The Deformation of Aluminium-Magnesium Alloys

H. NASR EL-DIN, S.F. MOUSTAFA, A.N. ABDEL-AZIM and A. ISMAIL - Central Metallurgical and Development Institute, P.O. Box 87, Helwan, Cairo, Egypt.

Abstract

Solute additions generally increase flow stress and decrease ductility. In an earlier study, the high purity Al-Mg alloys (0 to 6%) exhibited increases in both strength and ductility with Mg content at elevated temperature (<250°C). To more fully understand this behaviour, two commercial Al-Mg alloys (2 and 4 wt. %) were deformed in tension over a range of temperatures (25 to 250°C) and at strain rate 10^{-2} *min*$^{-1}$. *In the range 25 to 100°C, D.S.A. is the predominant operating mechanism, the strain rate sensitivity "m" is negative and the strain hardening exponent "n" becomes large. At warm temperature (250°C) a diffuse neck is formed and the increase in total elongation results from the increase in post uniform strain. As the Mg addition is increased the U.T.S. increases and the ductility decreases. This behaviour cannot be related only to Mg content, but also to the constituent particles (their size and distribution).*

Riassunto

L'aggiunta di un soluto normalmente porta ad un aumento della sollecitazione al flusso ed un decremento della duttilità. In un precedente studio, le leghe Al-Mg ad alta purezza (0-6%) hanno dimostrato a temperature elevate (<250°C) un incremento sia delle resistenze sia delle duttilità in funzione del tenore di Mg. In un'indagine più approfondita di questo comportamento, due leghe Al-Mg in commercio (2 e 4% peso) venivano deformate sotto tensione a temperature fra 25 e 250°C ed alla velocità di tensione 10^2 min. Nella gamma 25-100°C, il meccanismo operativo predominante era la DSA, la sensibilità "m" alla velocità di tensione era negativa, e l'esponente "n" dell'indurimento sotto tensione diventava grande. Alla temperatura semicalda (250°C), veniva a formarsi un collo diffuso e l'aumento dell'allungamento totale era derivato dall'aumento della tensione post-uniforme. Con l'aggiunta di più Mg, si osservava un incremento della resistenza alla rottura e un decremento della duttilità. Questo comportamento sarebbe da attribuirsi non soltanto al tenore del Mg, ma anche alle dimensioni ed alla distribuzione delle particelle costituenti.

Introduction

At ambient temperature, solute additions generally decrease ductility while increasing the initial strain hardening rate and flow stress [1].

At higher temperature, this behavior would be expected to continue where dynamic recovery mechanism operates (dislocation climb, cross slip, node unpinning, ...).

The amount of dynamic recovery is known to be dependent on the stacking fault energy "SFE" of the alloy [2, 3], and this energy is lowered by alloying. Therefore solid solution alloying normally retards dynamic recovery (dislocations split into partials, which impedes dislocation climb and increases the stress required for cross slip, ...).

Exceptions to this general behaviour have been noted in high purity [4] and commercial [5] Al-Mg alloys at elevated temperatures where solutes increase both flow stress and ductility. In another study [6], it was found that a commercial Al-4 wt% Mg alloy (5182-0) exhibited a marked improvement in tensile elongation compared with pure aluminium at elevated temperatures. These exceptions are in apparent contradiction to earlier studies [7-9] of high purity Al-Mg alloys (0 to 5 wt.% Mg) which showed that addition of magnesium decreased ductility over the range of temperatures (400 to 600°C) under torsion at high strain rate. These exceptions are few in number and not fully understood. So, it is of interest to examine the effect of Mg on the ductility of commercial Al-Mg alloys at elevated temperatures.

In this study, the effect of magnesium on the plastic behavior of two commercial Al-Mg alloys (2 and 4 wt.% Mg) deformed in tension over a temperature range of 25-250°C and at an initial strain rate $\dot{\varepsilon} = 10^{-2}$ min^{-1}.

