# Deformation behaviour of Mg-Al-Mn alloys at elevated temperatures

## K. Máthis, Z. Trojanová, P. Luká, J. Lendvai

*The deformation behaviour of Mg-Al-Mn alloys was investigated. The specimens were deformed at a constant strain rate at room and elevated temperatures (up to 300°C). The influence of three different Al additions (2, 5 and 6 wt. %) on the mechanical properties was also studied in the same temperature range. The aluminium addition increases the yield stress and ultimate tensile strength of the alloys at all temperatures investigated. The flow stress is decreasing with increasing temperature. The shape of the stress – strain curves depends on the test temperature. In some cases the stress – strain curves exhibit softening. The softening is sensitive to temperature. The course of the flow stress curves is a result of hardening and softening. The deformation behaviour is discussed.*

## INTRODUCTION

Excellent specific mechanical properties and low weight of magnesium alloys predestine these materials for application in the automobile and aircraft industry. The commercial magnesium alloys AM60 and AM50 are widely used due to their very good strength, ductility, castability and cold workability. High ductility and impact strength of alloy AM20 have been employed in the production of safety parts of automobiles.

In addition to magnesium, the AM alloy series contains two major alloying elements. Their beneficial effects on the properties of these alloys may be summarised as follows [1]:

Aluminium – increases the room temperature strength and hardness and improves the castability. The strength and ductility ratio is ideal if the concentration of the aluminium is about 6 wt. %.

Manganese – increases the yield strength and has beneficial effect on corrosion resistance because with iron it composes an intermetallic phase.

Microstructural changes (dislocation motion, diffusion of solute atoms, grain growth) play an important rule during the deformation and therefore, their investigation is very important to understand the mechanical behaviour of the alloys.

The objective of this paper is to investigate the influence of Al contents on the deformation behaviour of the AM series alloys deformed at temperatures between room temperature and 300°C.

## EXPERIMENTAL PROCEDURE

The AM series specimens supplied by the Technical University of Clausthal were prepared by squeeze casting. The specimens contain the following elements (nominal value in weight percent):

AM60 – Aluminium 6 wt%, Manganese 0.3 wt%
AM50 – Aluminium 5 wt%, Manganese 0.3 wt%
AM20 – Aluminium 2 wt%, Manganese 0.5 wt%

Cylindrical specimens with a gauge length of 29mm and a

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diameter of 4.95mm were deformed in tension. The tensile test were performed in an MTS machine in the temperature range from 20 to 300°C at a constant strain rate of $8.3 \times 10^{-5}$ $s^{-1}$.

Microstructural studies using a optical microscope were made "post mortem" as a function of the strain and of the temperature. The undeformed parts from the head of specimens and deformed parts of the tensile specimens were used. Specimens were first mechanically polished and finally etched (90s) in acetic picral.

