CONF-950201--23

UCRL-JC-122996
PREPRINT

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This paper was prepared for submittal to
1995 TMS Meeting
Las Vegas, NV
February 12-16, 1995

December 20, 1995

Lawrence Livermore National Laboratory

ENHANCED TENSILE DUCTILITY OF COARSE-GRAIN AL–MG ALLOYS

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Abstract

The effective forming of near-net-shape parts from aluminum alloys is of significant interest for automotive and aerospace applications. It has traditionally been thought that the very high tensile ductilities necessary for many near-net-shape forming operations, in excess of 100%, were only available in fine-grain superplastic materials. Tensile ductilities in excess of 300%, however, have been attained in coarse-grain, non-superplastic, binary Al–Mg alloys as a result of a solute-drag-controlled dislocation creep process. Such enhanced ductilities from non-superplastic Al–Mg alloys might offer an inexpensive alternative to superplastic alloys that often require elaborate processing to develop fine grain sizes. In this investigation, tension tests at various temperatures and strain rates were used to characterize the ductility, strain-rate sensitivity, and strain-hardening behavior of two binary alloys: Al–2.8 wt.%Mg and Al–5.5 wt.%Mg. Under the proper conditions, tensile elongations of 300% were achieved. The tensile elongations in these binary alloys were governed not by the onset of tensile instability in the classical sense, but by the rate of neck propagation when failure occurred by necking to a point. Predictions of tensile ductility for the case of failure by necking were made using a simple numerical model, and the results are correlated with data from the two binary alloys.

Superplasticity and Superplastic Forming
Edited by Amit K. Ghosh and Thomas R. Bieler
The Minerals, Metals & Materials Society, 1995

1 Introduction

Very large tensile ductilities of over 300% have been observed in coarse-grain, solid-solution alloys of aluminum and magnesium [1, 2]. In a number of these cases the materials were observed to deform by a solute-drag creep process, which is distinctly different from the grain-boundary sliding process that leads to superplastic ductilities [2, 3]. The high tensile ductility achieved by solute-drag creep in coarse-grain materials has been referred to as *enhanced ductility*, a term useful in distinguishing this behavior from superplasticity [3, 4]. Fine-structure superplasticity requires the development of a very fine, stable grain size, typically on the order of 5 μm or less [5]. Superplastic materials are often expensive owing to the special alloying additions and processing required to obtain fine grain sizes. Because enhanced ductility does not require a fine grain size, material costs can be significantly lower than for superplastic materials. The required ductility for forming near-net-shape parts can be met by enhanced-ductility, solid-solution alloys in many cases. Enhanced ductility can therefore offer a more economical alternative to superplasticity for these forming operations. The promises of practicality and economy in utilizing enhanced ductility motivate the present investigation.

An experimental study was made of the mechanical properties of two binary aluminum–magnesium alloys. Binary alloys were chosen in order to minimize the complications added by effects from additional alloying agents. For the binary alloys chosen the only alloying variable is magnesium concentration, either at 2.8 or 5.5 weight percent magnesium. Tensile tests were conducted on these materials at a variety of temperatures and strain rates. The resulting data were used to investigate the effects of magnesium content, strain-rate sensitivity, strain-hardening rate, and strength on tensile ductility. Finally, the tensile ductilities were correlated with predictions from a numerical model of neck propagation.

2 Experimental Procedures

Two high-purity castings of aluminum–magnesium alloys were obtained. The compositions of these casting by weight percent were 2.8% Mg (Al–2.8Mg) and 5.5% Mg (Al–5.5Mg) with a balance of Al in each case. Both castings were cylindrical with diameters of 76 mm. Sections of length 76 mm were cut from each casting and were homogenized in air at 500°C for 24 hrs. The height of each homogenized piece was reduced by upset forging at 300°C and subsequent warm rolling at 300°C from an initial height of 76 mm to a final thickness of 16 mm. The resulting plates were each rolled at room temperature to a final thickness of 5 mm. Following rolling, each plate was annealed at 450°C for 30 min. and then flattened by pressing at 450°C. Tension-test samples with 25.4-mm gage lengths were machined from the final plates of each alloy. Optical microscopy revealed a linear-intercept grain size of 30 μm for the Al–2.8Mg material and 250 μm for the Al–5.5Mg material.

