Microstructure and deformation behaviour of an AX61 magnesium alloy

Z. Trojanová*, M. Milnera

Department of Metal Physics, Charles University Prague, Ke Karlovu 5, CZ-121 16 Prague 2, Czech Republic

Received 9 December 2005, received in revised form 7 March 2006, accepted 7 March 2006

Abstract

Magnesium alloy AX61 (6 % Al, 1 % Ca, balance Mg) was investigated in tensile as well as compression tests at elevated temperatures up to 300 ℃. The form of the stress-strain curves is very sensitive to the test temperature and the strain rate. The deformation behaviour of the specimens can be attributed to the occurrence of hardening and softening during straining. Microstructure of samples showed incoherent particles that are reason for relatively high stresses obtained at lower temperatures and low ductility in tension.

Key words: magnesium alloy, hardening, softening, precipitation, dislocations

1. Introduction

Magnesium, magnesium alloys and composites have many potential applications because of their low density and good machinability but as a consequence of their hcp structure, they generally exhibit only limited ductility at ambient temperatures. The good castability of Mg alloys enables producing of thin wall parts with a complex form. Alloys prepared by the high-pressure squeeze casting have very high density and an acceptable grain size. Most of die cast or squeeze cast are Mg-Al alloys. Third alloying elements are used to improve properties of Mg-Al alloys. Among the alloying elements Ca is a promising elemental addition as a cheaper and lighter alternative to rare earth elements, also contributes to high temperature properties. Thus, the Mg-Al-Ca systems are very important for further development. When Ca added to Mg-Al binary alloys, the type of precipitating compound depends on the Ca/Al mass ratio. When this ratio is more than 0.8, presence of both Mg_2Ca and Al_2Ca were detected. They contribute to the considerable increase of hardness and the yield stress [1]. For the ratio below 0.8 only Al_2Ca was observed to have formed. Both types of precipitates were observed to form along the grain boundaries [2]. Gjestland et al. [3] showed that the creep resistance of AX alloy at 150 ℃ is similar to AE42 alloy with the added benefit of good corrosion resistance. Terada et al. [4] studied the creep mechanisms in the Mg-5%Al-1.7%Ca alloy. They found a change of deformation mechanism at the vicinity of 150 ℃. Microstructure and mechanical properties of Mg-Al based alloy with Ca addition have been studied by D. Wenwen et al. [5]. They estimated that the small amount of Ca increased the thermal stability of $Mg_{17}Al_{12}$ intermetallic phase, so that the creep resistance at elevated temperatures was improved.

The aim of the present work is to study the influence of temperature on tensile and compressive properties of Mg-Al-Ca alloy and to discuss possible hardening and softening mechanisms.

2. Experimental procedure

Mg-6%Al-1%Ca alloy specimens were used in this study. The alloy was prepared by squeeze cast technology. Test specimens used for tensile tests were machined from cast discs and they had a cylindrical form with a diameter of 5 mm and a gauge length of 27 mm. Quadratic compression samples with a base of 5 × 5 mm had length of 9.8 mm. Tensile as well as compression tests were performed in an Instron type machine at temperatures between room temperature and 300 ℃ and at a constant crosshead speed giving an

---

*Corresponding author: tel.: +420 2 21911357; fax: +420 2 21911490; e-mail address: ztrojan@met.mff.cuni.cz

initial strain rate of $6.17 \times 10^{-5}\ \mathrm{s}^{-1}$. The yield stress, σ_{02}, was estimated as the flow stress at 0.2% offset strain. The maximum stress, $\sigma_{\max}$, corresponds to the maximum value of the flow stress. Stress relaxation tests were carried out in order to estimate parameters of a possible thermally activated process. At a certain stress (strain) the machine was stopped and the stress was allowed to relax during 300 s. Microstructure of alloy has been studied using the light microscopy as well as scanning electron microscopy.

