SUPERPLASTIC BEHAVIOUR IN DYNAMICALLY RECRYSTALLIZING Al-Li ALLOY 8090

N. Ridley and R. Amichi
University of Manchester and UMIST, Materials Science Centre, Grosvenor Street, Manchester M1 7HS, UK

Abstract

The superplastic (SP) deformation behaviour of an Al-Li alloy (8090) sheet material which had been processed to develop superplasticity by strain enhanced/dynamic recrystallization has been examined over a wide range of temperatures. While the optimum temperature for SPF was ≈530°C, the alloy showed significant superplasticity at temperatures of 400°C and below. The reasons for the high resistance of the material to strain localisation are discussed. The application of rapid pre-straining led to an enhancement of SP behaviour, i.e. increased tensile ductility and reduced flow stresses, but the use of pre-annealing treatments was generally not beneficial.

Introduction

Aluminium alloys may be processed to develop a superplastic microstructure either by static recrystallisation prior to SP deformation, or by strain enhanced or dynamic recrystallization during the earlier stages of deformation. Grimes [1] has reported that Al-Li alloys may be processed to develop the required microstructure by either route. Previous studies by the authors [2] identified the optimum conditions for superplastic flow for Al-Li 8090 processed by both routes and showed that the statically recrystallised material had a lower potential for SP behaviour ie lower tensile ductility, higher flow stresses and slower optimum deformation rates. For both materials it was shown that SP flow could be markedly enhanced by control of the strain rate path.

The present work concentrates on the dynamically recrystallising material and investigates SP behaviour over a wider temperature range than was previously examined. The purpose of the work was to determine whether significant SP behaviour could be obtained in conventionally processed materials at temperatures appreciably below the previous determined optimum of

530°C, without substantially raising the flow stress. The advantages of a lower forming temperature would be reduced grain growth and a suppression of lithium loss from the surface of the alloy [3]. The effects of rapid pre-straining and pre-annealing treatments on superplastic behaviour have also been investigated.

Experimental

The alloy examined was Lital A(8090) of nominal wt% composition: Al-2.5Li-1.2Cu-0.6Mg-0.1Zr, produced by Alcan. The material was obtained in the form of sheet of 3mm thickness. Tensile specimens of 10mm gauge lengths and 5mm gauge width were machined with the gauge length parallel to the final rolling direction of the sheet. Tests were carried out in a three-zone split furnace, attached to the cross-head of an Instron tensile machine interfaced with a computer. Specimens were strained to failure or to predetermined elongations at constant strain rates in the range 10^{-2}-10^{-4} s^{-1}, for temperatures between 300°C to 530°C. The strain hardening exponent, n, and the strain hardening parameter, γ, (where $\gamma = (1/\sigma)\,\partial\sigma/\partial\varepsilon$) were determined as a function of strain from true stress-true strain curves. The strain rate sensitivity index, m, was also measured as a function of strain using jump strain rate testing. Further tests involved rapid initial strain rates to predetermined strains prior to deformation to failure at more optimum rates. The effects of pre-annealing treatments on microstructure and superplastic behaviour have also been examined.

Light microscopy and scanning electron microscopy were carried out on specimens etched in modified Keller's reagent. Thin foils for transmission electron microscopy (TEM) were prepared from 3mm discs in a twin jet electropolishing machine using 33% HNO_3 in methanol at 30°C and 18V, and examined in a Philips 400T microscope.

Results and Discussion

Mechanical Behaviour

Specimens were pulled to failure at constant strain rates for temperatures in the range 300-530°C, and the results are shown in Figure 1. It is clear that superplastic behaviour is apparent at 300°C, but becomes appreciable, >500% elongation, at temperatures of 400°C and above. At 500°C and 530°C, tensile elongations >900% were recorded for a strain rate of 5×10^{-4} s^{-1}. No attempt was made to establish an optimum strain rate at the lower temperatures as it was considered that anything less than 2×10^{-4} s^{-1} was unrealistically slow. Stress-strain data for a strain rate of 2×10^{-4} s^{-1} for the range of temperatures investigated are seen in Figure 2. It can be seen that at temperatures below 400°C, flow stresses increase sharply to commercially unattractive levels.

