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Effect of extrusion conditions on mechanical properties of Al–20Si–3Cu–1Mg alloy prepared from rapidly solidified powder

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A study on the optimization of extrusion conditions for a prospective Al–20Si–3Cu–1 Mg alloy prepared from rapidly solidified powder was carried out by evaluating tensile properties at room and elevated temperatures. It was found that extrusion conditions influence the as-extruded microstructure and mechanical properties of the alloy to a certain extent. The relationship between the as-extruded mechanical properties and such extrusion variables as temperature, reduction ratio and die shape, can be described by using temperature-compensated strain rate, so that the as-extruded properties can be tailored in a certain range by adjusting this process parameter. In addition, the comparison between the as-extruded and as-T6 tempered tensile properties at elevated temperatures has opened the question as to the necessity of applying the heat treatment to the alloy — a normal practice subsequent to the extrusion. The experimental results suggest that for the material used at temperatures at and above 200 °C, the T6 temper treatment can be eliminated.

1. Introduction

Aluminium alloys with high silicon contents, produced via the conventional ingot metallurgy (I/M) route, are generally considered as being difficult to process because of their brittleness [1]. The microstructural refinement, as a result of applying powder metallurgy (P/M) techniques can, however, remarkably improve their workability and resultant mechanical properties [2–9]. Hot working of the P/M Al–Si–X alloys has been successfully conducted using an extrusion process [10], during which the oxides that cover the air-atomized powder particles are broken up and redistributed by severe shearing, and thus fully densified products can be obtained [11–13]. The application of the P/M techniques makes the alloys very promising, particularly for use as new materials in automotive engines, owing to their unique properties such as low thermal expansion coefficients and good wear resistance.

Although extrusion itself is a thermomechanical process, the primary aim of extruding porous aluminium alloy billets is to consolidate and to shape the raw material into semi-products. Property control for non-heat-treatable P/M Al–Si–X alloys is normally achieved through adjusting their chemical composition and atomization techniques [2, 3, 9, 14]. For heat-treatable P/M Al–Si–X alloys, emphasis is usually placed on their ageing response. Insufficient attention has been paid to the optimization of the extrusion process to obtain desired mechanical properties. In the hot working of I/M aluminium alloys, tailoring properties by controlling microstructure, known as thermomechanical processing (TMP), has been widely accepted [15]. Obviously, the general prerequisite for applying the TMP to the P/M aluminium alloys is also satisfied. The stacking fault energies of P/M aluminium alloys, the same as those of conventional aluminium alloys, are usually high, and thus sufficient dynamic recovery occurs during hot extrusion. Some of the alloying additions are precipitated from supersaturated aluminium matrix at extrusion temperatures to form a fine distribution of second phases, owing to the rapid solidification involved in powder production. Therefore, there is a possibility of extending the TMP idea to powder extrusion and of integrating the property control to the initial purposes of extrusion for the P/M Al–Si–X alloys. It has been observed that for other rapidly solidified P/M aluminium alloys, structure and mechanical properties are particularly sensitive to extrusion conditions [16]. An improper processing condition may easily bring about either an incoherent structure or a coarsened microstructure, both degenerating mechanical properties of the final products. In the latter case the feature of initial fine microstructure, as a merit of rapid solidification, is lost. Therefore, the requirements of building structural coherency and of maintaining microstructural refinement place additional restrictions on extrusion conditions. Clearly, it is of great importance to investigate the effects of the main extrusion variables including temperature, reduction ratio and die shape on the resultant mechanical properties, and finally to derive an optimized processing condition for the P/M Al–Si–X alloys.

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2. Experimental procedure

The P/M Al–Si–X alloy under study is heat treatable, composed of 20% Si, 3.1% Cu, 1.3% Mg, 0.3% Fe (by weight) and balance aluminium. The powder of the alloy was air atomized and cooled at a rate of 10^4 to 10^6 K sec^{-1}. The morphology of the powder particles was tear-drop shaped in the majority, with sizes varying from 5 to 150 μm. The microstructure of the atomized powder was very fine with primary silicon crystal particle sizes ranging from 1 to 8 μm [17], many times finer than those in the I/M material (between 30 and 100 μm).

The atomized powder was first encapsulated in cans, and then cold precompacted into billets with a relative density of about 65% to facilitate subsequent degassing. After degassing, the porous billets were extruded on a 2 MN horizontal press with a container diameter of 50 mm. After considering the press capacity and product quality, the experimental extrusion temperature range was chosen between 300 and 475 °C, and the reduction ratio range between 5 : 1 and 60 : 1. In addition to round dies, rectangular dies with aspect ratios (die exit length : width) between 3 : 1 and 10 : 1 were employed so as to investigate the effect of die shape. Ram speed was kept at a relatively low value of 5 mm sec^{-1}. All the billets were consistently heated in the container of the press for 20 min to preclude extra variables. The temperature of the die was always preset at 50 °C below that of the container for the dissipation of the heat generated from friction and deformation. The extrudates were air cooled after extrusion, aiming at examining the microstructure and mechanical properties associated with industrial conditions.

In order to compare the as-extruded mechanical properties with the as-heat-treated, a standard scheme of subsequent heat treatment for the alloy, the T6 temper, was applied, which consisted of a solution treatment at 470 °C for 1.5 h followed by quenching in water, a natural ageing for 4 d and an artificial ageing at 120 °C for 24 h.

Tensile tests were performed on the specimens in both the as-extruded and as-T6 tempered conditions at room and elevated temperatures, using a Tira Test 2300 machine at an initial strain rate of 5.6×10^{-3} sec^{-1}. Specimens were coaxial with the extrusion direction and machined in accordance with the ASTM Standard B557M. The ratio between gauge length and diameter was 5. For elevated-temperature tests, a split furnace was fitted on the machine. Two thermocouples were placed in contact with the specimen necks. Tests were carried out after the temperature of specimens was stabilized. All the specimens were annealed prior to the tests at 100, 200 and 300 °C corresponding to their testing temperatures for 100 h to assess the thermal stability of the alloy in simulating service conditions.