3. Results and discussion

Microstructure of the as-cast alloy used in this study is introduced in Fig. 1. Grain boundaries are decorated by particles. SEM showed the details of the particles structure (Fig. 2a). SEM with energy disperse spectroscopy (EDS) indicated a Mg- and Al-containing phase, $Mg_{17}Al_{12}$, but also some areas with higher Al and Ca content. This phase can be Al_2Ca, which is known to locate at grain boundaries and suppress the formation of $Mg_{17}Al_{12}$. Details of the $Mg_{17}Al_{12}$ particle decorated by the particles containing Ca are visible in Fig. 2b. Stress-strain curves measured in tension at various temperatures are introduced in Fig. 3. Very low ductility (about 1 %) of the alloy studied at room temperature and 100 ℃ is obvious. Temperature dependence of the yield stress and the maximum stress is introduced in Fig. 4. Values at 50 and 150 ℃ were estimated from curves with stress relaxation tests. The maximum stress may be influenced by the stress relaxation and then these values are not introduced in the plot. Stress-strain curves obtained in compression tests are shown in Fig. 5. Higher values of ductility obtained at lower temperatures are obvious. Corresponding values of the yield stress as well as the maximum stress are in Fig. 6. From Figs. 4 and 6 it is visible that the yield stress decreases slowly with temperature up to 100–150 ℃, then the stress decrease is stronger. Complex microstructure with two types of intermetallic phases has the crucial meaning for strengthening during plastic deformation. Both precipitates are impenetrable obstacles for dislocation motion. Such obstacles may be overcome by the Orowan mechanism. An increase in the yield stress due to the Orowan process, $\Delta\sigma_{\mathrm{OR}}$, can be given by the relationship [6, 7]

$$\Delta\sigma_{\mathrm{OR}} = \psi \frac{AEb}{4\pi\,(1+\nu)\,\lambda}\left[\ln\frac{D}{r_0} + B\right], \qquad (1)$$

where $A = 1/(1-\nu)$ and $B = 0.6$ for screw dislocations and $A = 1$ and $B = 0.7$ for edge dislocations, E is Young's modulus, ψ is the Taylor factor, b is the Burgers vector, ν is Poisson's ratio, λ is the interparticle spacing, D is the harmonic mean of λ and r_0 is the inner cutoff radius of the dislocation ($= b - 3b$).

The dominant slip system in magnesium and magnesium alloys at room temperature is the basal one.

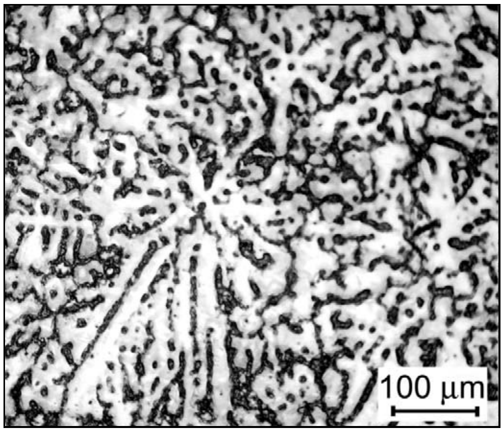

Fig. 1. Light micrograph of the as-cast sample.