## EXPERIMENTAL RESULTS

### Tensile tests

Tensile stress strain-curves of the three AM alloys at various temperatures are shown in figs.1-3. The test temperature significantly influences the shape of the stress-strain curves. At temperatures up to 100°C there is a very rapid work hardening at the beginning of the deformation. Most probably mechanical twinning contributes to the hardening in the largest amount. A preliminary study using acoustic emission measurements during straining confirms the twinning phenomenon. Softening increases with increasing temperature. At temperatures above 200°C the work hardening rate is close to zero; a dynamical balance between hardening and softening occurs.
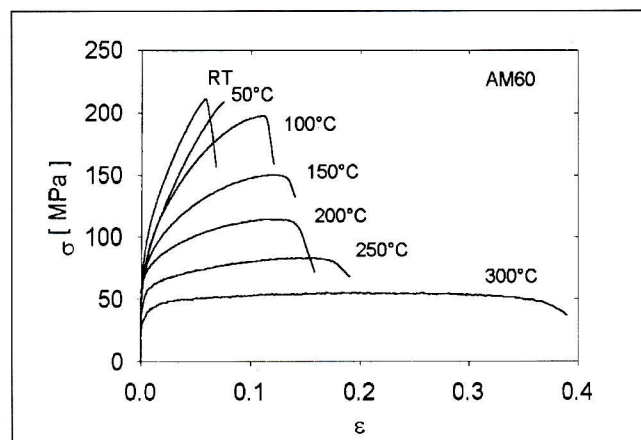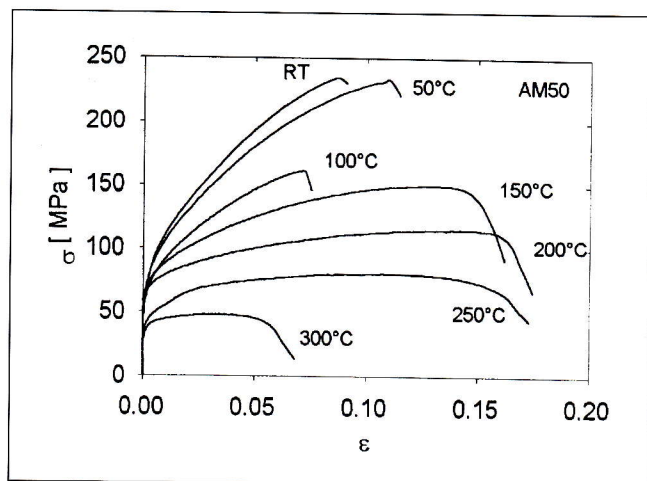


Fig.1 – *True stress- true strain curves for AM60*

Fig.1 – *Curve sforzo reale - deformazione reale per la lega AM60*

Fig.2 – True stress- true strain curves for AM50

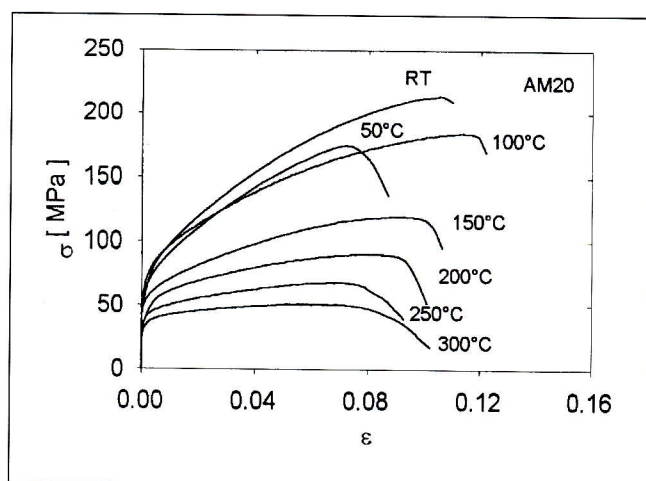Fig.2 – Curve sforzo reale - deformazione reale per la lega AM50



Fig.3 – True stress- true strain curves for AM20

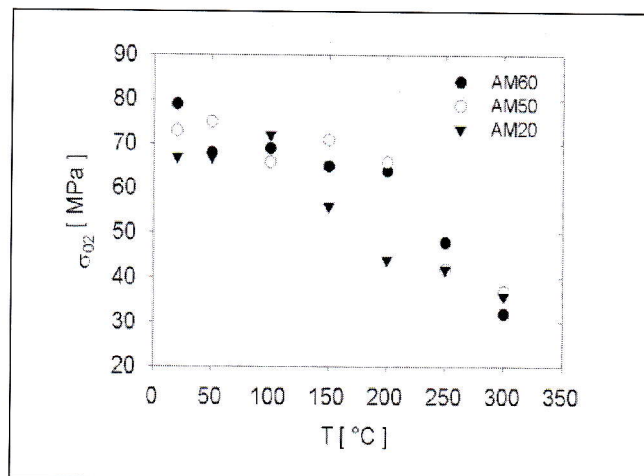Fig.3 – Curve sforzo reale - deformazione reale per la lega AM20



