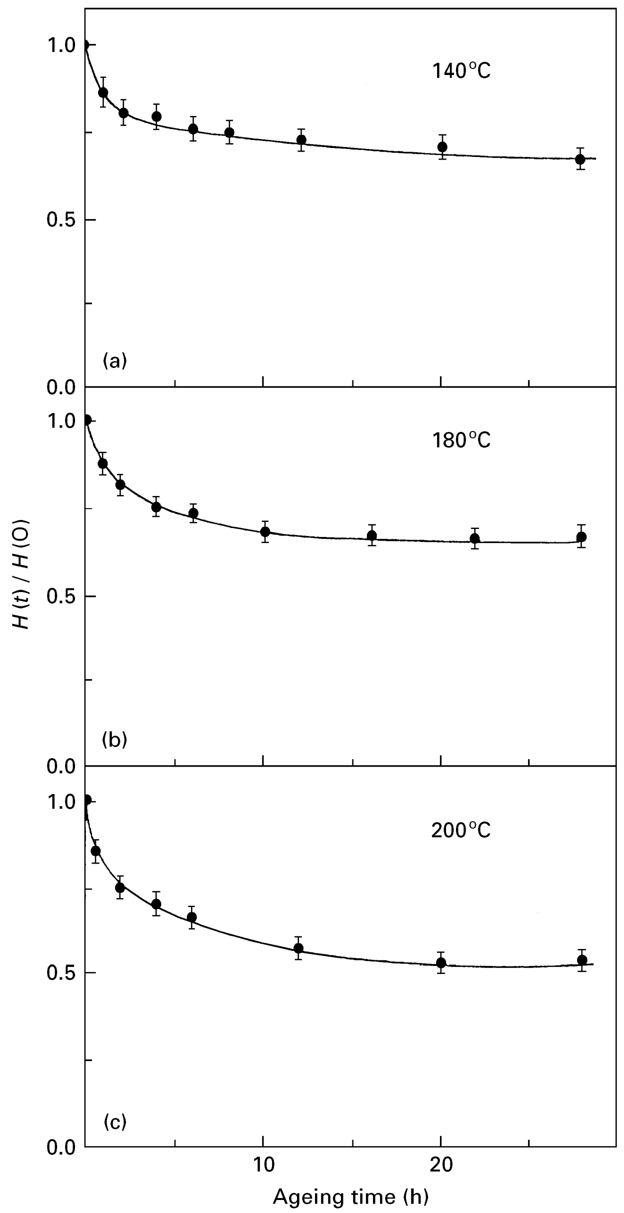

Figure 1 The variation of Vickers hardness ratio $H(t)/H(\mathrm{O})$ with ageing time: (a) Al–16 wt % Si; (b) Al–12.5 wt % Si–1 wt % Ni; and (c) Al–12.5 wt % Si–1 wt % Mg.

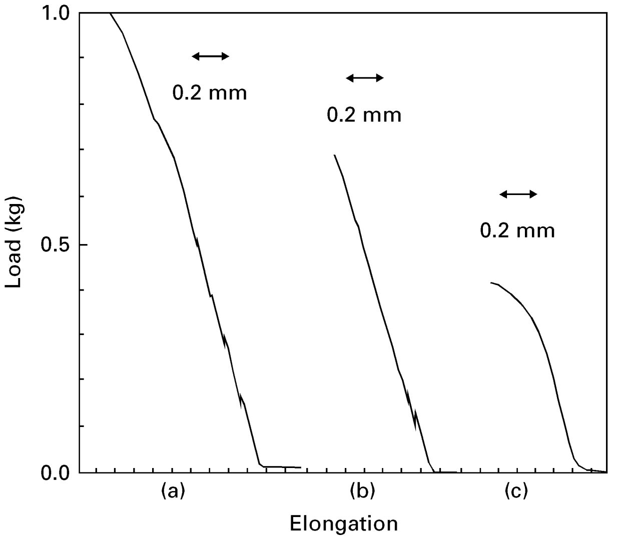

Figure 2 Load–elongation curves for Al–16 wt % Si melt spun ribbons. Strain rate $1.66\times10^{-5}\,\mathrm{s}^{-1}$: (a) as prepared; (b) aged up to $R(t)/R(\mathrm{O}) = 0.4$; and (c) aged 10 h at 250 °C.

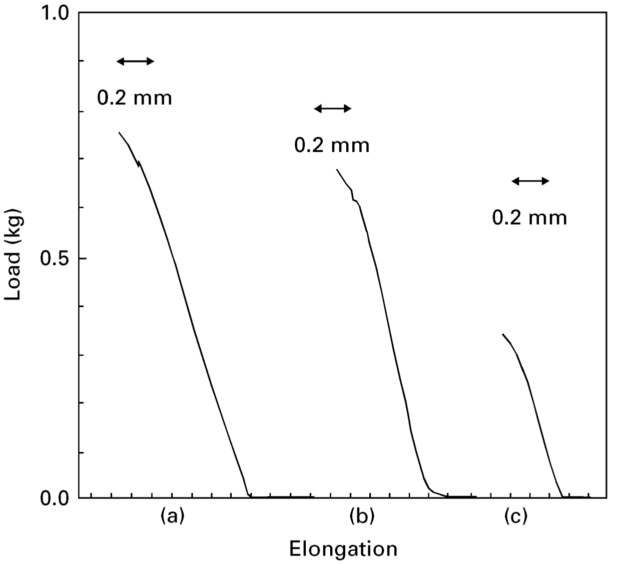

Figure 3 Load–elongation curves for Al–12.5 wt % Si–1 wt % Ni melt spun ribbons. Strain rate $1.66\times10^{-5}\,\mathrm{s}^{-1}$: (a) as prepared; (b) aged up to $R(t)/R(\mathrm{O}) = 0.4$; (c) aged 10 h at 250 °C.