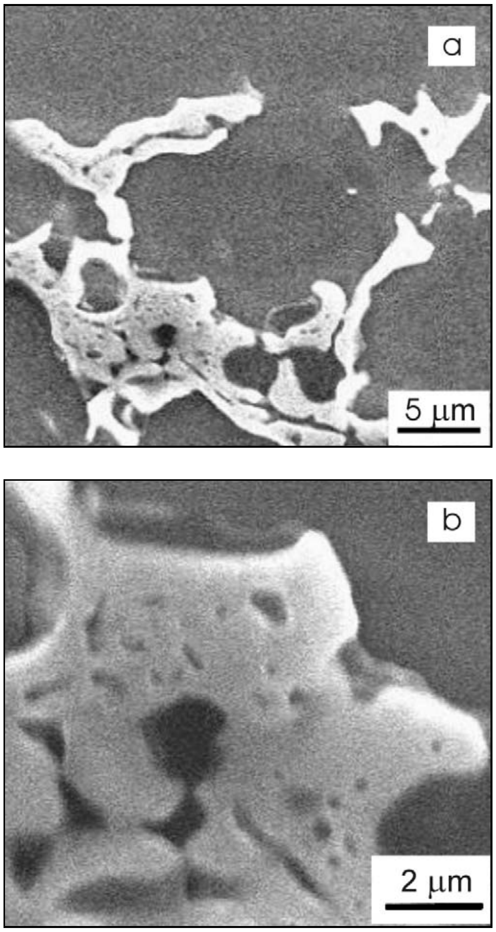

Fig. 2. a) SEM of the as-cast alloy. b) Detail of the particles.

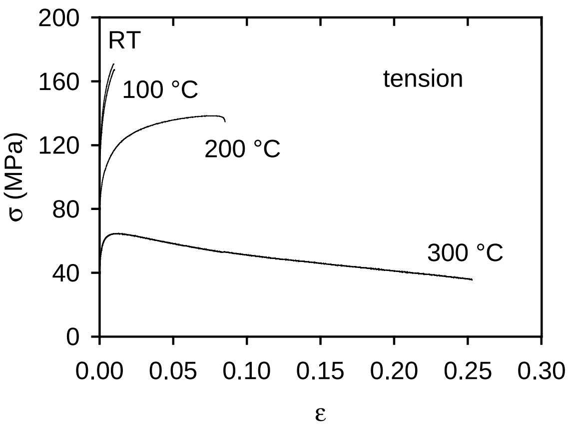

Fig. 3. Stress-strain curves obtained in tension at various temperatures.

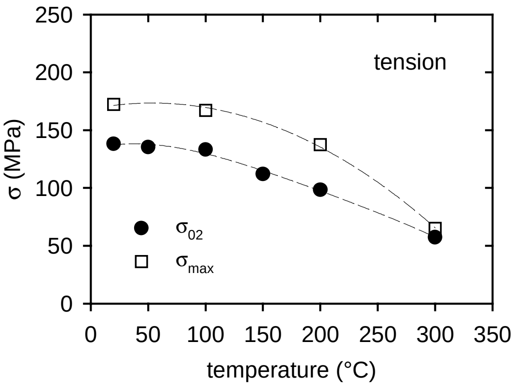

Fig. 4. Temperature dependence of the yield stress and the maximum stress obtained in tension.

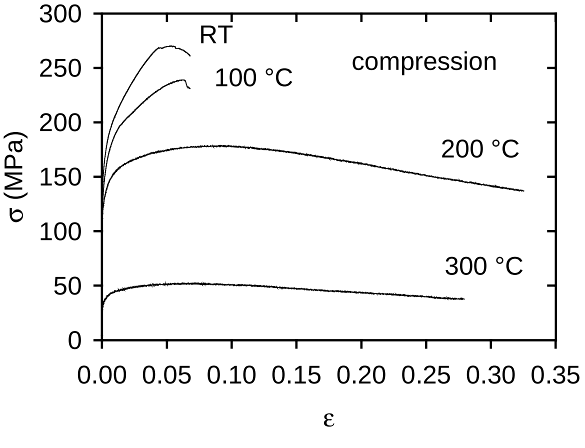

Fig. 5. Stress-strain curves obtained in compression at various temperatures.

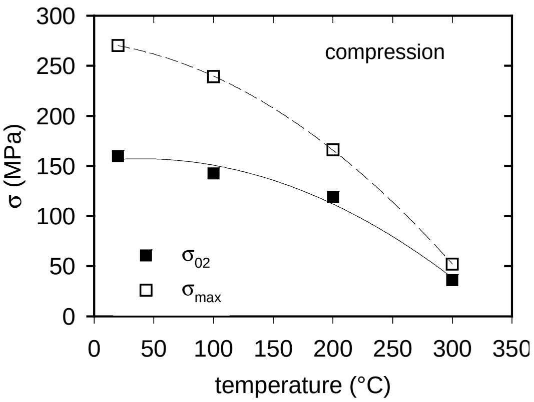

Fig. 6. Temperature dependence of the yield stress and the maximum stress for curves obtained in compression.