Optical metallographic specimens were prepared using normal techniques, and etched with a modified form of the Keller and Wilcox reagent (2% HCl–4% HNO_3–1% HF–H_2O). Observation was made on a Neophot-2 (Carl Zeiss, Jena) microscope. A Philips 400 transmission electron microscope (TEM) was also used to observe the microstructural evolution of the alloy throughout the processing route. The TEM specimens were prepared using ion-beam thinning at a current of 0.5 mA and an inclination angle of 20°.

3. Results and discussion

3.1. As-extruded tensile properties

3.1.1. At room temperature

The strain/stress curves of the material extruded under the differing conditions, exhibited no well-defined yield point, but a considerably high strain-hardening rate. The fracture plane was perpendicular to the tensile direction, and no necking at fracture was observed. Examination of the fracture surfaces revealed that fracture initiated exclusively at the edge of the specimens and propagated from the origin.

The variation of 0.2% proof and ultimate tensile strengths with extrusion temperature is shown in Fig. 1. In general, both strengths tended to be lower at higher extrusion temperatures. Clearly, this is largely attributed to the coarsened silicon crystal particles dispersed in the aluminium matrix at raised extrusion temperatures (Fig. 2), because their dispersion played a very important role in the strengthening mechanisms of the alloy. The relationship was not linear, and the difference over the temperature range studied was about 60 N mm^{-2}. Fig. 1 also shows that elongation was not as sensitive as strength to the varying extrusion temperatures except at 475 °C where microstructural coarsening resulted in the reduced ductility of the alloy (Fig. 2). This insensitivity implies the contribution of substructure (as shown later) to the properties, because, in principle, by this mechanism the

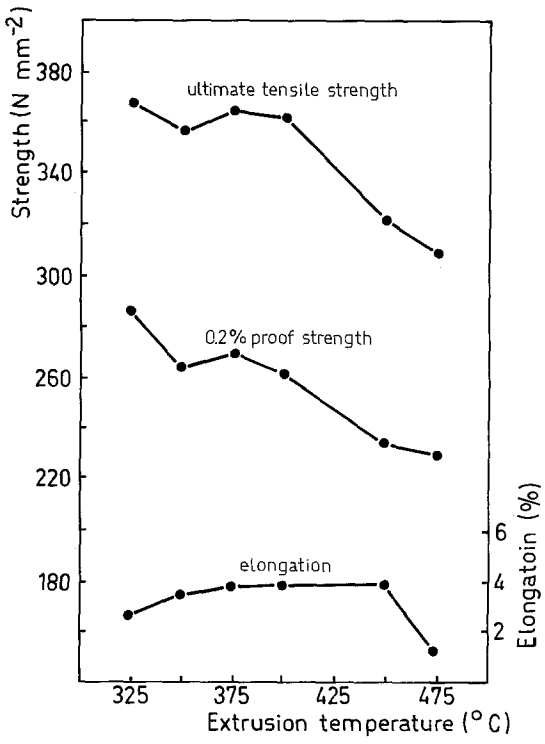


Figure 1 Relationship between extrusion temperature and as-extruded tensile properties at room temperature (reduction ratio 20 : 1 and ram speed 5 mm sec^{-1}).

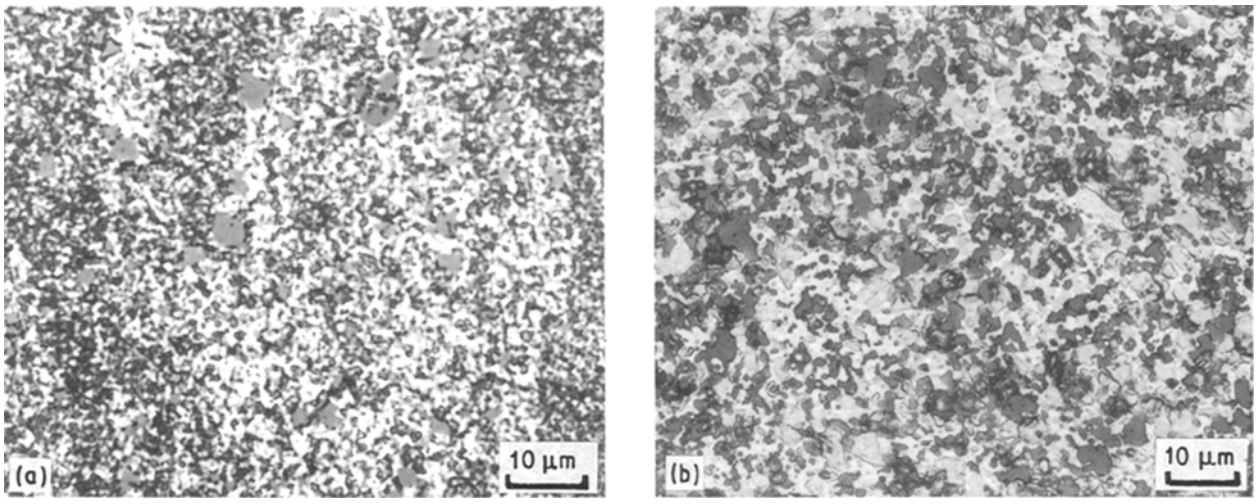


Figure 2 Comparison of the microstructure of the material extruded at (a) 325 °C and (b) 475 °C.

strength of a material can be improved at relatively low working temperatures without loss of ductility. This mechanical behaviour of the extruded material offers a range of extrusion temperatures within which the as-extruded strength can be adjusted without affecting its ductility. In optimizing extrusion temperatures, in addition to the mechanical properties, two additional factors have to be taken into consideration, namely that a very high pressure was required at very low extrusion temperatures and hot shortness started to appear in the rear part of extrudates at a temperature of 450 °C (Fig. 3). The optimal extrusion temperature range which leads to the satisfactory as-extruded strengths is thus between 375 and 400 °C. This range is very limited indeed.