It was shown by Ash and Hamilton [4] that strain hardening could make a significant

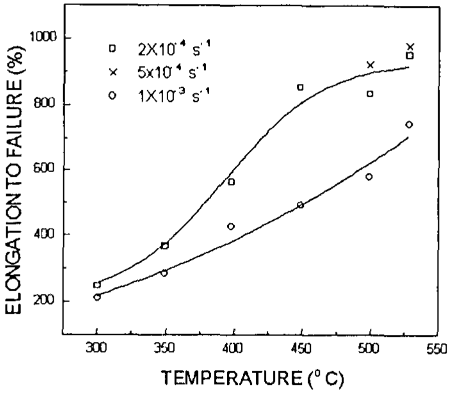

Fig.1 Elongations to failure.

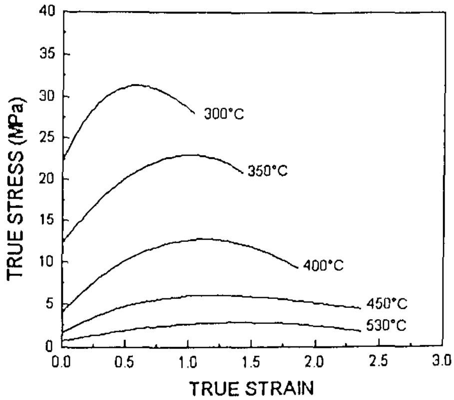

Fig.2 Stress versus strain for strain rate of $2x10^{-4}$ s^{-1}.

contribution to the tensile stability of alloys as the superplastic microstructure evolves by dynamic/strain enhanced recrystallisation. For the present alloy, measured values of m and n are plotted as function of strain for temperatures of 530°C, 540°C and 400°C. It can be seen that at 530°C at the start of the deformation the value of m is too low, <0.3, to maintain substantial tensile stability, but the n value is high, ≈ 0.4. Hence, without strain hardening the material would show early necking leading a low tensile elongation. As the strain increases and the SP microstructure evolves, the value of m progressively increases reaching a maximum value of ≈ 0.65 at strains in the range of 0.75-1.0, while the value of n decreases. Hence, the role of m in maintaining tensile stability becomes increasingly dominant while that of strain hardening diminishes as n approaches zero.

Similar behaviour is apparent at 450°C, but m increases more slowly. However, the high value of n in the early stages of deformation has inhibited mechanical instability until m becomes dominant leading to a substantial tensile strain to failure of 2.26 (860%). At 400°C, for the relatively high strain rate of 10^{-3} s^{-1}, m remains essentially constant with strain at ≈ 0.3, while n remains high before falling to zero at $\epsilon \approx 1.15$ (220%). Hence, tensile stability is attributable to the influence of both factors as this strain is approached. It is interesting to note that while the value of m may be regarded as marginal for SP flow, it is sufficiently high to permit a further tensile elongation of 200%, leading to an elongation to failure of 430%.

Effect of Rapid Pre-straining on SP Flow

The procedure of controlling the strain rate path by applying a rapid pre-strain rate followed by deformation at a lower, more optimum, strain rate was initially applied by Geary et al [5] as a means of minimising cavitation in the dynamically recrystallizing alloy, Supral