The number of independent mode of the basal slip is only two, which is not sufficient for the satisfying of the von Mises criterion [8]. Thus, to fulfil von Mises [8] criterion, a non-basal slip system should be active. The activity of a slip system depends on the critical resolved shear stress; the activity of a non-basal slip system requires a high stress. The critical resolved shear stresses for the non-basal slip systems of Mg and its alloys depend very significantly on the testing temperature. They decrease rapidly with increasing temperature.

The applied stress necessary for deformation of the crystal may be divided into two components

$$\sigma = \sigma_{\mathrm{i}} + \sigma^{*}, \tag{2}$$

where σ_{i} is an athermal component often called internal stress,

$$\sigma_{\mathrm{i}} = \alpha G b \rho_{\mathrm{t}}^{1/2}, \tag{3}$$

where G is the shear modulus, α a constant, b is the Burgers vector and ρ_{t} is the total dislocation density. The effective stress σ^{*} acts on dislocations during their thermally activated motion. The athermal component of the flow stress – the internal stress σ_{i} – was estimated from stress relaxation tests using Li's method [9]. Dislocations stored at obstacles are reason for the extremely high level of the internal stress estimated at lower temperatures. $\sigma_{\mathrm{i}}/\sigma_{\mathrm{ap}}$ (internal stress/applied stress) ratio is plotted as a function of temperature in Fig. 7. Rapid decrease of the internal stress for temperatures higher than 150 °C is a consequence of the recovery process,(-es) activity. Screw component of $\langle 11\bar{2}0\rangle$ dislocations in the basal planes may move on the prism planes. Therefore, the free path of dislocations increases and work hardening rate decreases. The activity of non-basal slip systems and cross slip of dislocations increases with temperature [10–14]. It means that the work hardening rate should decrease and the elongation to failure should increase with increasing temperature. Both are observed experimentally. The role of the non-basal $\langle 11\bar{2}3\rangle$ slip mode in

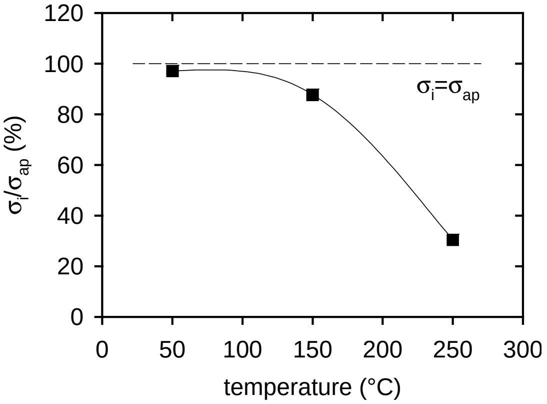

Fig. 7. Internal stress/applied stress ratio estimated for the first relaxation and various temperatures.

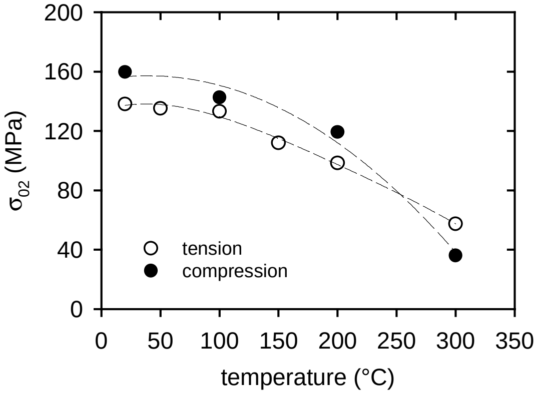

Fig. 8. Comparison of the yield stress obtained in tension and compression for various temperatures.

understanding mechanical behaviour of Mg alloys has been demonstrated by Agnew et al. [15].