The relationship between reduction ratio and tensile properties is shown in Fig. 4. Both the 0.2% proof and ultimate tensile strengths decreased by about 40 N mm^{-2} from 5 : 1 to 60 : 1. The reason may be that as strain in extrusion was extremely high, a "saturation" value of strength contributed by strain hardening was attained even at a relatively low reduction ratio. An excessively high strain at a high reduction ratio led to an increased driving force for softening which happened during subsequent cooling [18]. Moreover, because the P/M alloy with a very fine microstructure and a dispersion of massive silicon crystal particles strongly resisted strain during extrusion, the load required for the extrusion at the reduction ratio of 60 : 1 was twice as high as that at

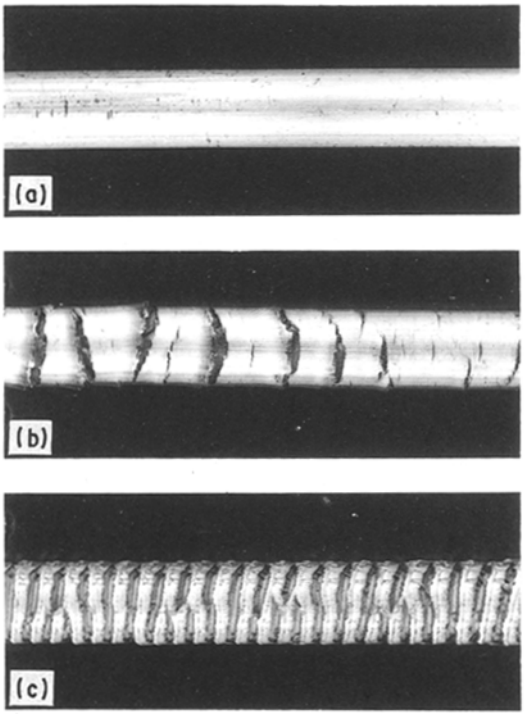


Figure 3 Surface quality of the material extruded at (a) 325 °C, (b) 450 °C and (c) 475 °C, showing that hot shortness starts to appear at 450 °C.

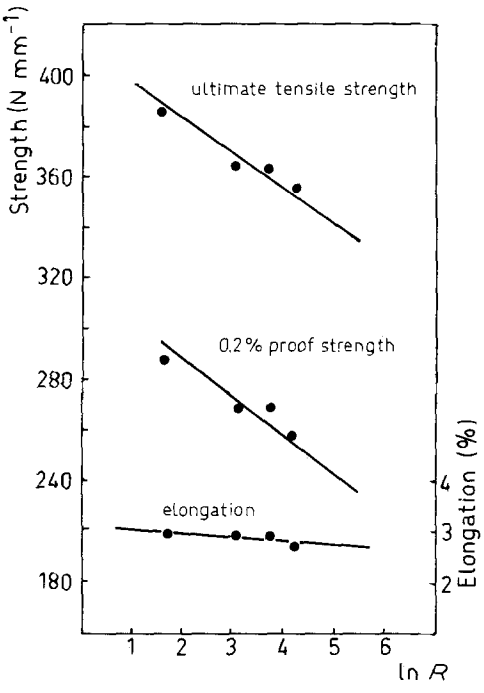


Figure 4 The as-extruded tensile properties at room temperature as a function of reduction ratio (extrusion temperature 375 °C and ram speed 5 mm sec^{-1}).

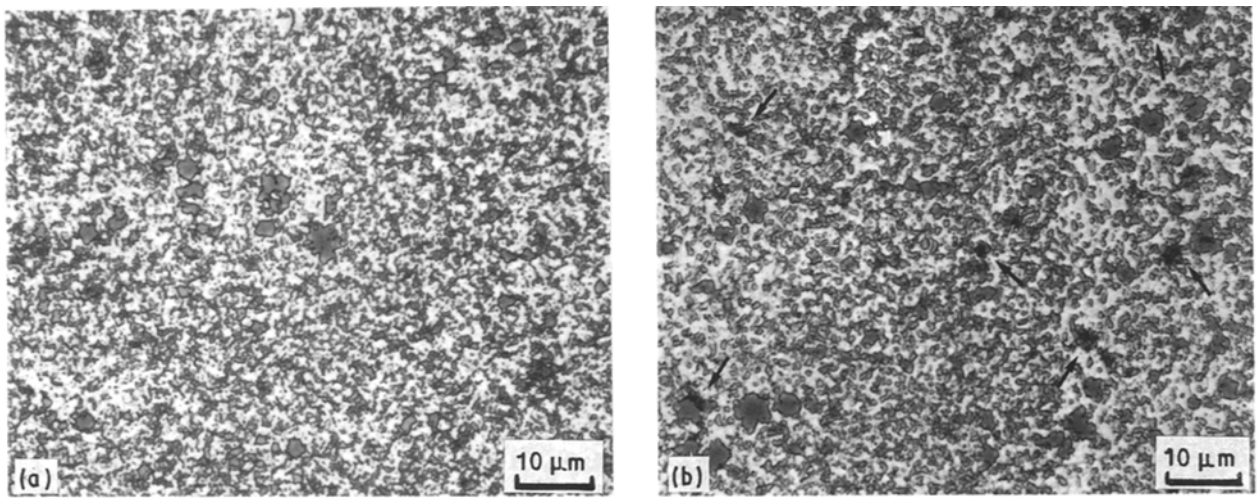


Figure 5 Optical micrographs of the alloy extruded at the reduction ratios of (a) 5:1 and (b) 60:1, showing the decohesion at the interfaces between the silicon crystal particles and aluminium matrix caused by the excessively large strain.