Experimental

Two commercial Al-Mg alloys containing 2 and 4 wt. pct were prepared in the form of cast billets of dimensions $30 \times 20 \times 660$ m^3. Billets were homogenized for 24 h at 450°C. They were then cold-rolled to a final thickness of 15 mm with intermediate and final annealing at 350°C for 30 min.

Standard ASTM, E-150 tensile samples were maintained at 25, 100, 175 and 250°C during testing in an electrical thermostatic chamber. There is no measurable temperature gradient in the gauge section. The samples were pulled to failure at constant cross-head speed of 0.5 mm per min. which produces an initial strain rate of (10^{-2} mm^{-1}).

Results and discussion

Influence of Temperature

Figs. 1 and 2 show a set of true stress-true strain curves for the two alloys, for temperatures between 25-250°C at a constant strain rate of 0.01 min^{-1}. The results of this study indicate that the ductility does increase with temperature together with decreasing stress levels. At the warm temperature, a diffuse neck is formed and extended after the maximum load. The temperature dependence of tensile ductilities in general follows the variation in the strain rate sensitivity m. As the temperature rises, the strain hardening becomes less effective and the strain rate hardening takes over the role (m-value controlled), where:

$$m = \Delta\sigma / \Delta \ \ln \dot{\varepsilon}$$

σ is the stress and $\dot{\varepsilon}$ is the strain rate. The value of m was obtained from strain rate change experiments using a factor of (40) change in strain rate.

The change in m with temperature suggests a change in deformation mechanisms. In the temperature range considered in this study, dynamic strain aging and dynamic recovery are the most likely processes affecting dislocation motion in Al-Mg alloys [10].

In the range 25 to 100°C, the Mg atoms interact with dislocations producing serrated yielding. Dynamic strain aging is the predominant operating mechanism and any recovery would be negligibly small, this can be clearly shown in Figs. 1 and 2.

Since these Al-Mg alloys continue to exhibit serrated flow after a critical deformation ε_o, the strain rate sensitivity becomes negative. This can be clearly seen in Fig. 3. This mechanism of deformation greatly restricts the tensile ductility.

As the temperature is increased, the loading curve of Al 4% wt. Mg alloy is no longer serrated curve, the solute pinning effects are decreased.

Outside of the serrated flow regime enhanced ductility of this alloy is accompanied with positive strain rate sensitivity as shown in Fig. 3. This positive value stabilizes any type of inhomogeneties by moving away from the peak influence of dynamic strain aging. The increasing of m with temperature suggests that the recovery is the predominant operating mechanism. The increased ductility with temperature can be explained in terms of two types of increases in m, one due to increase of temperature (at constant strain) and the other due to increase of strain at the higher temperatures.

As the coefficient of strain hardening "n" is a measure of the hardening when the deformation mechanism is the dynamic strain aging or a measure of softening during the recovery, so the value of "n" becomes large near the peak influence of dynamic strain aging (25-100°C) but decreases with temperature when recovery begins to dominate, as clearly illustrated in Table 1.

TABLE 1 - Variation of strain hardening exponent "n" with deformation temperature and Mg content

Mg wt% Temp., °C	2	4
25	0.57	0.74
100	0.52	0.68
175	0.49	0.59
250	0.34	0.56

It should be added that the work hardening exponent "n" is primarily a function of the general shape of the work-hardening curve. The low value of ductility obtained in these studies explains the large value of strain hardening exponent "n".

Variation in uniform and post-uniform strains with temperature are shown in Fig. 4. Outside the range at which the DSA is the predominant operating mechanism, uniform strain ε_u decreases with temperature. The variation in post-uniform strain indicates that the increase in total elongation with temperature results from increases in this component.

The loading curve of Al- 2 wt% Mg alloy tested at warm temperature 250°C represents serrations simultaneously with an extension of a diffuse neck. This may be explained by a competition of two deformation mechanisms DSA and dynamic recovery mechanisms. Due to the operation of DSA mechanism at this warm temperature, ductility is reduced in comparison with early study [5]. The appearance of serrations at this temperature is probably due to insufficient homogenization for this alloy which leads to slight decrease in Mg content in some areas. The stress-strain curve of the high purity Al-1% Mg alloy [4] shows serrations at 150°C.

