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LETTER

Influence of strain rate on strength and ductility in an aluminum alloy processed by equal-channel angular pressing

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Introduction

Processing through the application of severe plastic deformation (SPD) may be used to achieve exceptional grain refinement in bulk solids [1]. The materials produced in this way generally exhibit high strength but usually this is accompanied by a corresponding loss in the overall ductility. This duality in behavior, in which the strength increases but the ductility decreases, led to the introduction of the so-called paradox of strength and ductility [2] and it gave rise to numerous attempts to develop successful strategies for achieving both high strength and high ductility in nanostructured materials [3–15]. However, many of these approaches are applicable only to a limited range of materials and accordingly they are not generally available for use in all metallic systems. Examples of these specialized approaches include the ageing and introduction of nanoscale particles in an Al–Ag alloy [7] and a tailoring of the stacking fault energy in Cu through appropriate alloying [8].

The production of bulk nanostructured metals is now achieved relatively easily through the use of techniques such as equal-channel angular pressing (ECAP) [16] and high-pressure torsion (HPT) [17]. Moreover, the development of superior properties remains important because of the innovative potential for these materials in a wide range of applications associated especially with their use in extreme environments: for example, in biomedical or orthopedic applications or under cryogenic operating conditions in the oil and gas sectors [18]. It is therefore desirable to develop a more general approach that may be used to produce both high strength and ductility in all metallic systems when processing by SPD.

Early results showed the introduction of high strength and high ductility in Cu and Ti when these metals were processed to very high strains in ECAP and HPT, respectively [2]. However, this approach was not successful with the Zn–22 wt% Al eutectoid alloy, where pressing through a total of 24 passes, equivalent to a maximum imposed strain of ~24, revealed no evidence of the onset of a region of high ductility [19]. By contrast, an increase in ductility at high strains was reported recently for pure Cu in experiments conducted using ECAP processing up to a total of 25 passes [20, 21]. The present investigation was initiated specifically to examine whether the testing strain rate influences the tensile strength and ductility when using samples processed by ECAP.

The experiments were conducted using an Al–3 wt% Mg solid solution alloy, equivalent to Al–3.3 at.% Mg, containing 0.004% Si and 0.001% Fe as minor impurities.

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The as-received material was cut into rods with dimensions of 25 × 25 × 150 mm^3, these rods were swaged to a diameter of 10 mm and billets were cut for ECAP with lengths of 60 mm. Prior to ECAP, all billets were annealed at a temperature of 773 K for 1 h to give an average grain size of ~500 μm.

The processing by ECAP was performed at room temperature (298 K) for totals of four and eight passes using route B_c in which the billets are rotated by 90° in the same sense between each pass [22]. The solid die had an internal channel angle of $\Phi = 90°$ and an outer arc of curvature of $\Psi \approx 20°$ at the point of intersection of the two parts of the channel thereby giving an imposed strain of ~1 on each separate pass [23]. The billets showed no visible surface cracks when pressing up to eight passes but there was evidence for the development of deep serrations when the pressing was continued to a total of 10 passes.

Tensile specimens with gauge dimensions of 2 × 3 × 4 mm^3 were machined from the central regions of the billets with the gauge sections oriented parallel to the pressing direction. These specimens were tested in tension at 403 K using an Instron machine operating at a constant rate of cross-head displacement with initial imposed strain rates in the range from 1.0×10^{-3} to 1.0 s^{-1}. A temperature of 403 K was selected for the tensile tests because static annealing for 1 h has shown this is the highest feasible annealing temperature for this alloy at which there is essentially no grain growth [24–26]. Taking the melting temperature for the alloy as ~900 K, it follows that the tensile tests were conducted at an homologous temperature of ~0.45 T_m where T_m is the absolute melting temperature.

Earlier experiments showed the grain size in this alloy after processing by ECAP through four and eight passes is equal to ~0.3 ± 0.1 μm thereby demonstrating that the grain size has attained an essentially equilibrium size after pressing through four passes [26–28]. There are also results showing that the microstructure of the alloy becomes more homogenous and equiaxed after eight passes by comparison with smaller numbers of passes [27] and it is well known that higher numbers of passes lead to higher fractions of grain boundaries having high angles of misorientation [20, 29, 30].