5:1 [19]. The great exerted energy was converted into heat, and caused a large temperature rise during the extrusion at a high reduction ratio, with the result of some coarsening of the silicon crystal particles. This may explain the observed variation of strengths with reduction ratio. The elongation is surprising, which varies with the same trend as the strengths, being slightly greater at lower reduction ratios. Such a variation was also reported previously in other P/M aluminium alloys [20, 21]. Apart from the reason that a little second-phase coarsening caused by greater temperature rise during extrusion at higher reduction ratios, the fact that the aluminium matrix might not accommodate perfectly with the silicon crystal particles aligned in the extrusion direction under very high strains may be more important, because of the very severe shearing at the interfaces between the soft aluminium matrix and hard silicon crystal particles involved in the extrusion, as shown in Fig. 5. This might offer an easy path for cracks, resulting in the early failure of the material. Fractography has shown that the decohesion between the silicon crystal particles and the aluminium matrix, indeed, is a main cause for the final fracture of the P/M alloy at room temperature [22]. Therefore, for the best combination of strength and ductility of the extrudates, it is preferable not to use too high reduction ratios.

Die aspect ratio was not very influential on tensile properties, as shown in Fig. 6. It appeared that the room-temperature properties of the P/M alloy were insensitive to the alteration of the die shape. This result favours near-net-shape production, which means that extrudates with different profiles but consistent mechanical properties can be readily obtained.

It can be concluded from the above results that the tensile properties of the extruded material are mainly influenced by extrusion temperature, and reduction ratio that can be reflected by strain rate. Previous work suggested that the combined effect of these two factors on the as-extruded strength might be described by the temperature-compensated strain rate Z [19, 23–29]

$$Z = \dot{\varepsilon} \exp(\Delta H/GT) \quad (1)$$

where $\dot{\varepsilon}$ is the strain rate, ΔH is the activation energy for deformation, G is the universal gas constant, and T is the absolute temperature. In calculating Z, we used 140 kJ mol^{-1} as the ΔH value for the present Al–Si alloy [30]. For the strain rate, $\dot{\varepsilon}$, a mean value was calculated according to Feltham's formula [31] in combination with the minimized upper-bound solution [32]

$$\bar{\dot{\varepsilon}} = 6V_r D^2 \ln R \tan\omega/(D^3 - d^3) \quad (2)$$

where V_r is the ram speed, R the reduction ratio, D and d the diameters of billet and extrudate, respectively, and ω the semi-angle of the deformation zone given by

$$\omega = 54.1 + 3.45 \ln R \quad (3)$$

Temperature changes occurring during extrusion were considered, and the temperatures used in the calculation were the average values given by the

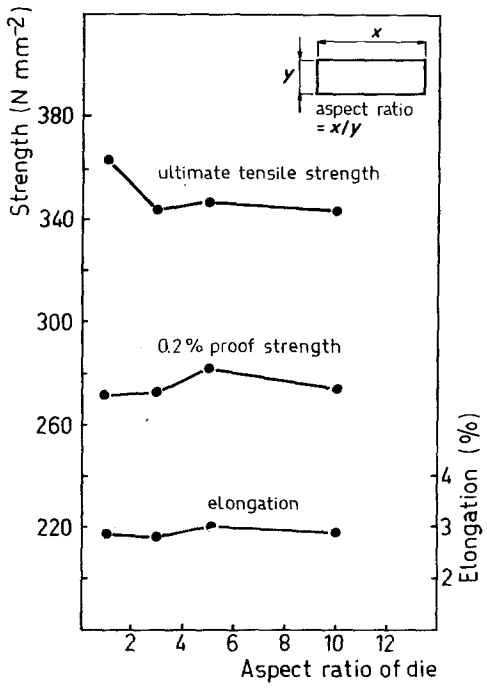


Figure 6 Effect of die aspect ratio on the as-extruded tensile properties at room temperature (extrusion temperature 375 °C, reduction ratio 20:1 and ram speed 5 mm sec^{-1}).

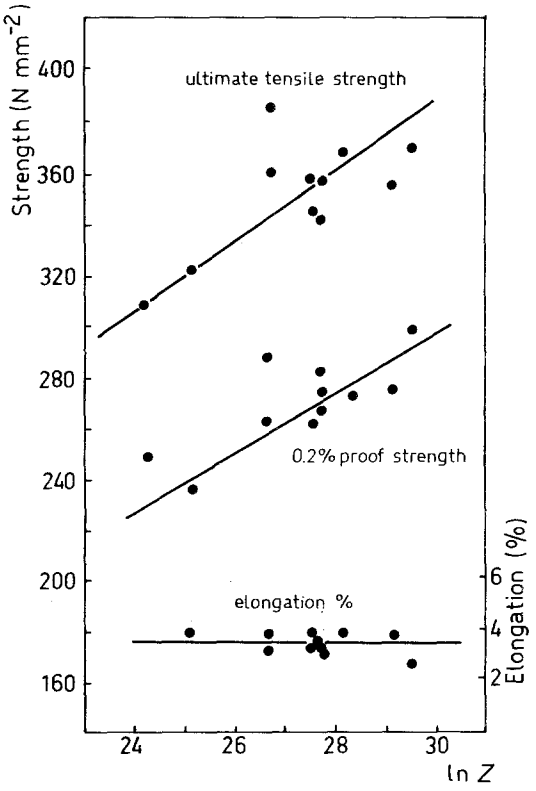


Figure 7 Relationship between the temperature-compensated strain rate and as-extruded tensile properties at room temperature.