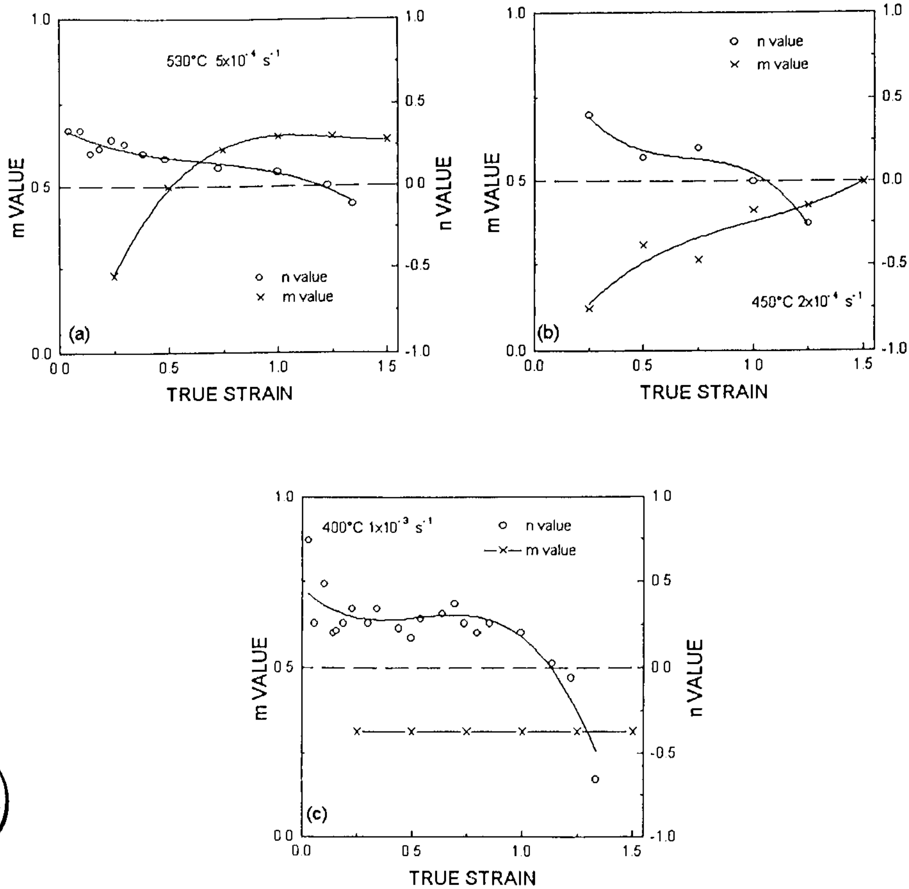

Fig.3 Variation of m and n with strain
(a) 530°C, (b) 450°C and (c) 400°C.

220, and so improving its superplastic ductility. Similar procedures have subsequently been applied to Al-Li alloys by Ghosh and Gandhi [6], Hamilton et al [4,7] and Amichi and Ridley [2], to enhance ductility and reduce the times to reach pre-determined strains. For an Al-Li alloy at 530°C, it was shown [2] that rapid pre-straining followed by constant velocity deformation led to a substantial enhancement in tensile ductility, i.e. from 900% elongation to 1800%. TEM studies showed that the rapid pre-strain rate (8.3×10^{-3} s^{-1}) gave a fully recrystallised (dislocation free) microstructure after a relatively small strain (0.4=50% elongation), whereas for deformation at the optimum constant strain rate of 5×10^{-4} s^{-1} the SP microstructure was still evolving (increasing m) after a strain of 0.75 (>100%), (see Fig.3a).

The combined effects of strain hardening and strain rate hardening on tensile ductility have

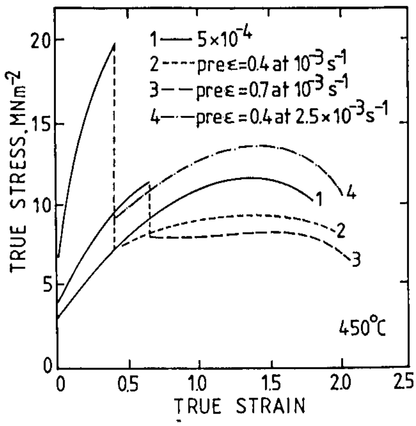

Fig.4 Effect of rapid pre-straining on stress versus strain.