Figure 1 shows plots of the stress–strain behavior for the samples processed through (a) four passes (4p) and (b) eight passes (8p). These plots demonstrate that at the lowest strain rates the samples pressed through eight passes exhibit lower flow stresses and higher elongations to failure than the samples pressed through four passes whereas at the fastest strain rates the flow stresses and elongations are reasonably similar. The highest elongations of ~225% were recorded for the samples pressed through eight passes of ECAP at the lowest strain rates of 1.0×10^{-3} and 3.3×10^{-3} s^{-1} whereas the maximum elongation after processing through four passes was ~120% at the same lowest strain rate of 1.0×10^{-3} s^{-1}.

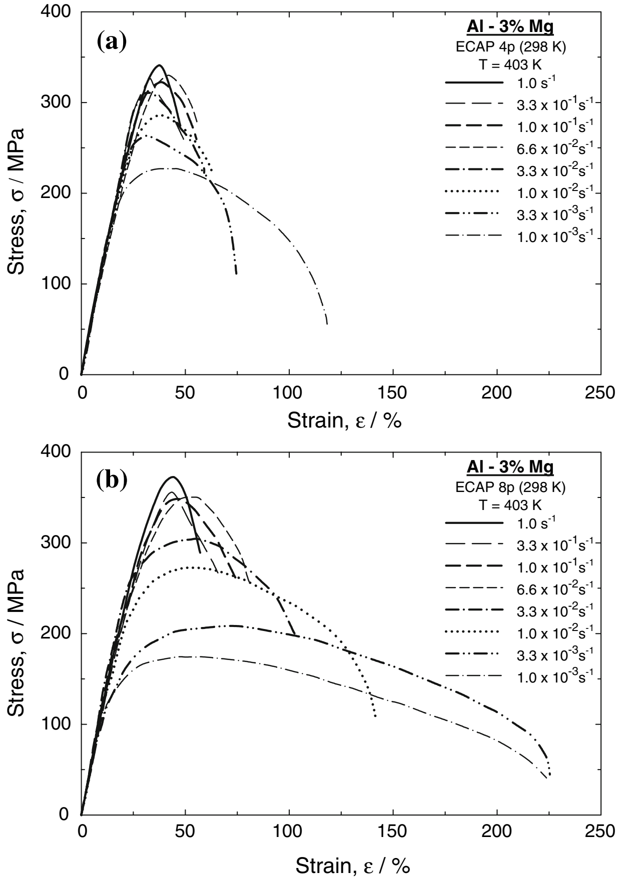

Fig. 1 Stress–strain behavior for specimens tested in tension at 403 K after processing by ECAP through **a** four passes and **b** 8 passes

A closer inspection of Fig. 1 permits a direct comparison of the individual stress–strain curves for the 4p and 8p specimens for imposed strain rates of (a) 1.0×10^{-3} and (b) 1.0×10^{-1} s^{-1}. At the lower strain rate it is evident that the samples follow the conventional behavior with a higher stress corresponding to a lower ductility. However, at the faster strain rate of 1.0×10^{-1} s^{-1} the sample pressed through eight passes exhibits not only a higher elongation to failure but also a higher strength compared to the sample pressed through only four passes. At this faster strain rate, the maximum elongation and the strength of the eight pass sample, defined as the maximum measured engineering stress, were ~75% and ~350 MPa, respectively, whereas these values were reduced to ~55% and ~320 MPa, respectively, for the sample processed through only four passes. This unusual behavior is evident also when inspecting the stress–strain curves for the samples pulled at an even higher strain rate of 1.0 s^{-1}. Thus, these results demonstrate that the conventional trend of high strength and low ductility is followed for tests conducted at strain rates up to ~10^{-1} s^{-1} but this trend breaks down and even becomes reversed when testing at more rapid strain rates.

The results obtained through systematic testing of the Al–3 wt% Mg alloy over a wide range of strain rates suggest there may exist a critical strain rate delineating a transition to superior mechanical properties which are achieved when testing at faster strain rates. If this is correct, it suggests an alternative approach for achieving both high strength and reasonably high ductility when testing after processing through SPD procedures such as ECAP or HPT.