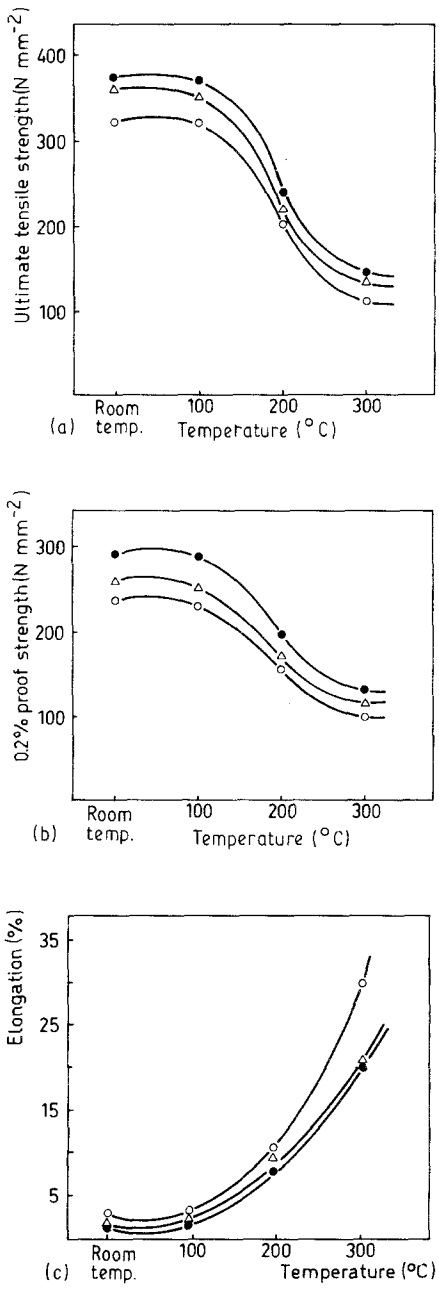


Figure 8 Effect of temperature on the as-extruded tensile properties of the material extruded at (●) 325 °C, (△) 400 °C, (○) 450 °C.

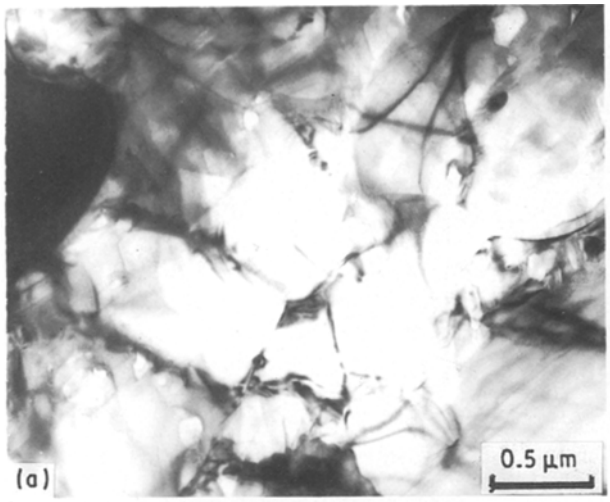
thermocouples inserted deeply in the container. Fig. 7 shows the relationship between ln Z and as-extruded tensile properties. The data covered the initial extrusion temperatures between 325 and 475 °C, the reduction ratios between 5:1 and 60:1, and the die aspect ratios between 1:1 and 10:1. The scatter in the figure can emanate from many sources. The main cause may be the static evolution in microstructure during the slow cooling from the extrusion temperatures, because the linear relation basically exists in a quenched material having experienced either dynamic recovery or dynamic recrystallization. Nevertheless, the indication is very clear that strengths increase with the rising temperature-compensated strain rate. As reported in an earlier paper [33], the variation is definitely associated with the size of granular silicon crystal particles, which has been shown to vary between 0.3 and 1.5 μm depending on extrusion conditions, and to have quantitative relationships with the temperature-compensated strain rate and the as-extruded strengths.

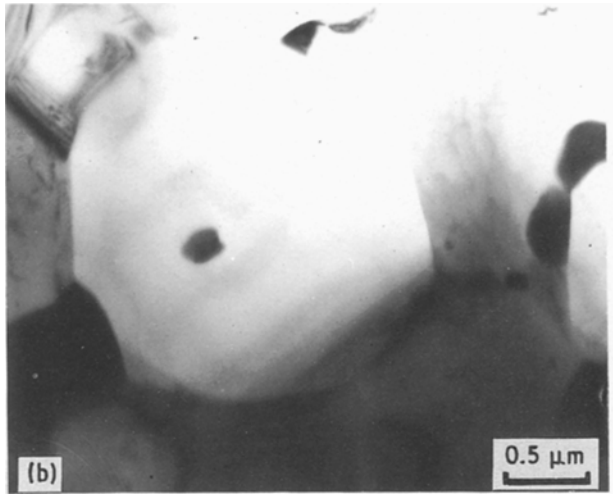
3.1.2. At elevated temperatures

At elevated temperatures, the strain/stress curves exhibited no definite yield point either. Only at 300 °C, was necking with appreciable plastic elongation prior to fracture observed. All the samples were broken on the plane perpendicular to the tensile direction. At 100 and 200 °C, fracture initiated at the edge of the specimens and then propagated, irrespective of extrusion conditions. At 300 °C, the initiation site of fracture was not observed.

The variation of high-temperature tensile properties with the extrusion temperature is shown in Fig. 8. It is evident that extrusion temperature still influenced high-temperature strengths. The main reason for this is that extrusion temperature determined the silicon crystal particle size prior to tensile testing, which is a function of extrusion conditions as indicated earlier. From the figure it can be seen that up to 100 °C, the extrudates almost had the same strength level as at room temperature, indicative of the stable silicon crystal particle size, and the retained substructure formed during extrusion, although the material was exposed at that temperature for 100 h. Above 100 °C, strengths and strain-hardening rate started to fall while ductility increased.