670 $\mathrm{MN\,m^{-2}}$ for Al–16 Si, Al–Si–Ni and Al–Si–Mg, respectively. Annealing the rods for 30 h at 250 °C results in a decrease of hardness of at most 10% for all alloys. The hardness values for the rods are comparable with the values quoted for commercial alloys of comparable compositions.

3.2. Tensile testing

Typical load–elongation curves are shown in Figs 2–4. The load–elongation relation is either linear up to fracture or linear up to a certain elongation beyond which it is curved until fracture. The load–elongation curves for the as-melt spun and intermediately aged samples of Al–16 Si are serrated. Data extracted from these curves are presented in Table I.

The UTS values differ greatly being 420, 270 and 100 $\mathrm{MN\,m^{-2}}$ for Al–16 Si, Al–Si–Ni and Al–Si–Mg, respectively. The toughness expressed as the area under the stress–strain curve until fracture was calculated from the load–elongation curves and presented also in Table I. In Table I, the strain ratio $\varepsilon/\varepsilon_f$ at which the load–elongation curve changes its slope, and the values of the slopes in the two regions are also given. ε_f is the fracture strain and σ is the stress.

4. Discussion

4.1. Microhardness

The high hardness of the as-melt spun ribbons is associated with the as-melt spun state. The as-melt spun state consists of a supersaturated solid solution with the possible presence of undissolved solutes having such a fine size that only α-Al lines appear in the X-ray diffraction patterns [10, 11].

The high hardness can be related to the effect of the solute atoms upon the solvent lattice and the nature of

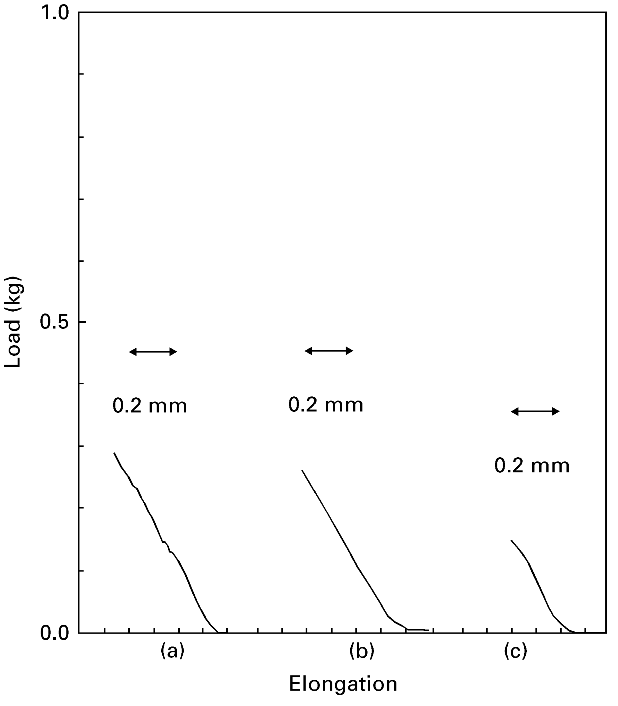

Figure 4 Load–elongation curves for Al–12.5 wt % Si–1 wt % Mg melt spun ribbons. Strain rate $1.66 \times 10^{-5}\,s^{-1}$: (a) as prepared; (b) aged up to $R(t)/R(O) = 0.4$; (c) aged 10 h at 250 °C.

the operative lattice forces, owing to the interaction of different atomic species. This explains the difference in hardness in the three melt spun alloys.

As precipitation begins with thermal annealing, the Al matrix is gradually deprived of the solutes. This results in an associated decrease in hardness. As ageing progresses, the size of the individual precipitate particles increases while their number decreases resulting in gradual softening.

Another factor, which may contribute to the decrease in hardness with thermal annealing, is related to internal stresses, which are retained on cooling to room temperature. Such stresses may arise from the difference in thermal expansion of the precipitates and the solvent. These internal stresses when added to the compressive stress of the hardness indentor will aid in plastic flow and thereby give a decrease in hardness.

The relaxations of hardness starts later than that of resistivity [10, 11]. Also, the relaxation kinetics of hardness is slower than that of resistivity. This may be related to the fact that electrical resistivity, which is sensitive to point defects, recovers first while hardness, which depends on line imperfections, may require higher temperatures for recovery. Furthermore, hardness is closely related to precipitate size.