been considered by Caceras and Wilkinson [8] and Hamilton et al [4,7] using an instability parameter, I, derived from earlier work by Hart [9] and Nichols [10], where $I=(1-\gamma- m)/m$. The greatest mechanical stability is associated with I $\leq$ 0. Hence, substitution of measured values of m and γ for various rapid pre-strain rates in this relationship can enable the extent to which specimens can be deformed prior to the onset of excessive necking, to be predicted. Using this approach, it was apparent that at the temperature of interest, 450°C, it would not be possible to apply rapid strain rates much in excess of 10^{-3} s^{-1}. Consequently, the effects of two pre-strain rates, 1×10^{-3} s^{-1} and 2.5×10^{-3} s^{-1}, applied for a pre-strain of 0.4 (50% elongation) were examined. While the higher rate led to some enhancement of tensile ductility (>600%el.) on subsequent deformation at 5×10^{-4} s^{-1}, it also caused an increase in the maximum flow stress from 11MNm^{-2} to 13MNm^{-2}. However, the lower pre-strain rate led to enhancement of tensile ductility to a similar extent, but decreased the flow stress to $\approx$9MNm^{-2} (Fig.4).

The effect of a higher pre-strain of 0.7 (100% elongation) for the pre-strain rate of 1×10^{-3} s^{-1} is also shown in Figure 4, and led to a further enhancement of strain to failure and to a reduction in flow stress to $\approx$8MNm^{-2}. Although these flow stresses are higher than the corresponding value of $\approx$5MNm^{-2} at 530°C without pre-straining, there would be beneficial effects of SPF at the lower temperature of 450°C, as outlined in the Introduction. Alternatively, the application of a rapid pre-strain rate at 450°C prior to deformation at the slower strain rate of 2×10^{-4} s^{-1} , would lead to an even lower flow stress than the maximum value of 6 MNm^{-2} seen in Figure 2, for no pre-strain. The considerable SP strains attainable at 450°C (>800%el.) and the relatively low flow stresses involved should enable the effective use of back pressure to suppress cavitation, which is a characteristic of SP flow in aluminum alloys, including Al-Li [11].

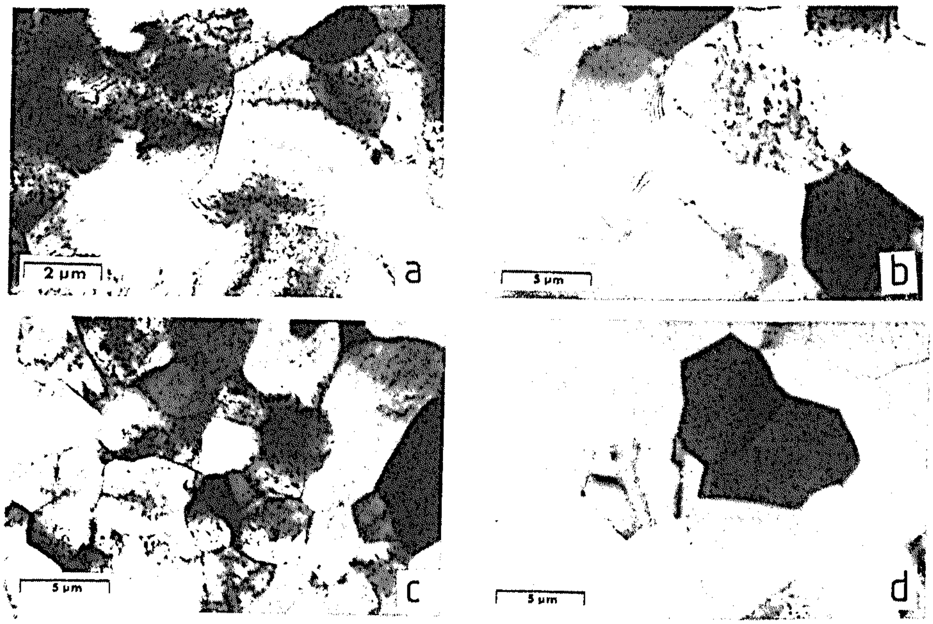

Fig.5 TEM micrographs (a) as-received, (b) annealed 30 minutes at 530°C, (c) annealed 90 minutes at 500°C, and (d) annealed 60 minutes at 530°C.