It is worth mentioning that the extruded material shows fairly attractive high-temperature mechanical properties. At a possible service temperature as high as 300 °C, an ultimate tensile strength of over 130 N mm^{-2} is obtainable, which is much higher than





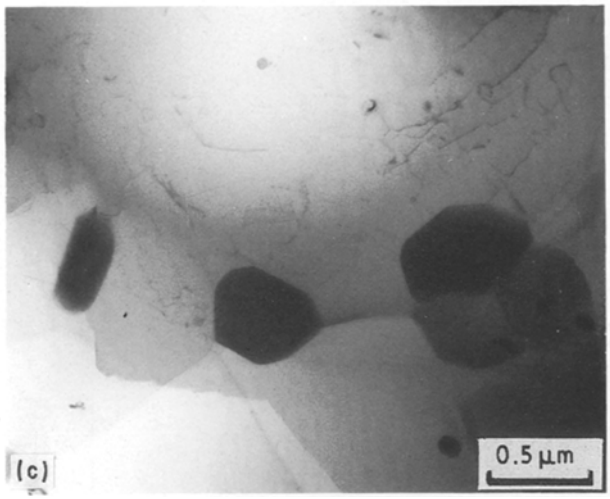


Figure 9 Transmission electron micrographs of the alloy (a) in the as-extruded state showing the high-density dislocation substructure, (b) in the as-solution-treated state showing the recrystallized equiaxed grains, and (c) in the as-aged state showing the distribution of precipitates.

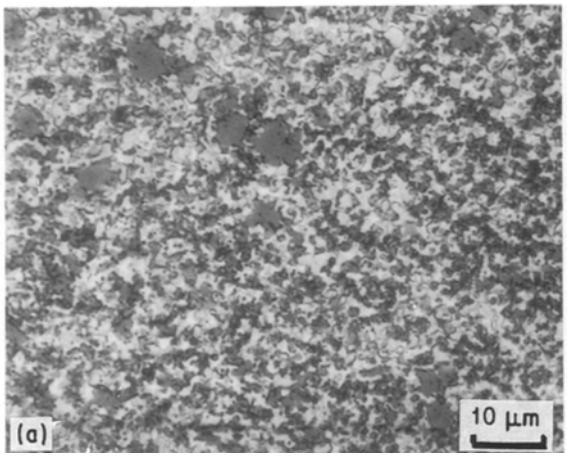
that of the I/M material of similar composition (about 47 $N mm^{-2}$) and comparable to other high-strength aluminium alloys.

3.2. As-heat-treated tensile properties

3.2.1. At room temperature

During the T6 temper heat treatment, several events of microstructural changes happened, as shown in Fig. 9. Because the extruded microstructure was not thermodynamically stable, it was statically recrystallized when the material was exposed to the elevated temperature in the solution treatment. As the material contained the age-hardening elements, copper and magnesium, it responded to ageing treatment by forming precipitates. More importantly, owing to the exposure of the material to the very high temperature in solution treatment, the coarsening of silicon crystal particles inevitably took place (Fig. 10). Consequently, the reduction in strength contributed by recrystallization and silicon-crystal particle growth counteracted the precipitation strengthening to a certain extent. Therefore, the extrusion condition dependence of mechanical properties could not be expected to be as strong as that before the T6 temper.

In general, the tensile data obtained from the T6-tempered specimens were more reproducible than those from the extruded specimens, implying a microstructural homogenization process occurring during the heat treatment. Fig. 11 shows the variation of the as-T6 tempered tensile properties with extrusion temperature. It can be seen that the 0.2% proof and



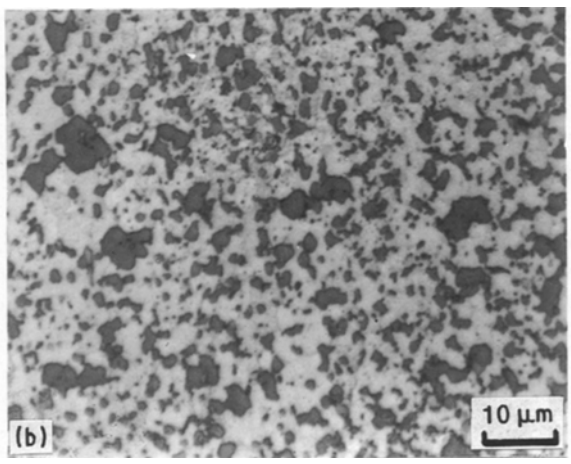


Figure 10 Comparison of the microstructure (a) before and (b) after the T6 temper treatment, showing the coarsening of silicon crystal particles (extrusion temperature 400 °C).

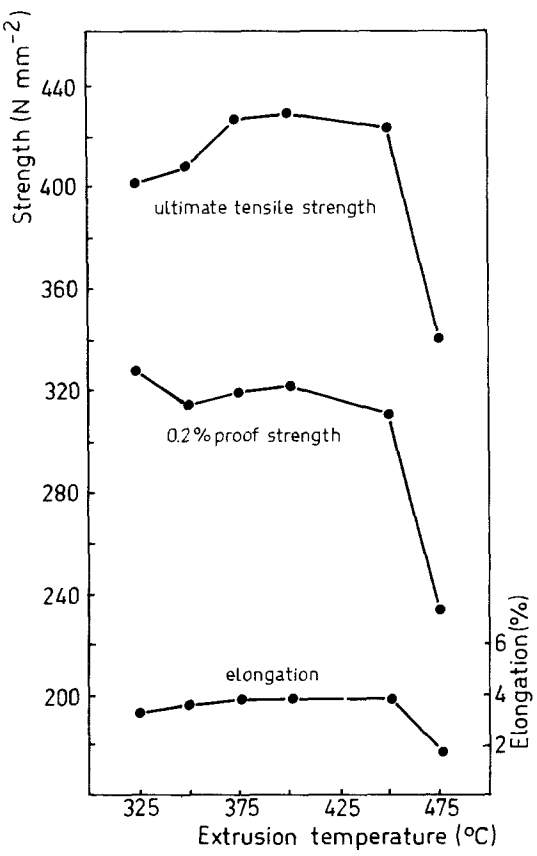


Figure 11 Relationship between extrusion temperature and the as-T6 tempered tensile properties at room temperature.