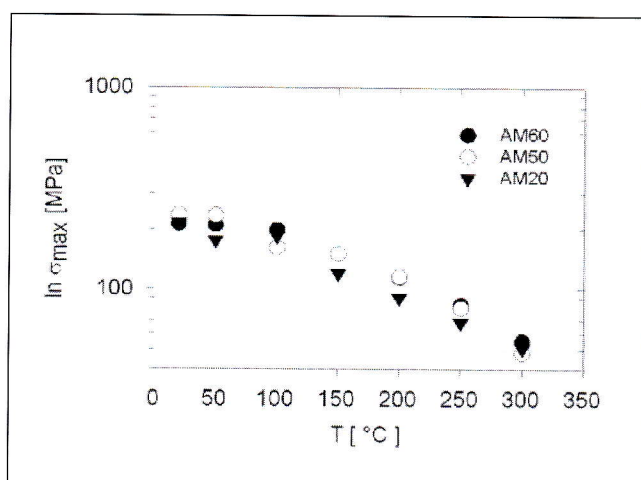Fig. 4 – Temperature dependence of $\sigma_{02}$

Fig. 4 – Dipendenza di $\sigma_{02}$ dalla temperatura



Fig. 5 – Temperature dependence of $\ln\sigma_{max}$

Fig. 5 – Dipendenza di $\ln\sigma_{max}$ dalla temperatura

Figures 4-5 show the temperature dependence of the yield stress $\sigma_{02}$ (defined as the stress required for a plastic strain of 0.2%) and the ultimate tensile strength $\sigma_{max}$ (defined as the maximum stress). Both the yield stress and the tensile strength decrease with increasing temperature. The decrease of the yield stress with temperature is faster above 200°C for AM60 and AM50, and above 100°C for AM20. Similar effect of temperature on the yield stress of AZ91 magnesium alloy has been reported by Drozd et al. [2].

Microstructure

On the basis of the equilibrium phase diagram of Al-Mg is well-known [3] that the aluminium composes with magnesium three solid solution: α-phase with hexagonal lattice. β-phase is the solution $Mg_{17}Al_{12}$ with face centred lattice, and the γ-phase is the solution $Al_3Mg_2$. Almost pure Mn particles, with bcc lattice compose in the matrix some round particles as can be seen in fig.6.
The microstructure changes during the heat treatment influence the mechanical properties of the alloy. With increasing temperature the initial Mg-Al solid solution starts to decompose. Gradually α-and β-phase are formed [4]. The volume fraction of intermetallic phases increases and Mg-rich solid solution grains are surrounded by $Mg$-$Mg_{17}Al_{12}$ divorced eutectic lamellas at grain boundaries. Moving dislocations pile up at the β-phase - matrix interface and at grain boundaries. Further movement of the blocked dislocations assumes thermally activated processes.

In the grain interiors twins were observed. They are both annealing twins and deformation twins (fig.7). The number of twins increases with increasing temperature.
Grain growth was observed at temperatures above 200°C.

DISCUSSION

Even if magnesium is a very widely studied material, its deformation behaviour at elevated temperatures and the influence of solute atoms on the deformation behaviour are poorly understood. The yield stress increases with increasing solute content. The increment of the yield strength Ds due to solute atoms can be given by the following equation:

