DEFORMATION MODE IN AZ31 MAGNESIUM ALLOY DURING COMPRESSION TESTS

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Abstract
Usage of magnesium alloys constantly increase, especially in the area of automotive industry. Classification of magnesium alloys for forming, production process by rolling, extrusion and forging have been presented. Moreover, the difficulties in magnesium manufacturing have been presented as well. The relations between microstructure and deformation parameters in AZ31 magnesium alloy have been studied. Two main deformation processes: twinning and slipping have been shown. The changes in the plastic characteristics as a function of the Zener-Hollomon parameter have been presented. The research carried out enabled the understanding of the phenomena taking place during deformation and annealing of the investigated AZ31 type alloy. The results will constitute the basis for modelling the structural changes.

Keywords: magnesium alloy, high temperature deformation, dynamic recrystallization, slip, twinning

1 Introduction

The current trends in the automotive, aircraft and space industries focus first and foremost on a reduction of the vehicle weight and saving energy, thereby protecting the environment. Such a set of technical, economical and ecological aspects arouses a considerable interest of the industry in light alloys. Owing to a number of their advantageous mechanical properties including, first of all, low density (1.74 g/cm^3), magnesium alloys are more and more frequently used as an engineering material. There is a regular increase visible in the number of components made of magnesium alloys in the car structure [1-4].

However, for the production of components from magnesium alloys, casting processes are still most often applied. Alloys used for plastic working are less popular compared to those processed via casting and therefore, the number of their grades is much smaller. The number of alloying components in cast magnesium alloys is always higher than in alloys subject to plastic working. Alloys from the group Mg-Al-Zn-Mn have the best set of properties, for they contain as much as 8 % Al with an addition of Mn (up to 2 %) and Zn (up to 1.5 %). From among elements subjected to plastic working, sheet metal deserves special attention, for it can be applied for the construction of light vehicles [3-8].

In connection with the complexity of the phenomena which take place in the microstructure, a number of studies in the field of Mg-Al-Zn alloys subjected to plastic working are focused on

detecting the mechanisms of deformation and structure reconstruction during deformation. There are two main mechanisms of deformation of magnesium alloy – slip and twinning. Magnesium alloys crystallize with hexagonal close pack (HCP) structure and they have very limited number of slip systems [9-11].

In this study, an attempt has been made to identify the effect of deformation parameters on the microstructure of alloy AZ31. The reconstruction mechanisms of the alloy structure and mathematical relations have been determined, taking into account the effect of deformation parameters on the structure and properties of the Mg-Al-Zn alloy in thermo-plastic treatment.

2 Methodology

Hot rolled bars made from alloy AZ31, 20 mm in diameter, constituted the research material. Chemical composition was presented elsewhere [12]. After rolling and annealing, alloy specimens were subjected to axial-symmetric compression at temperatures ranging from 200 to 450 °C at 0.01 and 1.0 s^{-1} strain rates.

Structural examination was performed on a cross-section parallel to the axis of a sample. The samples were included in a conducting material and etched in a solution intended for etching magnesium alloys, containing: 4.2g $(NO_2)_3C_6H_2OH$ – picric acid**,** 70ml C_2H_5OH – ethyl alcohol, 10ml H_2O – water 10ml CH_3COOH – glacial acetic acid. Structural evaluation was performed using an Olympus light microscope, in bright field. Images were recorded for a quantitative examination. Quantitative analyses of the grain size were conducted using the techniques of quantitative metallography.

3 Results

In the initial state after rolling in the temperature range of 400-200 °C, a large amount of deformation twins was present in the alloy structure [13-15]. Application of annealing after the rolling in the temperature range from 350 to 500 °C, with soaking time from 30 to 1800 s, leads to grain coarsening and an intense decrease in the amount of twins in the microstructure. The acquired data point to the constant growth of the grains under the influence of rising temperature and elongation of the annealing time. The changes of the average grain size in the isothermal holding conditions, in a material which does not contain second phase particles, may be described by means of an equation (1) describing the grain growth as a function of temperature and soaking time.

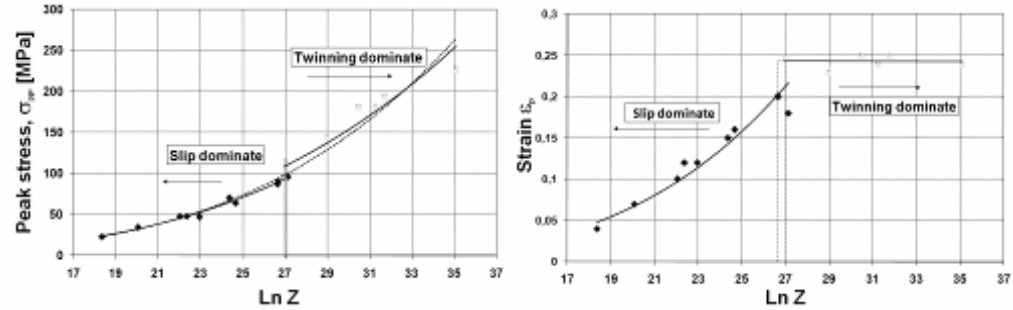
$$d^q = d_0^q + K_{st} \exp\left(-\frac{Q_3}{RT}\right) \tag{1}$$