ultimate strengths were improved to various degrees as compared with those in Fig. 1. This means that the effect of precipitation strengthening was dominant at room temperature over that of recrystallization and silicon crystal particle growth. The ultimate tensile strength of the material extruded at 325 °C was relatively low, indicating a premature failure probably caused by imperfect interparticle bonding at the low extrusion temperature [22]. The 0.2% proof strength was kept at the same level over the extrusion temperatures except at 475 °C, where strength was detrimentally reduced. In comparison with the as-extruded ductility, there appeared to be no reduction in elongation after the T6 temper. Thus the T6 temper can substantially improve the room-temperature strengths of the material while the ductility remains at a low level. For the highest strength obtainable after the T6 temper, the optimal extrusion temperature range is between 375 and 400 °C, which is consistent with the result obtained from the extrudates.

Both 0.2% proof and ultimate strengths did not vary appreciably over the ranges of reduction ratio and die aspect ratio investigated, and all were improved more or less after the T6 temper. The average Young's modulus was raised from 83 to 92 kN mm^{-2}, which is in agreement with the measurements made by other workers [34]. This improvement could be attributed to the fine precipitates and the enhanced bonding at the interfaces between silicon crystal particles and aluminium matrix, resulting from the heat treatment. The elongation values of the material extruded at high reduction ratios were still slightly lower, being consistent with those of the as-extruded material.

3.2.2. At elevated temperatures

The T6-tempered material was tested at elevated temperatures using the same approach as that for the extruded material. In the tensile behaviour, only at 300 °C was necking visible and were fracture surfaces jagged. Below that temperature, fracture surfaces were flat and fracture initiated at the edge of the specimens [22]. The effect of temperature on tensile properties is presented in Fig. 12, which is in good agreement with the hardness measurements [7]. It can be seen that the extrusion conditions did not affect the properties of the T6-tempered material at high temperatures as much as those of the extruded material. It is quite understandable that at high temperatures the strength of a material is principally controlled by the balance between work hardening and dynamic softening, being much less dependent upon previous working history.

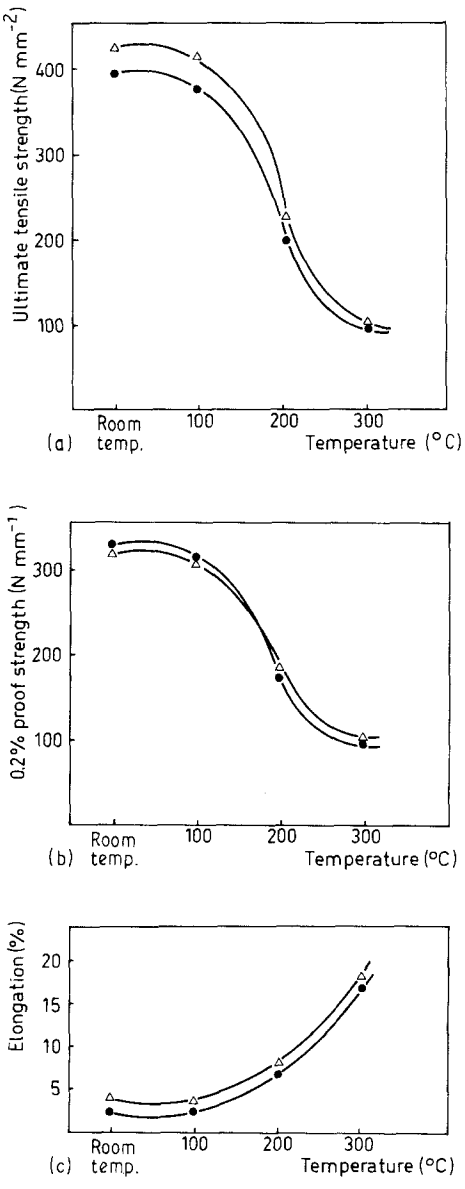


Figure 12 Effect of temperature on the as-T6 tempered tensile properties of the material, extruded at (●) 325 °C, (△) 400 °C.

The comparison of the thermal stability between the as-extruded and T6 tempered properties is shown in Figs 13 and 14. Up to 200 °C the as-T6 tempered strengths dropped to be equal to the as-extruded values. This implies that with increase in temperature the precipitation strengthening effect given by copper- and magnesium-containing intermetallics was weakening, and instead, the reinforcement of the silicon crystal particles mainly determined the mechanical properties at high temperatures. Because a solution treatment was involved in the T6 temper treatment, silicon crystal particles were coarsened (Fig. 10) and beneficial substructure (Fig. 9) was eliminated. As a balanced result, the as-extruded strengths at above 200 °C appeared better. This finding is very important. For the first time the negative effect of the heat treatment on the high-temperature properties of the Al–Si–X alloy system has been observed, because the T6 temper or modified T6 temper has been taken as a normal practice for this alloy system, including Al–20Si–3Cu–1Mg alloy [2–4, 7]. The present results suggest that at least for the P/M alloy studied, processing procedures depend upon service conditions of the material. For application temperatures below 200 °C, heat treatment is, of course, necessary to take advantage of its ageing response. For uses at higher temperatures, however, the T6 appears to be unnecessary because the heat treatment gives rise to the disadvantages of coarsening silicon crystal particles and of eliminating beneficial substructure. In this case, the material is better used in the as-extruded condition. Moreover, because the magnesium- and copper-bearing precipitates are thermally unstable, the necessity of their additions seems to be doubtful. Clearly, a better way of maintaining high strengths at elevated temperatures is to add a transition element such as iron or nickel.