Two types of tension tests were performed on each material, the first being elongation-to-failure tests. Tensile elongation-to-failure tests were performed at constant strain rates and temperatures of 300°C, 400°C, and 500°C in order to evaluate tensile ductility. The second test type was the strain-rate-change test. These tests were performed at several constant temperatures in order to evaluate the strain-rate sensitivity of each material. Temperatures used for strain-rate-change tests were 300°C, 400°C, and 500°C, with the strain rates ranging from 10^{-4} s^{-1} to 2×10^{-2} s^{-1}. All strain rates were prescribed during testing as a constant rate-of-change in true strain. Before each strain-rate-change test, an initial prestrain of 10% was introduced in order to ensure a stable microstructure. Strain rates were varied from slow to fast, and the full series of rates was repeated until sample

Table 1: Conditions for the tensile elongation-to-failure tests and the resulting failure elongations (e_f) are given.

Al–2.8Mg

T (°C)	$\dot{\epsilon}$ (s^{-1})	e_f (%)	$\dot{\epsilon}/D$ (m^{-2})
200	1.0×10^{-4}	84	2.1×10^{15}
200	1.0×10^{-3}	51	2.1×10^{16}
300	1.0×10^{-3}	136	5.0×10^{13}
342	1.0×10^{-3}	147	7.1×10^{12}
400	1.0×10^{-4}	325	7.2×10^{10}
400	1.0×10^{-3}	191	7.2×10^{11}
400	1.0×10^{-2}	275	7.2×10^{12}
400	1.0×10^{-1}	139	7.2×10^{13}
500	1.0×10^{-4}	282	3.1×10^{9}
500	2.3×10^{-3}	242	7.2×10^{10}
500	2.3×10^{-2}	202	7.2×10^{11}

Al–5.5Mg

T (°C)	$\dot{\epsilon}$ (s^{-1})	e_f (%)	$\dot{\epsilon}/D$ (m^{-2})
200	1.0×10^{-4}	51	2.1×10^{15}
300	1.0×10^{-4}	228	5.0×10^{12}
300	1.0×10^{-3}	62	5.0×10^{13}
300	1.0×10^{-2}	39	5.0×10^{14}
300	1.0×10^{-1}	41	5.0×10^{15}
342	1.0×10^{-2}	108	7.1×10^{12}
400	1.0×10^{-4}	254	7.2×10^{10}
400	1.0×10^{-3}	235	7.2×10^{11}
400	1.0×10^{-2}	126	7.2×10^{12}
400	1.0×10^{-1}	54	7.2×10^{13}
500	1.0×10^{-4}	248	3.1×10^{9}
500	2.3×10^{-3}	238	7.2×10^{10}
500	2.3×10^{-2}	284	7.2×10^{11}

failure occured.

3 Results and Discussion

Shown in Fig. 1 is a plot of data from three different tensile elongation-to-failure tests for the Al–5.5Mg material. Data are plotted as true stress versus true strain where each test is at constant temperature and constant strain rate. Relatively little strain hardening is exhibited, especially at high temperature and low strain-rate where the greatest ductility is observed (over 230% in Fig. 1). These data are typical of all the elongation-to-failure tests for the Al–5.5Mg material. Results from the Al–2.8Mg material were very similar to those from the Al–5.5Mg material, except that the Al–2.8Mg material was slightly weaker than the Al–5.5Mg material at testing temperatures below 400°C due to a lower magnesium content [6]. Elongations obtained for both materials were remarkably similar under identical testing conditions. Table 1 gives the critical testing parameters and results of the tensile elongation-to-failure tests.

The strain-rate-change test results at 300°C, 400°C, and 500°C are shown for the two binary alloys in Fig. 2 as logarithm of flow stress versus logarithm of strain rate. The Al–5.5Mg material is stronger than the Al–2.8Mg material at the lowest temperature shown in Fig. 2 (300°C). The slope of the data in Fig. 2 is equal to the strain-rate sensitivity, m. Data for both binary alloys show slopes of $m = 0.33$ at temperatures of 400°C and above in the range of strain-rates given. In this case a strain-rate sensitivity of $m = 0.33$ is indicative of the solute-drag creep mechanism known to control deformation in these materials [3, 6]. At low temperatures and high strain rates the strain-rate sensitivity decreases to $m = 0.2$ and eventually decreases further into the region of power-law breakdown [6]. Because little or no strain hardening is observed (ie. Fig. 1), the strain-rate sensitivity will control tensile ductility [2, 7]. Ductility is expected to be highest under conditions promoting solute-drag creep, creating a high strain-rate sensitivity of $m = 0.33$.

