# RECOVERY OF AlMg ALLOYS: FUNDAMENTAL ASPECTS IN RELATION WITH MECHANICAL PROPERTIES

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**ABSTRACT** Several fundamental aspects involved in static recovery are considered and discussed with respect to experimental results for AlMg alloys: the elastic energy stored during cold-working and its release during recovery, the isothermal kinetic evolution of the flow stress and the modification of the strain-hardening behaviour measured on tensile curves at constant strain rate. Models relating the mechanical properties to dislocation density and cell structure parameters are proposed.

**Keywords:** *recovery, stored energy, flow stress, work hardening.*

## 1. INTRODUCTION

Several fundamental aspects involved in the static recovery of Al-2.5%Mg alloys are considered, in relation with mechanical properties such as yield stress and work-hardening. Recovery treatments have been performed mainly at 160 and 220°C, after a cold-rolling prestrain varying between 0.1 and 3. The microstructure of the alloys has been directly observed by transmission electron microscopy after cold-rolling and annealing. A number of experimental techniques, such as electrical resistivity, X-ray Bragg peak broadening, differential scanning calorimetry, have been used jointly to quantify the energetics and the evolution of various physical parameters involved in recovery: the dislocation density, the stored elastic energy, the heterogeneity of the dislocation distribution in a cell structure.

The details of the experimental results have been presented elsewhere [1-4]. We focus here on two aspects of recovery: first the evaluation of the elastic energy stored during cold-rolling and released during subsequent recovery. Then the correlation between the dislocation microstructure parameters with the observed kinetic evolution of both the yield stress and the strain-hardening coefficient measured at constant strain-rate.

## 2. STORED ELASTIC ENERGY AND DISLOCATION DENSITY

The elastic strain energy stored during plastic deformation is indeed clearly non linear with the average dislocation density due to its sensitivity to the dislocation microstructure. This is an obvious but important point since the thermodynamical driving force for recovery or recrystallization is precisely this stored strain energy. Although the microscopic mechanisms leading to the formation of dislocation microstructures are still controversial [5], it is admitted that the underlying first parameter is the decrease of the dislocation line energy occuring through the screening of their strain field. The organization of the dislocation structure in cells may be dictated by such a principle.

In order to clarify this point, we have measured separately the dislocation density $\rho$ by electrical resistivity and specific mass measurements on the one hand, and the strain energy E released during a subsequent calorimetric experiment on the other hand [1,2]. The results are shown in Fig. 1 at increasing cold-rolling prestrains $\varepsilon$ and after different recovery times at 220°C following a prestrain of 3.

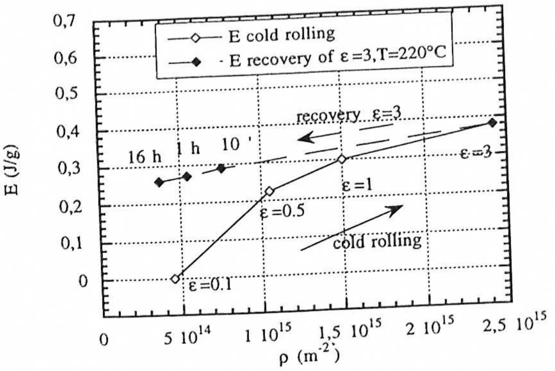

Fig.1: Stored elastic energy versus dislocation density after different prestrains and after different recovery durations from $\varepsilon$=3.

The slope $\delta E/\delta\rho$, which corresponds to a "dislocation chemical potential", is equal to the classical line tension expression $Gb^2/2$ only at small strain, and decreases then continuously with strain. This is due to the development of a hetereogeneous dislocation microstructure: cells are formed and consequently the self-screening length of the dislocations, instead to scale on $\rho^{-1/2}$, scales on $\rho^{-1/2}M_S$, where $M_S$ is a dislocation structure parameter, smaller than one and decreasing with $\varepsilon$. When the initial microstructure is not drastically modified during recovery (i.e. for not too long recovery durations), in such a way that the chemical potential stays constant and equal to this of the initial state, the stored energy decreases then almost linearly with the dislocation density.

These results demonstrate that for a given dislocation density the stored energy depends on the path used to produce this dislocation density. It is much higher for a cold-rolling/recovery treatment than for a direct cold-rolling. This may be of importance to understand the effect of recovery on subsequent recrystallisation, which is driven by the stored energy.

## 3. YIELD STRESS AND WORK-HARDENING

### 3.1 Yield stress

During recovery the yield stress (here the stress at 0.2% yield) decreases according to a logarithmic kinetics [3,4]. One example is given in Fig.2 for the alloy heated at 120°C for various prestrains.