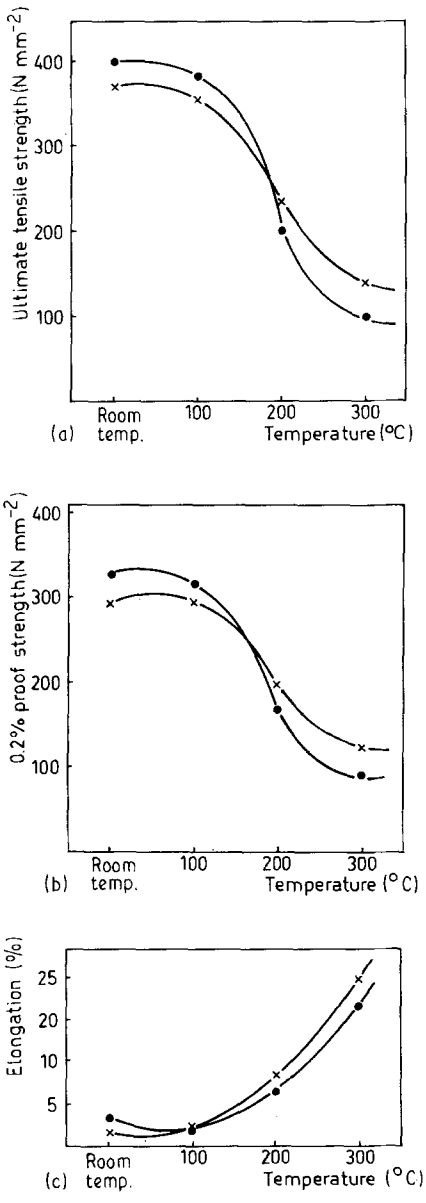


Figure 13 Comparison of the high-temperature tensile properties between (×) the extruded and (●) the T6 tempered material extruded at 325 °C.

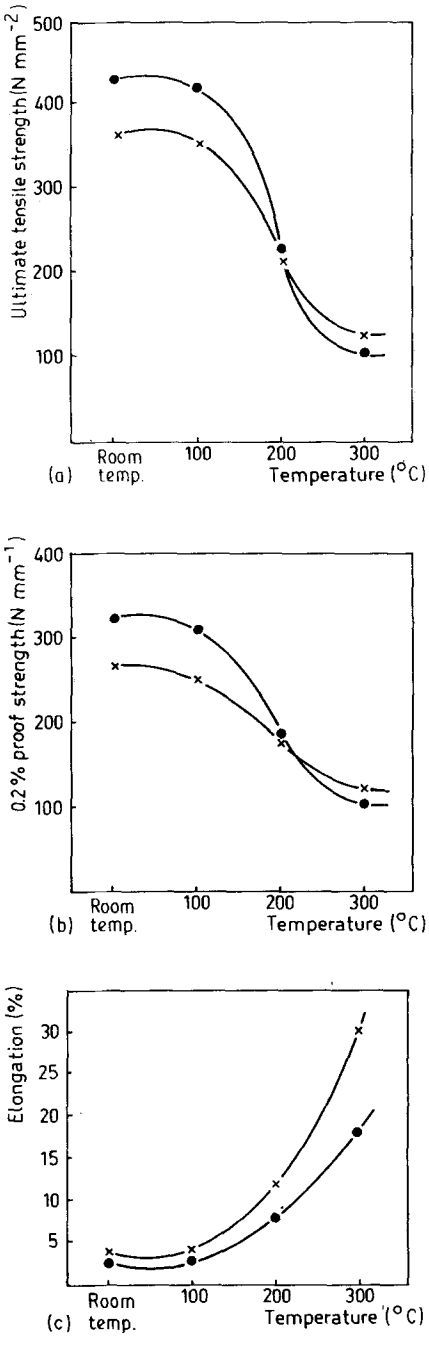


Figure 14 Comparison of the high-temperature tensile properties between (×) the extruded and (●) the T6-tempered material extruded at 400 °C.

4. Conclusions

1. The room-temperature strengths of the extruded P/M Al–20Si–3Cu–1Mg alloy increase with decreasing extrusion temperature and reduction ratio. Elongation is not sensitive to the extrusion temperature, although it is slightly lower at higher reduction ratios. The die aspect ratio does not significantly affect the as-extruded tensile properties. The relationship between extrusion conditions and properties can successfully be described using the temperature-compensated strain rate, Z. The optimal extrusion conditions have been found at extrusion temperatures between 375 and 400 °C, and at reduction ratios below 40:1.

2. The extruded material is completely stable up to 100 °C. With further increase in temperature, strengths and strain-hardening rate decline while ductility increases. Up to 300 °C, an ultimate tensile strength of over 130 N mm^{-2} can be obtained under the optimal extrusion conditions, being much higher than that of the I/M material. The optimized extrusion conditions also hold for the T6-tempered product.

3. The T6 temper worsens the high-temperature mechanical properties of the material, due to the coarsening of the silicon crystal particles and the recrystallization of the aluminium matrix. The processing procedures of the P/M Al–20Si–3Cu–1Mg alloy are thus service-condition dependent. For use at and above 200 °C, the T6 temper should be excluded. Replacement of copper and magnesium by a transition element such as nickel or iron, is strongly suggested in order to achieve better high-temperature mechanical properties.

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