McNelley et al. have shown that data of flow stress versus strain rate from binary Al–Mg alloys can be unified onto a single curve by compensating strain rate with diffusivity [6]. Therefore, the diffusion-compensated strain rate, $\dot{\epsilon}/D$ where D is the diffusivity of Mg in Al, can be used to correlate data from different temperatures and strain rates. Because

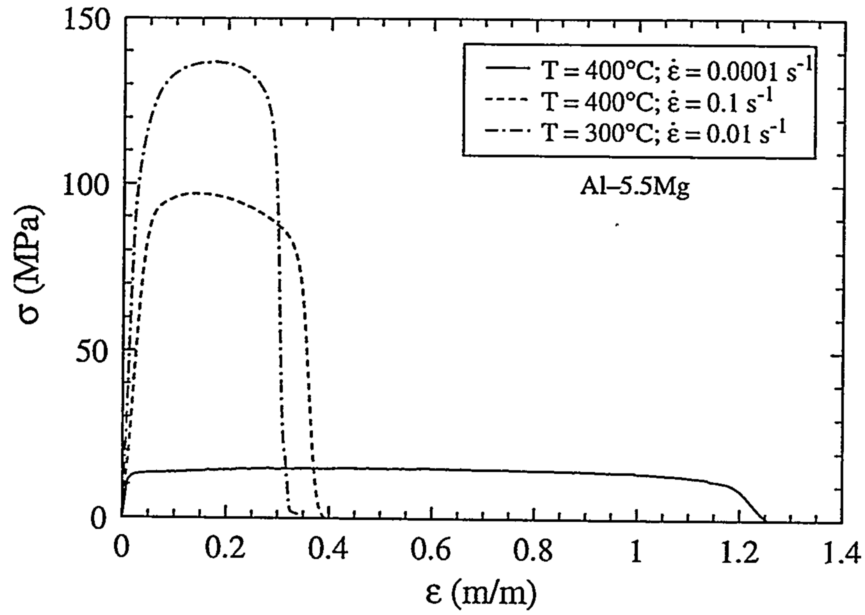

Figure 1: Data from tensile elongation-to-failure tests for the Al–5.5Mg material under three different testing conditions are plotted as true stress versus true strain.

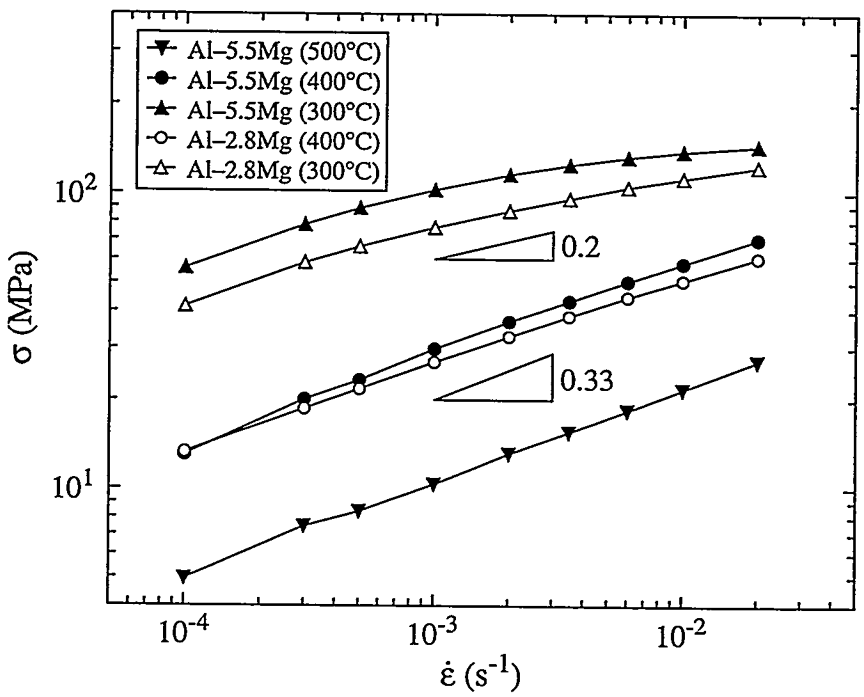

Figure 2: Data from tensile strain-rate-change tests for Al–2.8Mg and Al–5.5Mg tested at 300°C, 400°C, and 500°C are plotted as logarithm of flow stress versus logarithm of strain rate.