Influence of the Magnesium Additions

The results show a decrease in ductility with Mg content over the range of temperature tested in this study as shown in Figs. 1 and 2. The variation of total elongation with temperature is represented in Table 2. The total elongation to fracture ε_t, can be expressed as the sum of uniform strain ε_u and the post-uniform strain ε_{pu}. The uniform strain is primarily a function of the rate of decrease in $d\sigma/d\varepsilon$ with strain. The influence of the strain rate sensitivity (m) on the uniform strain is very small, but (m) is more influenced in the post-uniform strain [11]. If the work hardening rate $d\sigma/d\varepsilon$ is plotted against the strain for the two alloys, the results in Fig. 5 are obtained. It can be seen that at the ambient temperature, while the work hardening rate is increased with the magnesium addition, the rate of decrease with strain does not greatly change. At warm deformation, the rate of decrease of $d\sigma/d\varepsilon$ with strain is quite different in the two alloys.

TABLE 2 - Variation of total elongation pct with deformation temperature and Mg content

Mg wt% / Temp., °C	2	4
25	16.36	14.1
100	30.0	24.6
175	41.4	23.2
250	57.6	37.7

An increase in ultimate strengths with Mg content as for the work hardening capacity is expected. The variation in tensile strength with Mg content over the range 25 to 250°C is shown in Table 3. There is some increase in the tensile strength compared with an early study [11]. Since the uniform strain is about the same in the two alloys, the stress difference $(\sigma_u-\sigma_E)^*$ is a reasonable reflection of the capacity of the alloys to work-harden. The variation in work hardening capacity with Mg content is shown in Table 4.

TABLE 3 - Variation of ultimate tensile strength σ_{UTS} (MPa) with deformation temperature and Mg content

Temp., °C \ Mg wt%	2	4
25	195	304
100	188	265
175	131	151
250	92	122

TABLE 4 - Variation of work hardening $[\sigma_u - \sigma_E]$* (MPa) with deformation temperature and Mg content

Temp., °C \ Mg wt%	2	4
25	15.3	28.2
100	15	24.3
175	10.6	12.7
250	6.0	10.3

* σ_u: *Ultimate tensile strength* σ_E: *Stress at elastic limit*

A decrease in ductility with magnesium addition at temperatures less than ~375°C and greater than ~450°C was seen in high purity Al-Mg alloys. These alloys were deformed in torsion at high strain rate $\dot{\varepsilon} = 3.93\ S^{-1}$ [7]. H.J. McQueen and et al [3] have explained the decrease in ductility with increasing Mg at high temperatures (>0.6 Tm) on the basis of lowering the stacking fault energy (SFE). This in turn inhibits dynamic recovery.

Influence of Grain Boundary Precipitation

Among microstructural factors, grain boundary precipitate has often been considered to play an important role. The initial structure is shown in Fig. 6. It consists of equiaxed dendrites of Al with a fine precipitate, and is expected to be a precipitate of $Mg_2\ Al_3$ in the dendrites interior and at dendrite boundaries. Fig. 7 indicates the structure of these alloys deformed in tension at ambient temperature. Continuous precipitates at grain boundaries are shown. It is thought to be precipitates of (Fe, Mn) Al_6 [gray], Mg_2Si [block], Mg_2Al_3 (fine precipitate). The presence of these considerable amounts of grain boundary precipitates greatly inhibits dislocation motion and would explain the increase in tensile strength and the decrease in ductility.

Conclusions

(1) In the range 25 to 100°C, dynamic strain aging is the predominant operating mechanism. The strain rate sensitivity becomes negative after a critical deformation.

(2) At warm temperature (250°C) a diffuse neck is formed. The increase in total elongation results from the increase in post-uniform strain.

(3) The work hardening rate is increased with the magnesium addition and at the warm temperature the rate of decrease of $d\sigma/d\varepsilon$ with strain is different in the two alloys.