$$\Delta\sigma = \psi(\tau - \tau_0) \qquad (1)$$

where $\psi$ is the Taylor factor (for Mg it lies between 4 and 6), $\tau$ and $\tau_0$ is the critical resolved shear stress (CRSS) of the alloyed and pure single crystal Mg, respectively. The concentration dependence of $\Delta\sigma$ is ambiguous for Mg alloys because a decrease in the CRSS due to addition of solute atoms was also observed in some cases [5]. From fig. 4 it can be seen that the yield stress $\sigma_{02}$ at room temperature increases with the concentration of Al. At temperatures higher than 100°C the concentration dependence of the yield stress is not monotonous; the values of the yield stress of AM50 alloy are higher than those of AM60 alloy. The maximum stress exhibits a similar non-monotonous concentration de-
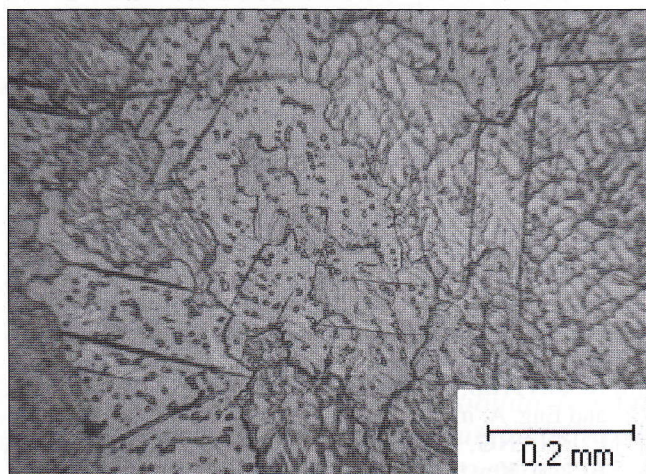
*Fig. 6 - AM20, as cast*
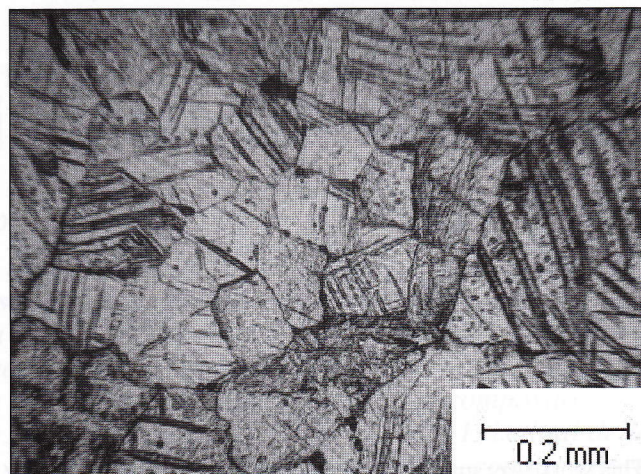
*Fig. 6 - AM20, tal quale dopo fusione*



*Fig. 7 – AM20, deformed at 250°C*

*Fig. 7 – AM20, deformato a 250°C*

pendence (fig. 5). The values of the maximum stress of AM50 alloy are higher than those of AM60 alloy at temperatures above 150°C. Above 100°C the strength of AM series alloy investigated starts to decrease with temperature. The decrease of the strength may be connected with the activity of non-basal slip systems.

According to the Von Mises rule five independent slip systems are necessary to be operated in order to deform polycrystalline materials. This is not fulfilled for metals with hexagonal lattice. There are not five independent slip systems with the same crystallography. It is necessary that another non-basal slip systems are activated or deformation occurs by twinning. In Mg alloys the activity of the pyramidal and/or prismatic slip systems is expected. On the other hand, twinning takes also place, advancing the further deformation. The macroscopic work hardening rate of polycrystalline Mg alloys is a sum of two microscopic processes (like for Mg single crystals in stage B):

i) Dislocation storage; mainly dislocations are blocked by the dislocation forest and impenetrable non-dislocation obstacles (such as grain boundaries, small particles, precipitates);

ii) Dislocation annihilation; the main recovery processes are cross slip and climb of dislocations.

It is interesting to note that, as observed by TEM observations, the presence of the double cross slip of basal screw dislocations through the prismatic planes is typical for Mg single crystals deformed at room temperature. The double cross slipped dislocations can interact with basal dislocations and the dislocation annihilation can occur. The cross slip as well as the annihilation results in a decrease in the work hardening rate. The same processes are expected to occur in polycrystalline Mg alloys. We assume that in the course of deformation a part of the dislocations gliding in basal slip system can cross slip in a prismatic plane and therefore, the work hardening rate should decrease, which is experimentally observed. Temperature and foreign atoms influence the intensity of cross slip of dislocations. With increasing temperature the stress necessary to induce cross slip decreases. It means that more dislocations can cross slip and the frequentness of annihilation of dislocations increases. Therefore, the work hardening should decreases with increasing temperature, which is observed. Cross slip as dynamic recovery balances strain hardening. The value of the maximum stress could be considered as characteristics of the cross slip activity. The tensile strength $\sigma_{MAX}$ should decrease with increasing temperature in the same way as the stress necessary for cross slip. The relationship between $\sigma_{MAX}$ and temperature should then be similar as the temperature dependence of

the critical stress for cross slip [2], i.e.