solute-drag creep in the binary alloys causes enhanced ductility, a plot of tensile ductility against $\dot{\epsilon}/D$ should also yield a single curve. Such a plot is given in Fig. 3 with data from both binary alloys at various temperatures and strain rates. In general, the data taken even at different temperatures and strain rates give similar elongations when the values of $\dot{\epsilon}/D$ are similar (Table 1 and Fig. 3). It is demonstrated in Fig. 3 that ductilities of 200% to over 300% are obtained for both binary, coarse grain Al–Mg alloys when deformed under conditions for which $\dot{\epsilon}/D < 10^{12}$ m^{-2}. Also given in Fig. 3 are lines showing the change in strain-rate sensitivity with $\dot{\epsilon}/D$, with m values given on the right vertical rule. The rise in tensile ductility for both binary alloys corresponds directly to the rise in strain-rate sensitivity with decreasing $\dot{\epsilon}/D$. This result is not surprising since the strain-rate sensitivity is known to govern the rate of neck growth in such materials [2, 4, 7–9]. Because failure in these high-purity alloys occurs by necking to a point, as opposed to cavitation or fracture, tensile elongation is limited by the rate of neck growth. The Al–2.8Mg ($\bar{d}$ = 30 μm) and Al–5.5Mg ($\bar{d}$ = 250 μm) materials exhibited no observable difference in neck shapes between tests at similar values of $\dot{\epsilon}/D$ giving $m \approx 0.3$. The strain-rate sensitivity therefore governs tensile ductility for the two binary alloys. The necks developed at failure in both Al–Mg materials were observed to be more severe, steeper, than those typically observed in fine-grain superplastic materials, as would be expected from the differing m values (0.5 versus 0.3).

4 Numerical Predictions

By making a few simple assumptions it is possible to construct a model of neck growth in strain-rate-sensitive materials [9–11]. These assumptions include: a small, slightly varying initial perturbation in cross-sectional area; a slightly varying neck of long wavelength; no strain hardening; and power-law creep where $\sigma \propto \dot{\epsilon}^m$ [11]. The assumption of a slightly varying neck of long wavelength, which gives the fastest neck growth, allows for a uniaxial stress state where the rate of area reduction of any section along the length of the specimen is independent of the rest of the length [9, 11]. Assuming a failure condition will allow the use of this model in predicting tensile elongations in materials where failure is limited by neck growth. The failure condition is chosen here to be the point at which the minimum cross-sectional area decreases to less than 90% of the maximum cross-sectional area:

$$a_{\text{min}} < 0.9 \cdot a_{\text{max}} \quad . \tag{1}$$

The numerical model was used with the above failure condition to predict the tensile elongation of a strain-rate-sensitive material as a function of the strain-rate sensitivity.[1] As the numerical model requires an initial perturbation in the cross-sectional area of the sample to initiate necking, a range of reasonable values were chosen. Failure was calculated for three different initial perturbations in sample area: $\delta = 1.0\%$, $\delta = 0.5\%$, and $\delta = 0.1\%$. Other authors have shown these to be reasonable values for predicting neck growth [4, 12]. The results of these calculations are plotted in Fig. 4 as predicted tensile elongation versus strain-rate sensitivity for the three choices of initial perturbation. Also plotted in Fig. 4 are the data for the binary alloys. The data are consistent with the predicted values for cases where $0.1\% \leq \delta \leq 1.0\%$. The agreement between predictions and test data indicate that for materials which fail by necking the strain-rate sensitivity governs tensile elongation. The good agreement between this numerical model and actual data of tensile elongation is expected from the success seen in analytic models which also predict high ductilities

[1]Details of the numerical model can be found in references [9–11].

