Strength and plasticity of SPD magnesium alloy at low temperatures

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The aim of this study was to determine the mechanisms controlling the plastic deformation of the processed by Severe Plastic Deformation (SPD) Mg-Al-RE (Mg-1.7Al-0.66Ce-0.36La-0.23Nd-0.18Mn-0.05Pr) alloy over a wide temperature range.

Method and microstructure

The SPD method by Equal Channel Angular Pressing (ECAP, 8 passes) method was used to form the ultrafine-grain microstructure of the alloy [1].

The average grains size of SPD samples is d ≈ 1-2 µm (see fig.1), and the average dislocation density ρ inside the grains is the order of $\rho \approx 0.5 \times 10^{14}$ m^{-2}.

Part of grains contained lot of dislocations but the others with high angle grain boundaries were dislocation free.

The particles with size 1-10 µm containing aluminium, lanthanum, cerium and neodymium (Al11RE3) were found.

In addition, in the polycrystals, subjected to severe plastic deformation, a formation of the specific crystallographic texture (~55° inclined from the extrusion direction) was observed.

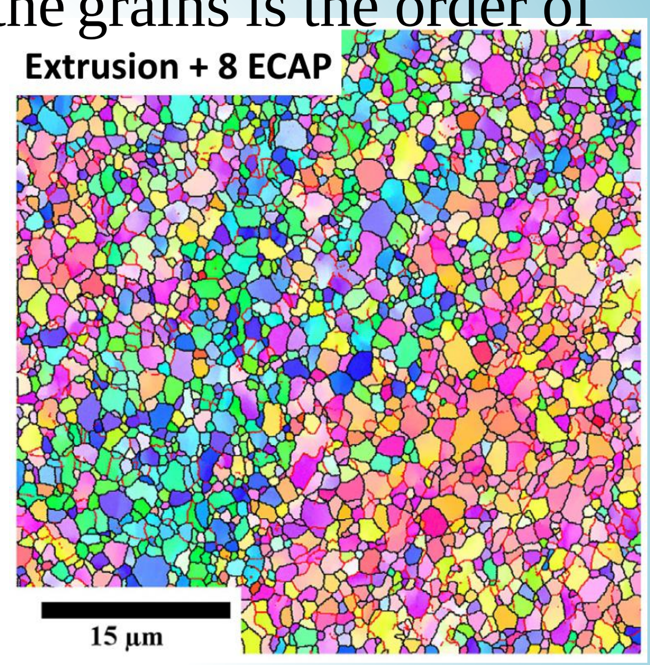

Fig.1. Microstructure of magnesium alloy after SPD.

Plastic deformation was carried out by tension at a constant strain rate $\dot{\varepsilon}$ ~10^{-4} s^{-1} in the temperature range of 0.5–400 K using special cryogenic high-performance equipment.

[1] Minarik P., Kral R. et al. Acta Materialia. 107, 83 (2016)

Plastic deformation

The plastic deformation of Mg-Al-RE alloy with modified microstructure by extrusion and 8 passes of ECAP was studied.

The stress-strain curves (fig.2) illustrate nonmonotonically increase in plasticity and decrease in strength with temperature increasing. Low plasticity is observed in the temperature range of 0.5–210 K.

With an increasing of temperature in the range of 210–400 K, the plasticity of the samples rapidly increases. In this case plastic deformation carried out without necking at unchanged flow stress up to 20% of deformation. These features are apparently associated with the intensification of dynamic recovery processes at 290 and 400 K.

The strength of polycrystals in the range of 0.5–290 K changes insignificantly, but an increase in temperature from 290 to 400 K leads to a significant its decreasing.