$$\ln \sigma_{MAX} = K_0 - K(\gamma, \dot{\varepsilon})T \qquad (2)$$

where $K_0$ is a constant and $K(\gamma, \dot{\varepsilon})$ is a function of the stacking fault energy $\gamma$ and the strain rate $\dot{\varepsilon}$. Figure 5 shows that this relationship is valid for the test temperatures above 100°C. A similar temperature dependence of the maximum stress has been reported for AZ91 alloy [2,6]. This means that from 100°C cross slip of screw dislocation segments is the dominant recovery process. Very probably at higher temperatures, where diffusion is faster, climb of dislocations takes places, too.

The non-monotonous concentration of the tensile strength is probably a consequence of the non-monotonous concentration dependence of the critical stress for glide in the prismatic slip system.

The formation of twins contributes also to deformation. Twinning may reorient the basal planes that become more favourable for slip. Zhang et al. [7] have reported this behaviour. The twinning planes are {1,0,-1,2} and {3,0,-3,4} but at higher temperatures twins were observed in plane {1,0,-1,3} too [1]. Higher amount of twins is observed at 250°C (fig.7).

The deformation behaviour above 200°C and changes in the microstructure indicate dynamic recrystallization. This is in agreement with the work of Burrows et al. [8] who investigated dynamic recrystallization of Mg. They observed dynamic recrystallization between 260°C and 370°C and suggest that the recrystallization process involves both grain boundary migration and dynamic subgrain rotation. Due to grain growth the yield stress decreases according to the Hall-Petch rule:

$$\sigma_y = \sigma_0 + k_y d^{-1/2} \qquad (3)$$

where d is the mean grain size, $\sigma_0$ is a constant and $k_y$ is the stress intensity factor for plastic yielding. The value of $k_y$ for Mg alloys is about 210 MPa $\mu m^{1/2}$ [9]. This relatively large value of $k_y$ is very probably a consequence of the required activity of non-basal slip systems.

The Al content has a strong influence on ductility as well (Figs.1-3). Ductility of AM60 alloy increases with increasing temperature. At 300°C an extremely high value of ductility of about 40% is observed, which is atypical for these materials. A maximum ductility of AM50 and AM20 is observed at 200°C and at 100°C, respectively. At room temperature the highest elongation was observed for AM20 alloy. It seems that lower aluminium content improves the room temperature ductility while higher aluminium contents are beneficial for the high temperature ductility.

## CONCLUSIONS

The experimental results demonstrated the influence of Al content in magnesium alloys. Higher concentration of aluminium raises the yield stress and the high temperature ductility.
On the other hand with decreasing content of aluminium the room temperature ductility is increased.
The shape and the temperature dependence of the stress-strain curves and the results of optical microscopy indicate that dynamic recovery, dynamic recrystallization and deformation twins are significant softening mechanisms.

## ACKNOWLEDGEMENTS

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— A B S T R A C T —

### COMPORTAMENTO A DEFORMAZIONE DI LEGHE Mg-Al-Mn A TEMPERATURE ELEVATE

Nel lavoro è stato studiato il comportamento a deformazione di leghe di magnesio ternarie Mg-Al-Mn. I campioni sono stati deformati ad una velocità di deformazione costante, sia a temperatura ambiente sia a temperature elevate (fino a 300°C). Si è anche studiata l'influenza di tre differenti addizioni di Al (2,5 e 6% in peso) sulle proprietà meccaniche alle stesse temperature.

L'aggiunta di alluminio aumenta il carico di snervamento ed il carico di rottura delle leghe a tutte le temperature utilizzate. Il flow stress diminuisce con l'aumento della temperatura. La forma delle curve sforzo-deformazione dipende dalla temperatura di prova.
In alcuni casi le curve sforzo-deformazione evidenziano fenomeni di softening. Il softening è sensibile alla temperatura. L'evoluzione del flow stress risulta influenzato da fenomeni sia di incrudimento che di softening. Viene discusso il comportamento a deformazione.