To more clearly delineate this transition in flow behavior, Fig. 2 plots the maximum true stress against the imposed initial strain rate for the 4p and 8p samples, where the slope of this type of plot gives the value of the strain rate sensitivity, *m*. At the lower strain rates the strain rate sensitivity changes from $m \approx 0.2$ for the 8p sample to $m \approx 0.05$ in the 4p sample and this is consistent with the lower flow stress and the higher ductility in the 8p material. The low strain rate sensitivity of ~0.05 is consistent with a thermally activated flow process at this relatively low homologous temperature and the value of $m \approx 0.2$ in the samples processed through eight passes suggests a possible additional contribution from grain boundary sliding and superplastic flow at these low strain rates where this is due to the higher fraction of boundaries having high angles of misorientation in samples pressed through larger numbers of ECAP passes. The development of some grain boundary sliding at the lower strain rates suggests that necking may be at least partially suppressed leading to higher elongations to failure [31]. This trend is confirmed in Fig. 3 where the total elongations are plotted against the imposed initial strain rates for both the 4p and 8p samples and it is apparent, therefore, that the results recorded in Fig. 2 and 3 are mutually consistent. Nevertheless, the Al–3 wt% Mg alloy fails to achieve true superplastic elongations which are defined as tensile elongations to failure of at least 500% [32].

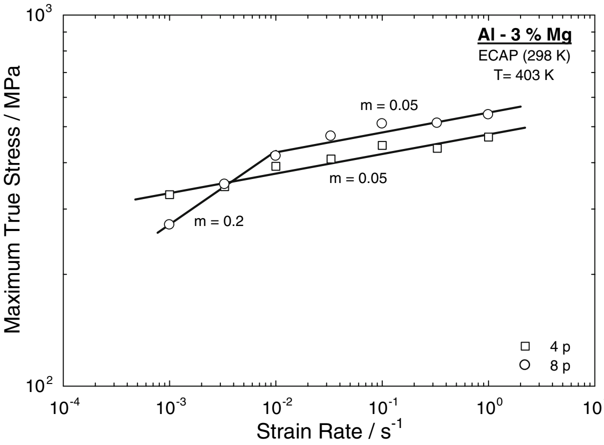

Fig. 2 Maximum true stress versus imposed strain rate for the 4p and 8p samples tested at 403 K showing the values of the strain rate sensitivity, *m*

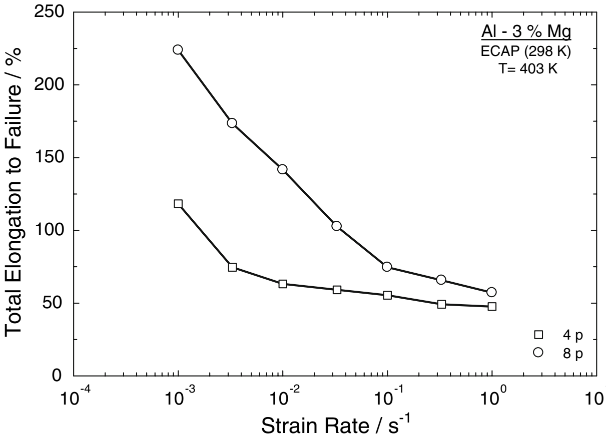

Fig. 3 Total elongation to failure versus imposed strain rate for the 4p and 8p samples tested at 403 K

In practice, the earlier literature is inconsistent on the variation of strength and ductility in materials processed using SPD techniques. On the one hand, high strength and higher elongations were achieved after processing to high strains for samples of Cu after 16 passes of ECAP and Ti after five revolutions of HPT when testing in tension at a strain rate of ~10^{-3} s^{-1} [2]. On the other hand, no such high strength and higher elongations were recorded in the Zn–22 wt% Al alloy when processing by ECAP to 24 passes and testing at strain rates of either 1.0×10^{-3} or 1.0×10^{-2} s^{-1} [19]. The occurrence of high strength and high ductility after processing to very high strains is probably due to the transition from the heavily-deformed and heterogeneous microstructures present at the lower strains when processing by ECAP to the more homogeneous structures that develop after larger numbers of passes in ECAP [27, 33]. However, the present results suggest that, in addition, the testing strain rate may also play a critical role.

In summary, an Al–3 wt% Mg alloy was processed by ECAP through four or eight passes and then tested in tension at 403 K using strain rates in the range from 1.0×10^{-3} to 1.0 s^{-1}. The results show that at the lower strain rates the samples pressed through eight passes exhibit lower flow stresses and higher ductilities than the samples pressed through four passes but at faster strain rates, at and above ~10^{-1} s^{-1}, there is evidence for both higher strength and higher ductility after pressing through eight passes. At these faster strain rates, the strain rate sensitivity is ~0.05 in both the 4p and the 8p samples.

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