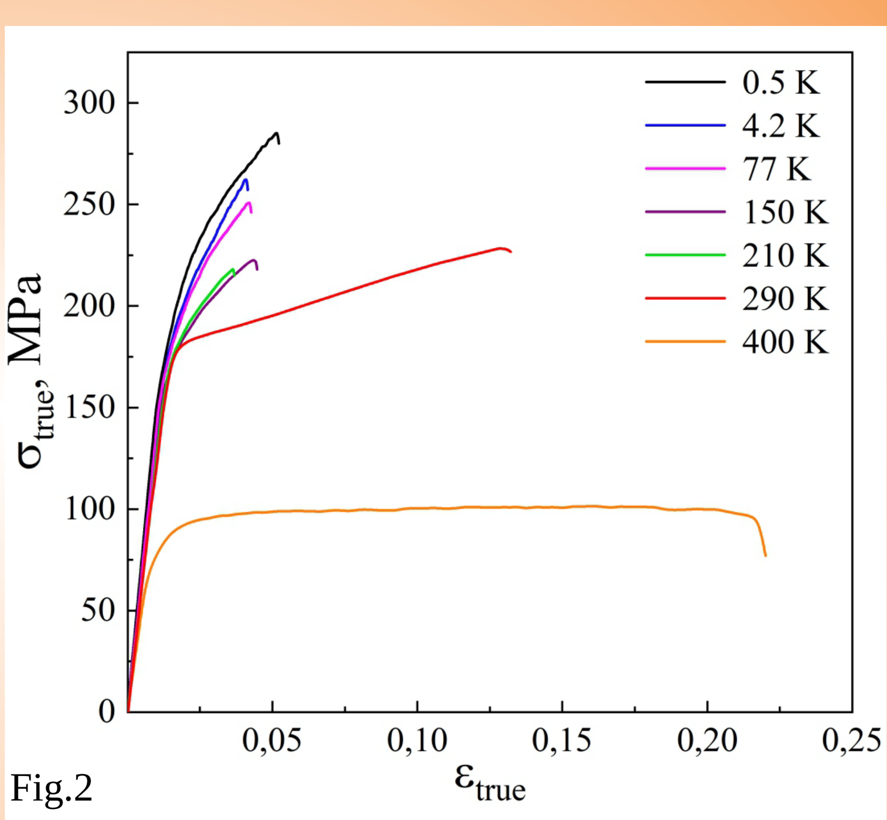

Fig.2

In the region of extra low temperatures 0.5 – 4.2 K an unstable plastic deformation, so-called low-temperature jump-like deformation (LTJD), was observe (shown on fig.3). The amplitude and intensity of instability depend on temperature of deformation. It can be discussed in the concept of the avalanche-like dynamics of dislocations being the cause of discontinuous plastic deformation under conditions of low temperatures and high stress.

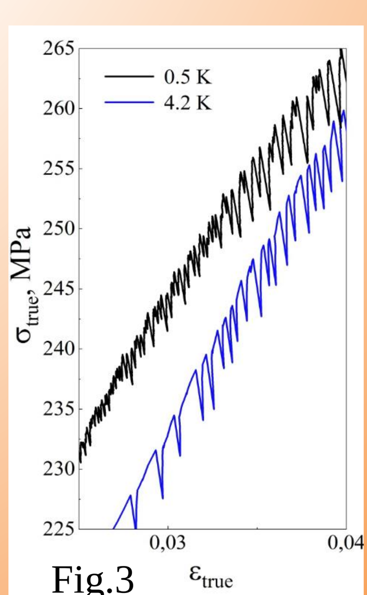

Fig.3

Strain hardening rate

The work hardening rate coefficient θ:

$$\theta = d\sigma_{true}/d\varepsilon_{true}$$

On the beginning stage, all curves illustrate a short elastoplastic transition which means a rapid decreasing of strain hardening rate at stress closer to the yield point. Further development of the strain hardening coefficient depends on the temperature and illustrate three types of strain hardening dependencies.