Where: d- the grain size after holding at temperature T during the time t, [µm]; d_o – the initial grain size, [µm]; Q_3 – activation energy for the process of grain growth [kJ/mol];

Optimized coefficients from equation (1) for the investigated magnesium alloy AZ31: K_{st} = 9.63, Q_3 = 173 kJ/mol, q = 1.04

The alloy samples after annealing at a temperature of 450°C, with the holding time of 300s, were used for an axisymmetric compression test. For those parameters, the alloy showed a minimal inhomogeneity of the grain size; the variability coefficient amounted to 115%, with the average grain size of 38 µm. Population of flow curves of alloy AZ31 after compression was presented in other publications [10]. Generally, these results indicate that a decrease in the test temperature from 300 to 250 °C causes a radical changes in character of flow curve.

The changes in the peak flow stress σ_{pp} and the corresponding deformation are presented in Fig. 1 as a function of the Zener-Hollomon parameter. A dependence of an exponential nature was observed between stress σ_{pp} and parameter Z. A better matching of measuring points was obtained when the calculations were made by means of data separation, i.e. the values for the curves with a classical course of changes in stress were separated from those for curves which pointed to the course of twinning **(Fig. 1a)**. Similarly, in the case of deformation ε_p, for the classical course of the curve, a dependence of an exponential nature as a function of parameter Z was found **(Fig. 1b)**. For the range of parameters where twinning predominated, such a dependence was constant; no increase of the value of ε_p was observed with an increase of Z.



a) b)

Fig.1 Peak flow stress σ_{pp} (a) and deformation ε_p (b) corresponding to peak stress as a function lnZ, Z- Zener – Hollomon parameter [s^{-1}], .

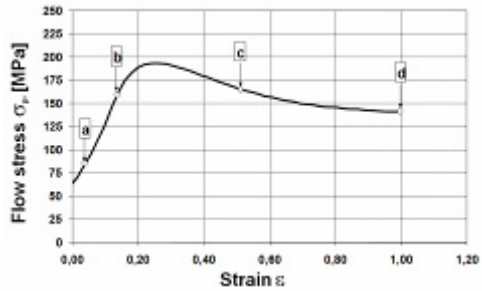
On the basis of the compression tests carried out for the investigated alloy, two types of flow curves were observed. A classical curve, where the dominant mechanism in the microstructure was a slip, as well as a characteristic curve, where twinning dominated in the microstructure.

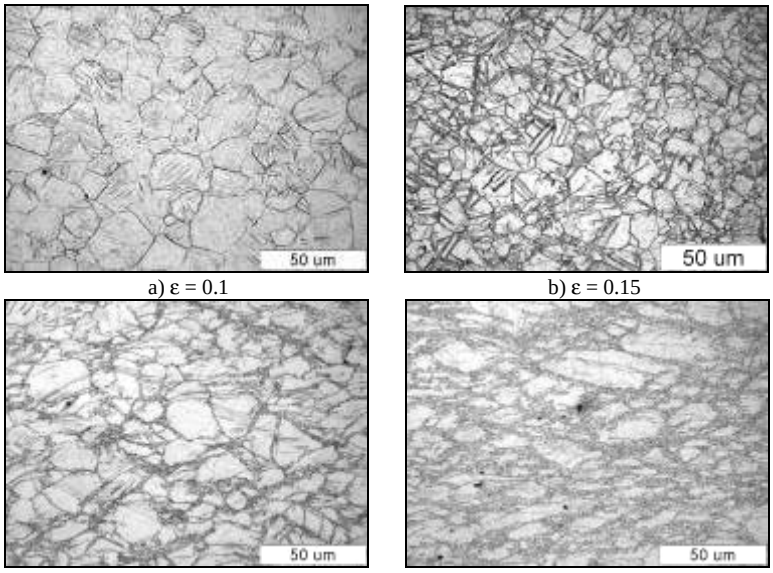
The changes in the alloy structure deformed at a temperature of 250 °C at a rate of 1 s^{-1} with an increasing deformation, where the plastic flow corresponds to the twinning process, are presented in **Fig. 2 a-d**. At the initial stage of deformation (ε = 0.1), the grains become subject to deformation, while twins are being created in the structure (**Fig. 2a, b**). Further increase in the deformation intensifies this process – the amount of twins grows (**Fig. 2 b**). At a deformation ε = 0.5, very fine, recrystallized grains are observed in the structure, on the boundaries of primary grains and deformation twins (**Fig. 2 c**). For a deformation ε = 1.0, primary grains are deformed and little chains of new grains are present around them. Despite reaching a steady flow state, a part of unrecrystallized material still remains in the microstructure (**Fig. 2 d**).