Exceedingly high hardness values were obtained by rapid solidification in concentrated Al–Si–M alloys [12, 13] with (Si + M) exceeding 30 at %. M is a transition metal. A hardness value of 3000 $MN\,m^{-2}$ was reported [12] for melt spun Al–17 Si–13 Ni, while values ranging from 7000–10 000 $MN\,m^{-2}$ were obtained [13] in melt spun alloys with $15 < Si < 40$ and $15 < M < 20$. This has been related to the bonding nature of M–Si and M–Al atoms which have more attractive interaction than Al–Si bonding.

4.2. Tensile behaviour

It seems that serrations are associated with the binary Al–Si alloy containing no additional alloying elements. The appearance of serrations in the as-melt spun or partially aged samples may be associated with the presence of a minimum amount of Si in solid solution. The absence of serrations in the fully aged Al–16 Si samples can be attributed to Si precipitation and subsequent growth of Si particles which probably favours smooth deformation. The absence of serrations in the Al–Si–Ni and the Al–Si–Mg alloys may be due to the presence of Ni and Mg additions. These additions may create atmospheres which impede vacancies generated by elongation from effecting locking of dislocations. Although the elongation encountered in the present concentrated alloys is small, these serrations may be likened to the Portevin–Le Chatelier [14] effect observed in dilute alloys.

Table I shows that the UTS and elongation values of the Al–Si–Mg alloy are too low compared with the

TABLE I Mechanical properties obtained from the tensile tests

Alloy	UTS $MN\,m^{-2}$	Elongation %	Toughness $MN\,m^{-2}$	Change of slope at $\varepsilon/\varepsilon_f$ %	Average slope of stress/strain $10^{10}\,N\,m^{-2}$	
					Region 1	Region 2
Al–16 Si						
As-melt spun	420	1.7	3.5	57	3.0	1.8
Annealed +	280	1.0	1.3	–	2.6	2.6
Annealed + +	150	1.1	0.9	42	2.8	0.8
Al–Si–Ni						
As-melt spun	270	1.4	1.9	80	2.3	1.2
Annealed +	220	1.2	1.1	79	2.7	1.0
Annealed + +	130	0.6	0.4	80	2.5	1.0
Al–Si–Mg						
As-melt spun	100	0.8	0.5	–	1.2	1.2
Annealed +	90	0.8	0.4	–	1.0	1.0
Annealed + +	50	0.5	0.2	87	1.3	1.0

+ annealed until $R(t)/R(O) = 0.4$.
+ + annealed 10 h at 250 °C.

other two alloys. This may be associated with the rapid solidification of this particular alloy composition. The resulting solidified structure probably favours an early crack initiation and its subsequent spreading over the section causing fracture.

Comparison with commercial alloys of similar composition, prepared by classical foundry methods, shows that the rapid solidification process improved the tensile properties significantly in the Al–16 Si and Al–Si–Ni alloys. The rapidly solidified Al–16 Si has a UTS value of 420 $MN\,m^{-2}$ as compared to a value of 310 $MN\,m^{-2}$ for the engineering alloy Al-392. Also for the rapidly solidified Al–Si–Ni alloy, the UTS value is about 40% higher than commercial alloys of nearly the same composition. However, no significant improvement was effected in the Al–Si–Mg alloy.

Comparing with unidirectionally solidified alloys [15] of compositions similar to the alloys studied here, the Al–Si eutectic has a UTS value of 137 $MN\,m^{-2}$, while the ternary eutectic Al–11 Si–4.9 Ni has a UTS value of 157 $MN\,m^{-2}$. These values are higher than the Al–Si–Mg alloy but much lower than those for Al–16 Si and Al–Si–Ni alloys being 420 and 270 $MN\,m^{-2}$, respectively. However, the elongation per cent of the unidirectionally solidified alloys are about 6–7% which are higher than those of the melt spun alloys being about 1% as shown in Table I.

On the other hand, the rapidly solidified powder metallurgical Al–16 Si alloys [16] have the same or a slightly higher (about 10%) UTS value than the melt spun ribbons of almost the same composition.

Finally, it is expected that the actual UTS values of the ribbons are higher than those presented in Table I. This is because machining [7] or polishing [17] the edges of the ribbons resulted in an increase in UTS of the ribbons by about 30%. This increase is attributed to the removal of microcracks at the ribbon edges.

5. Conclusions

1. For all the alloys studied, rapid solidification resulted in a significant increase in hardness over their classically prepared counterparts. Al–12.5 Si–1 Mg has the highest hardness value of 1500 $MN\,m^{-2}$.

2. The effect of rapid solidification on improving the tensile strength depends sensitively on composition. As compared to classically prepared alloys of comparable composition, the UTS values for Al–16 Si and Al–12.5 Si–1 Ni are higher, while that for Al–12.5 Si–1 Mg is the same or even lower.

3. The improvement in hardness and UTS of the as-melt spun ribbons is thought to be partially related to the amount of silicon in solid solution. Also the decrease in hardness and UTS to about half their initial values after thermal ageing can be attributed to silicon precipitation and the subsequent growth of silicon particles.

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