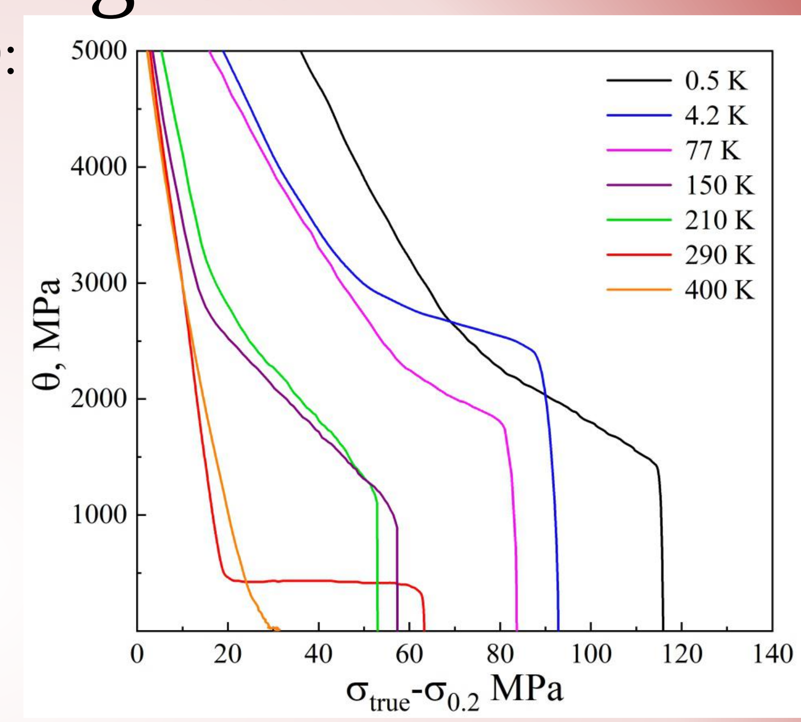

Fig.4

The stage II is not observed for the low-temperature region 0.5-210 K, and pronounced staging and slow decline of hardening rate on the stage III were observed until to failure. Curves for 290 K shown the the long stage with constant value of θ until to failure. During the high-temperature tensile at 400K the plastic deformation process carried out with absent of hardening rate. In this case, when θ approach to zero, deformation takes place in steady-state conditions, i.e. under constant stress and constant strain rate.

Temperature effect

The temperature dependencies of the yield strength $\sigma_{0.2}$ and work hardening rate coefficient θ presented on figures 5 and 6.

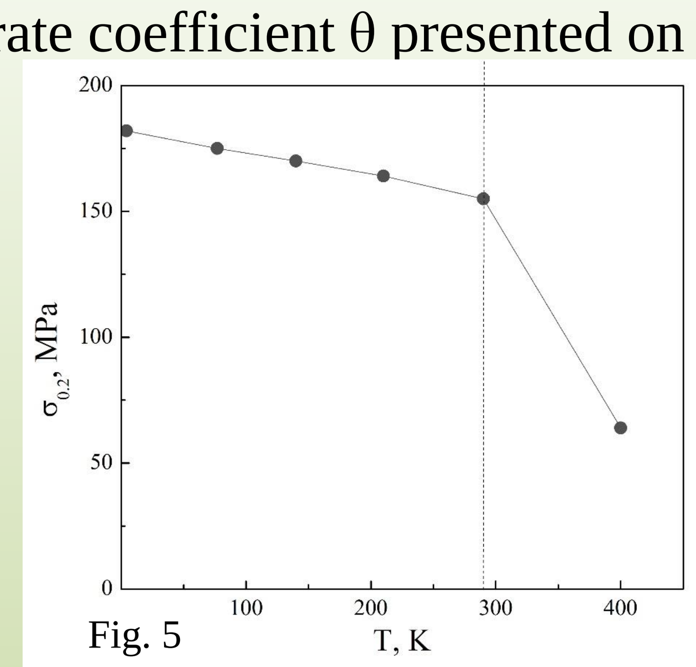

Fig. 5

Below the room temperature the monotonically decreasing the $\sigma_{0.2}$(T) dependence was observed.

In the case of the dependence of θ(T), where is value of θ was calculated at 2% of deformation, the coefficient θ changes linearly in the temperature range 0.5-290K.

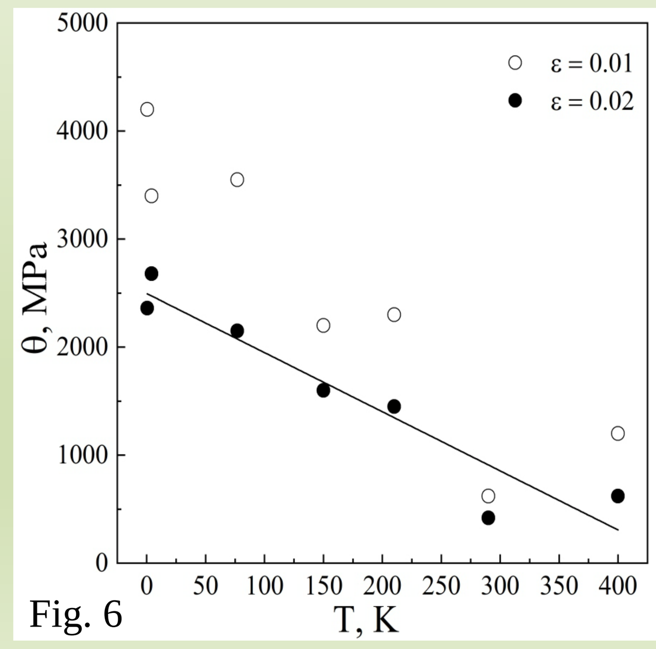

Fig. 6

Stress relaxation and activation volume

The analysis of stress relaxation results was carried out by the Feltham equation $\Delta\sigma_R = \alpha ln(\beta t+1)$, α and β – relaxation parameters dependent on temperature and stress, t - time. The relationship between the parameters α and the activation volume *V* by the relations $\alpha = kT/V$.