Pu and Huang [12] have recently outlined processing routes for the development of SP behaviour in an Al-Li alloy at relatively low temperatures, <450°C. While the material showed a reasonable SP response at 350°C, flow stresses were high (>20MNm^{-2}). However, at temperatures >450°C, where the flow stresses would be expected to be lower, the alloy showed poor SP behaviour.

Effect of Pre-annealing Treatment

Previous work [2] has shown that the effect of rapid pre-straining is to enhance the transformation of the starting material to a fully recrystallized, dislocation-free, microstructure, capable of sustaining SP flow. In an attempt to enhance the superplastic deformation potential of the material prior to deformation, studies were carried out on the effect of pre-annealing treatment on the as-received material, which showed a highly dislocated sub-grain structure (Fig.5a). Specimens annealed in a salt bath for times of up to 90 minutes were examined using the TEM. In accord with previous studies [12], it was observed that the material had a high resistance to static recrystallization, with dislocated sub-grains being visible after 30 minutes at 530°C and 90 minutes at 500°C (Fig.5b and c). However, a well developed grain/sub-grain structure which was essentially free from dislocations was obtained after annealing for 60 minutes at 530°C (Fig.5d).

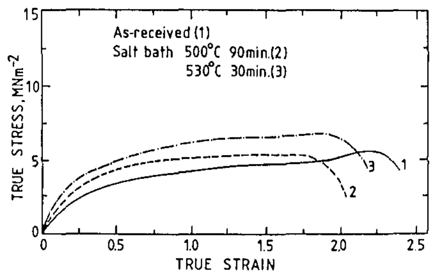

Fig.6 Effect of pre-annealing on stress versus strain at 530°C and $5x10^{-4}$ s^{-1}.

On subsequent deformation under the optimum conditions determined for the as-received material [2] (530°C; $5x10^{-4}$ s^{-1}), it was observed that, apart from small strains, the *m* values measured as a function of strain were lower than the *m* values for the as-received material. As a consequence, the elongations to failure were reduced and the flow stress levels were increased on pre-annealing (Fig.6). These differences were believed to be due to the smaller evolving grain sizes of the as-received material, compared to material which had been pre-annealed and, as a consequence, had undergone some grain growth. The observations are essentially consistent with the earlier study [2] which showed that strain enhanced/dynamic recrystallization resulted in superior superplastic behaviour over that associated with the static recrystallization route.

Conclusions

1. Al-Li (8090) alloy sheet material which had been commercially processed to develop superplasticity by strain enhanced/dynamic recrystallization, showed a considerable potential for SPF over a wide range of temperatures. Superplastic behaviour was apparent at 300°C and became significant at 400°C, well below the optimum SP deformation temperature of 530°C.

2. Strain hardening made a significant contribution to tensile stability over the range of temperatures studied. The rate at which the recrystallized structure evolved on straining, characterized by increasing *m*, decreased with falling temperature. At 530°C, *m* increased relatively rapidly, while at 400°C *m* remained essentially constant at ≈0.3, with increasing strain.

3. The application of a relatively rapid pre-strain at 450°C led to an enhancement of tensile ductility, and to a maximum flow stress of ≈8MNm^{-2} at a strain rate of $5x10^{-4}$ s^{-1}, and ≈6MNm^{-2} at $2x10^{-4}$ s^{-1}. These flow stress levels at this reduced deformation temperature, should permit the effective use of back pressure to inhibit cavitation, which is a characteristic of SP flow in Al alloys.

4. The use of pre-annealing treatments had an adverse effect on the SP deformation potential of the as-received material at the optimum deformation temperature of 530°C.

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