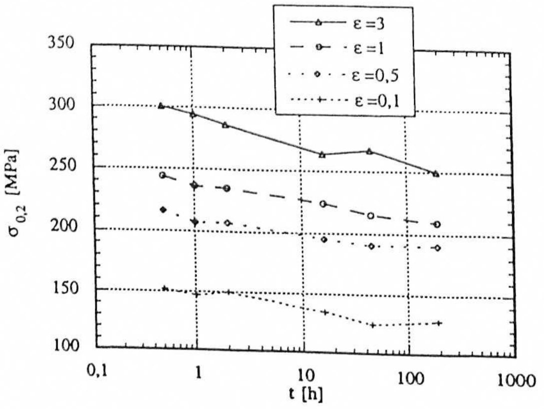

Fig. 2: Time evolution of the yield stress at 120°C.

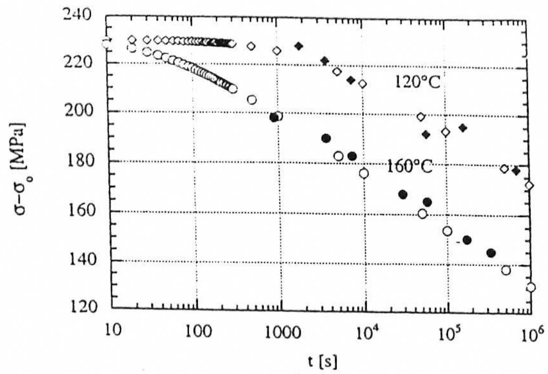

Fig.3: Yield stress evolution at 120 and 160°C. ε=3. model: white/ experiment: dark symbols.

According to Friedel [6], such a kinetics can be explained on the basis that first the applied stress $\sigma$ is equilibrated by the internal stress $\sigma_i$, and then that this internal stress relaxes during recovery with a rate proportional to the dislocation annihilation frequency. We made an adaptation of this model at the dislocation level, writing that the micro-strain rate $\dot{\varepsilon}_p$, which results from the rate of the stress relaxation $d\sigma_i/dt$, namely

$$\frac{d\sigma_i}{dt} = -\dot{\varepsilon}_p E, \tag{1}$$

is related, via the Orowan law, to a (thermally activated) motion of the reorganizing dislocations [4]. This leads to a general form of the relaxation rate of the internal or applied stress:

$$\frac{d\sigma_i}{dt} = -\frac{64}{9M^3\alpha^2}\frac{\sigma_i^2}{E}\nu_D \exp(-\frac{U_0}{kT})\mathrm{sh}(\frac{\sigma_i v}{kT}) \tag{2}$$

Use has been made of the proportionnality of the dislocation contribution to the yield stress to the square root of the dislocation density [7]:

$$\sigma_i = \alpha G \rho^{1/2} \tag{3}$$

E and G are respectively the Young modulus and the shear modulus, $\nu_D$ the Debye frequency , $U_0$ and v are the activation energy and the activation volume for the dislocation motion. A comparison of the model, obtained by integration of (2), with experimental data is shown in Fig.3.

## 4. CONCLUSION

Several fundamental aspects of the recovery of AlMg alloys have been considered. The first is related to the elastic energy stored during cold-rolling and released during further recovery. It is shown to be sensitive to the dislocation microstructure, and the variation of the dislocation chemical potential versus cold-rolling strain and recovery strength is measured. Two others aspects are studied: the yield stress and the strain-hardening coefficient during deformation at constant strain-rate. A model is proposed, based on a Kocks constitutive plasticity law, where modifications of dislocation storage and dislocation annihilation occuring consecutively to the formation of a cell structure are taken into account.

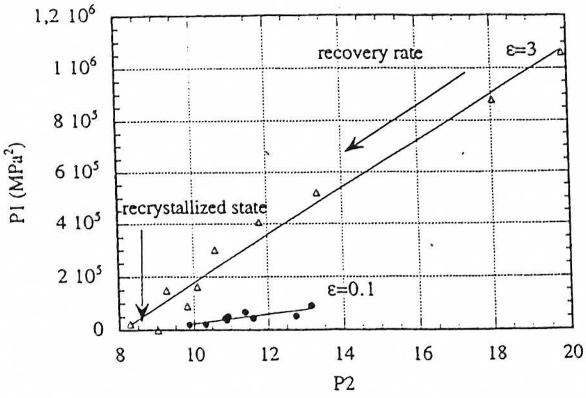

Fig.6: Evolution during recovery of the parameters $P_1$ and $P_2$ described in the text, for two prestrains.

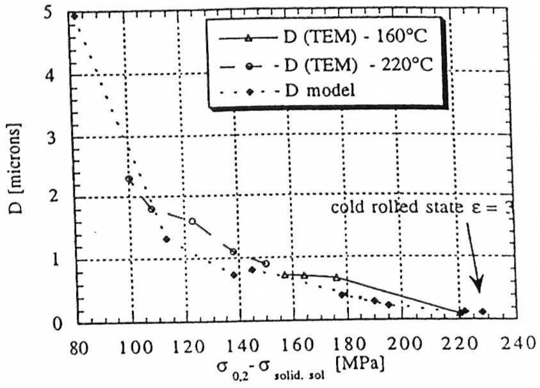

Fig.7: After recovery cell size measured by TEM or deduced from the strain-hardening model.

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