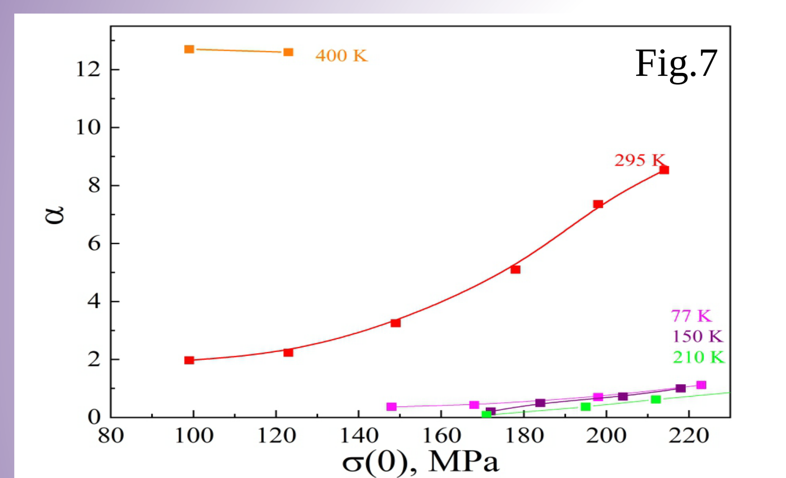

Fig.7

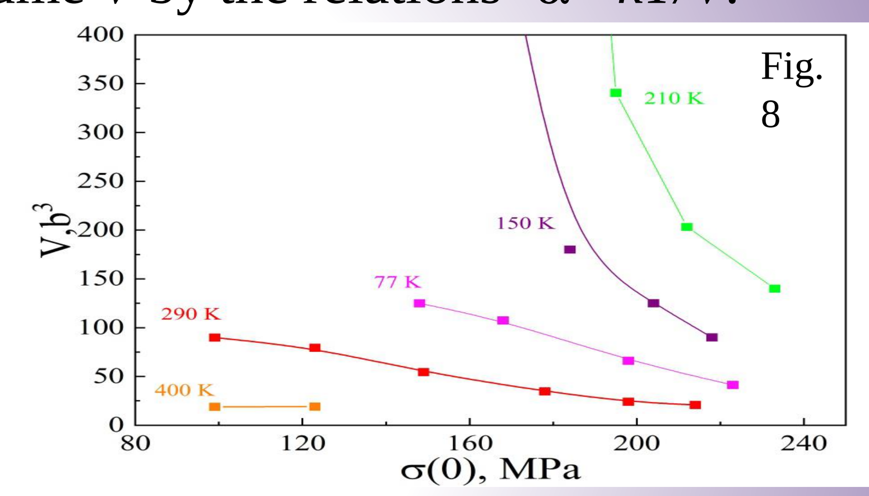

Fig. 8

The significant influence of recovery processes on stress relaxation is illustrated by the dependence of the parameter α on stress.

The small values of the activation volume calculated from the stress relaxation data are apparently due not only to changes in the barrier energy, but also to a significant effect of recovery processes on the relaxation parameters.

SUMMARY: The yield strength $\sigma_{0.2}$ weakly decreases with temperature from 180 MPa to 150 MPa in the range of 0.5-290 K, and rapidly decreases to 60 MPa at 400 K. Three types of strain hardening evolution were observed:

- In the 0.5-210 K region, a high strain hardening rate decreases rapidly with strain, followed by high strength and low ductility;
- Room temperature is characterized by a low but constant strain hardening rate, accompanied by rather high stresses and deformations.
- Increasing the temperature to 400K reduces strength and increases ductility with almost no strain hardening rate.

The values of activation volume and activation energy obtained from the relaxation experiment allowed us to assume that there is the three types of thermo-activated processes controlling plastic deformation of the studied structure:

- In the range of 77-210K, the process overcoming impurity atoms by moving dislocations:
- In the room temperature region multiple basal slip dominates;
- with an increase in *T* up to 400 K, the activity of recovery processes increases.