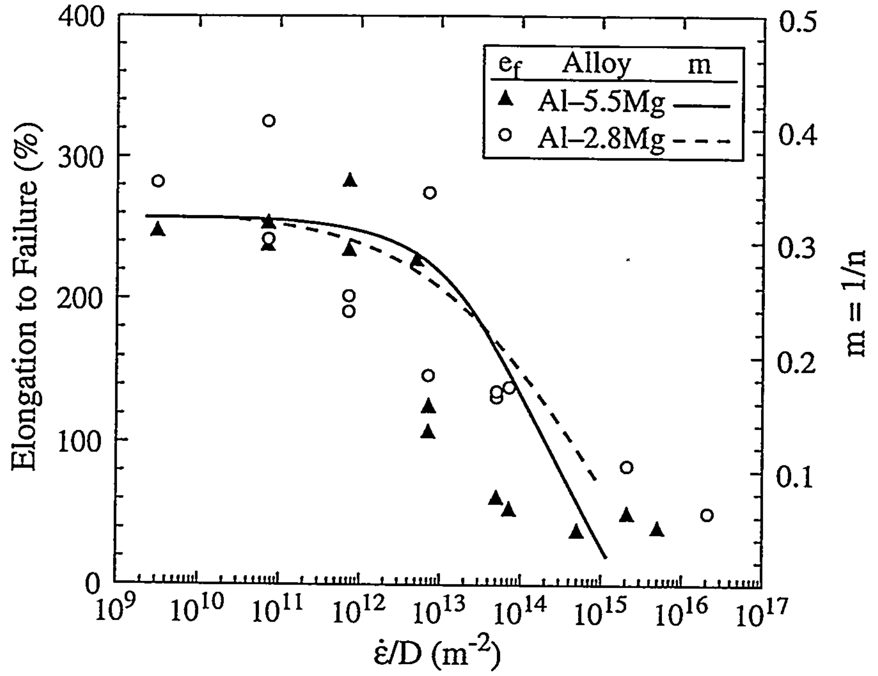

Figure 3: Tensile elongation to failure is plotted versus diffusion-compensated strain rate. Also shown on the second vertical axis is the strain-rate sensitivity, $m = 1/n$. The diffusion coefficient, D, for Mg diffusion in Al is given by $D_0 = 5 \times 10^{-5}$ m^2/s with a corresponding activation energy of $Q = 136$ kJ/mol [6].

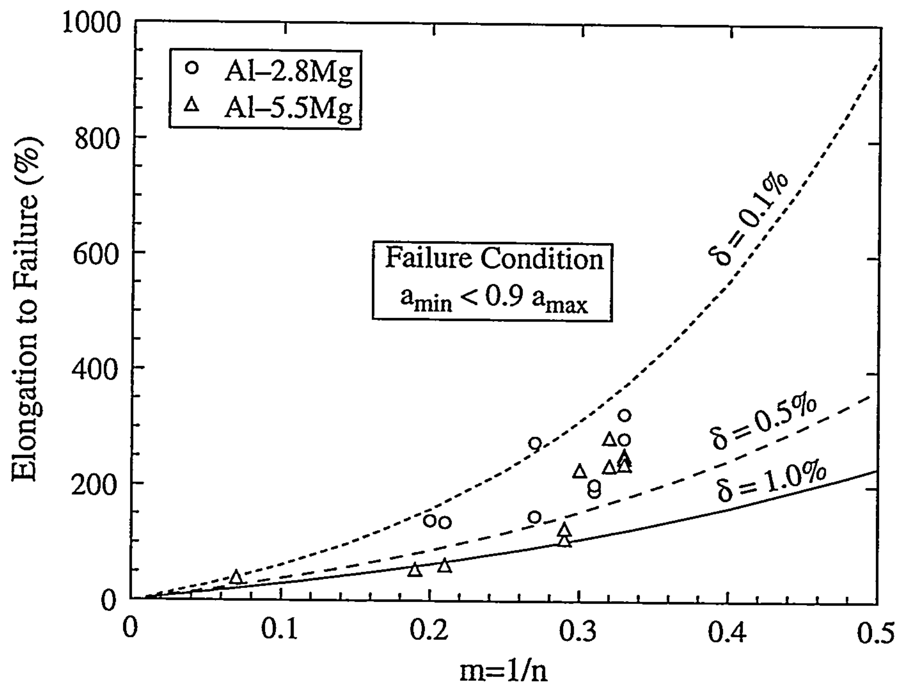

Figure 4: Predicted elongations to failure are shown versus strain-rate sensitivity, $m = 1/n$, assuming that failure occurs when the minimum sample area is 10% less than the maximum sample area. Predictions are made for three different initial perturbations in the sample area, δ.

for $m = 0.3$ [4, 12]. Data from other materials have also been observed to produce high ductilities when m is equal to 0.3 and greater [8].

5 Conclusions

Solute-drag creep of binary Al–Mg alloys yields a high strain-rate sensitivity of $m = 0.33$ which can result in enhanced ductility with tensile elongations of up to 325%. Magnesium concentration in the range of 2.8 to 5.5 weight percent was found to slightly affect strength, with higher concentrations increasing strength, but to have no significant effect on tensile ductility. In the two binary Al–Mg alloys studied, which failed by necking, tensile ductility was found to correlate strongly with the strain-rate sensitivity. Since the strain-rate sensitivity was found to be nearly equal for the two alloys in the solute-drag regime, it is not surprising that their tensile ductilities were also similar. A numerical model of neck growth predicts the enhanced ductility observed in these materials, indicating that tensile ductility is controlled by strain-rate sensitivity when failure occurs by necking to a point.

6 Acknowledgements

The authors would like to thank Mr. Rick Gross for performing the mechanical tests. One author, E.M.T., would like to express his gratitude to Lawrence Livermore National Laboratory for assistance in the advancement of his Ph.D. thesis program at Stanford University. This work was performed under the auspices of the United States Department of Energy by the Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-48.

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