Comparison of the yield stress obtained in both deformation modes is shown in Fig. 8. Higher deformation stresses which have been observed in compression (in comparison with tension) may be caused by residual thermal stresses. Since the alloy was fabricated by squeeze casting at an elevated temperature, the material contains residual thermal stresses at room temperature due to the mismatch in the thermal expansion coefficients between the alloy and the intermetallic phases. In practice, the alloy experiences tensile stresses whereas the intermetallic phases experience compressive stresses. During the plastic deformation test the applied stress may be added to the residual thermal stress. While during the tensile test both stresses have the same sign during the compression, test tensile stress in the alloy must be overcome for the compression deformation. Tensile stresses decrease with increasing temperature and they may converse at certain temperature to compression ones. This is also reason why the tensile/compression stress ratio is opposite at 300 °C.

4. Conclusions

Deformation properties of the magnesium alloy AX61 were studied in tension as well as in compression in the temperature interval from room temperature up to 300 °C. Very low ductility obtained at temperatures up to 100 °C increases at elevated temperatures. $Mg_{17}Al_{12}$ precipitates decorated by Al_2Ca phase are the reason for high strengthening and low ductility at lower temperatures. Stable incoherent precipitates cause the main strengthening in the alloy. Rapid decrease of the dislocation density at temperatures higher than 150 °C is manifested by the decrease of the internal stress. The cross slip and subsequent annihilation of dislocations are reason for the decrease of mobile dislocation density. Higher flow stress obtained in compression test up to 200 °C is very probably caused by the tensile residual stresses present in the alloy.

Acknowledgements

M. M. acknowledges gratefully the financial support by the Austrian Research Association (MOEL059). This work is a part of the Research Project 1M 2560471601 "Eco-center for Applied Research of Non-ferrous Metals" that is financed by the Ministry of Education, Youth and Sports of the Czech Republic.

References

[1] PEKGULERYUZ, M.: Magnesium Alloys and Their Applications (Ed.: Kainer, K. U.), DGM, Wiley-VCH 2003, p. 65.
[2] NINOMIYA, R.—OJIRO, T.—KUBOTA, K.: Acta Metall., 43, 1995, p. 669.
[3] GJESTLAN, H.—NUSSBAUM, G.—REGAZZONI, G.: Mater. Sci. Eng. A, *134*, 1991, p. 197.
[4] TERADA, Y.—ISHIMATSU, N.—SOTA, R.—SATO, T.—OHORI, K.: Mater. Sci. Forum, *419–422*, 2003, p. 459.
[5] WENWEN, D.—YANGSHAN, S.—XUEGANG, M. —FENG X.—MIN Z.—DENGYUN, W.: Mater. Sci. Eng. A, *356*, 2003, p. 1.
[6] SCATTERGOOD, R. O.—BACON, D.: Phil. Mag., *A31*, 1975, p. 179.
[7] YEH, Y. H.—NAKASHIMA, H.—KURISHITA, H.—GOTO, S.—YOSHINAGA, H.: Mater. Trans. JIM, *31*, 1990, p. 284.
[8] VON MISES, R.: Z. Angew. Math. Mech., *8*, 1928, p. 161.
[9] LI, J. C. M.: Canad. J. Appl. Phys., *45*, 1967, p. 493.
[10] STOHR, J. F.—POIRIER, J. P.: Phil. Mag., *25*, 1972, p. 1313.

[11] ANDO, S.—NAKAMURA, K.—TAKASIMA, K.—TONDA, H.: J. Jpn. Inst. Light Met., *42*, 1992, p. 765.

[12] MÁTHIS, K.—NYILAS, K.—AXT, A.—DRAGOMIR-CERNATESCU, I.—UNGÁR, T.—LUKÁČ, P.: Acta Mater., *52*, 2004, p. 2889.

[13] MÁTHIS, K.—TROJANOVÁ, Z.: Kovove Mater., *43*, 2005, p. 238.

[14] LUKÁČ, P.—MÁTHIS, K.: Kovove Mater., *40*, 2002, p. 281.

[15] AGNEW, S. R.—YOO, M. H.—TOMÉ, N.: Acta Mater., *49*, 2001, p. 4277.