(4) As the Mg addition is increased the U.T.S. increases and the ductility decreases. This behavior can not be related only to Mg content, but also to the constant particles (their size and distribution).

Acknowledgement

The authors are very grateful to Prof. M.R. El-Koussy for interesting discussions.

References

[1] McLeon, D., *Mechanical Properties of Metals*, John Wiley & Sons, Inc., New York, 1962, p. 162.
[2] Jonas, J.J., Sellars, C.M., and Tegart, W.J. McG., Met. Rev., 1969, Vol. 14, p. 1.
[3] McQueen, H.J. and Jonas, J.J., Mat. Sci. and Technology, 1975, Vol. 6, p. 393.
[4] Ayres, R.A., Met. Trans. A., 1979, Vol. 10A, p. 849.
[5] Shehata, F., Painter, M.J. and Pearce, R., J. Mech. Work. Tech., 1978, Vol. 2, p. 279.
[6] Ayres, R.A., Met. Trans. A, 1977, Vol. 8A, p. 487.
[7] Cotner, J.R., Tegart, W.J. McG., J. Inst. Metals, 1969, Vol. 97, p. 73.
[8] Sellars, C.M., Tegart, W.J. McG., Int. Met. Rev., 1972, Vol. 17, p. 1.
[9] Sellars, C.M., and Tegart, W.J. McG., Mem. Sci. Rev., Met., 1966, Vol. 63, p. 731.
[10] Morris, J.G., Mater. Sci. Eng., 1974, Vol. 13, p. 101.
[11] Lloyd, D.J., Met. Trans. A, 1980, Vol. 11A, p. 1287.

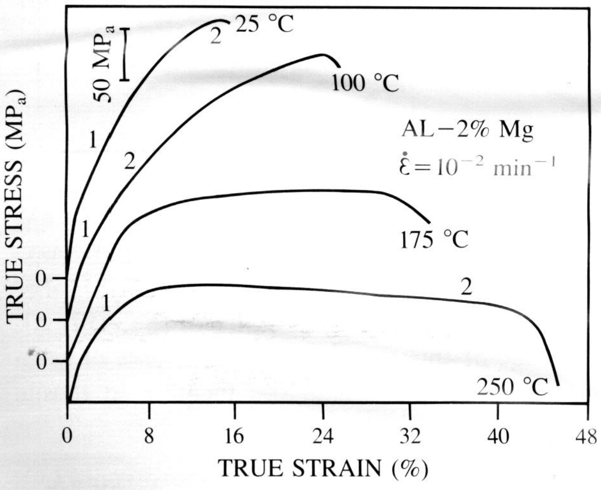

Fig. 1:
True stress vs true strain curves for Al-2 wt.% Mg at different temperatures and constant strain rate ($\dot{\varepsilon}=10^{-2}\,\text{min}^{-1}$).
1. The beginning of the serrations. 2. The end of serrations.

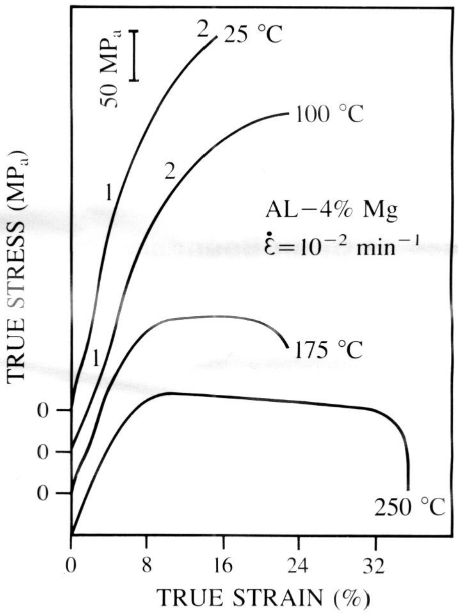

Fig. 2:
True strain curves for Al-4 wt.% Mg at different temperatures and constant strain rate ($\dot{\varepsilon}=10^{-2}\,\text{min}^{-1}$).
1. The beginning of the serrations. 2. The end of serrations.