The changes in the alloy microstructure, deformed at a temperature of 300 °C at a rate 0.01 s^{-1}, together with the deformation increase, where the nature of flow has a classical course, are presented in **Fig. 3 a-d**. After deformation ε = 0.15, a migration of some of the grain boundaries is observed (**Fig. 3a**). An increase in the deformation up to 0.1 leads to achieving the maximum on the flow curve (σ_{pp}). In the structure, the migration of grain boundaries intensifies and the first dynamically recrystallized grains appear (**Fig. 3b**) For the deformation from 0.1 to 0.3, the structure is of a biomodal nature. New fine grains as well as primary, disappearing ones, are present (**Fig. 3c**). For the deformation ε = 0.4, the structure is fully dynamically recrystallized (**Fig. 3d**). The deformation corresponds to the beginning of the steady state of plastic flow.

In the relations between the deformation process parameters and the alloy grain size after recrystallization are presented. Dependencies of exponential nature between these parameters are shown (2):

$$d_{rec} = 27,39 \times Z^{-0.02}, [\mu m] \quad (2)$$





a) ε = 0.1 b) ε = 0.15

c) ε = 0.5 d) ε = 1.0

Fig.2 The flow curve and microstructure of the investigated alloy after compression at a temperature of 250 °C at a strain rate of 1.0 s^{-1} (twinning dominates).

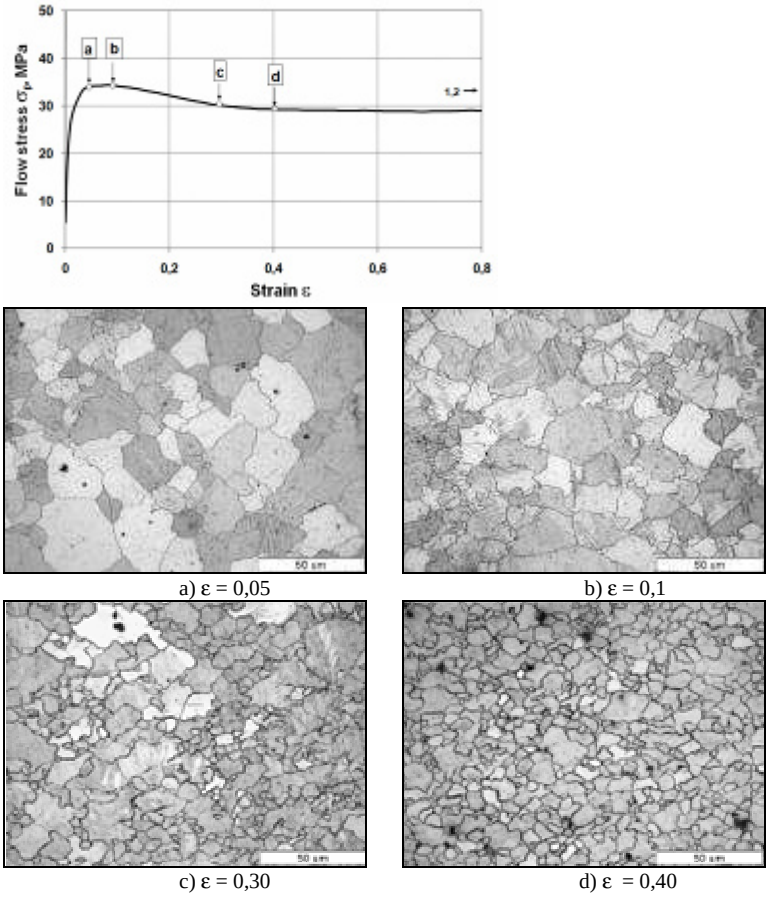
4 Discussion

Hot rolled bars, made of an alloy of the AZ31 type, constituted the initial material. The alloy was characterized by a single-phase structure with a grain size dependent on the annealing temperature. A decrease has been discovered in flow stress together with a rise in the process temperature and a drop in the deformation rate, which is connected with the course of the dynamic structure reconstruction processes.

It has been shown that there is a strong relationship of an exponential nature between the peak flow stress, σ_{pp} and Zener – Hollomon parameter. Deformation ε_p, for the classical course of the curve, a dependence of an exponential nature as a function of parameter Z was found. For the range of parameters where twinning predominated, such a dependence was constant (linear dependence). The activation energy of hot deformation was low and amounted to 150 kJ/mol. This results from low flow stress values for magnesium alloys and from a strong tendency to dynamic recrystallization.

After deformation at 250°C the initial stage of the flow is connected with the twinning effect. As the deformation in the microstructure increases, fine recrystallized grains appear both on the

boundaries and in the twinned regions. The appearance of a large amount of recrystallized grains leads to an intense decrease in the yield stress.



a) ε = 0,05 b) ε = 0,1

c) ε = 0,30 d) ε = 0,40

Fig.3 The flow curve and microstructure of the investigated alloy after compression at a temperature of 300 °C at a strain rate of 0,01 s^{-1}.

Measurements of the recrystallized grain point to a size reduction of the grain in the recrystallization process of as much as 7µm for the deformation at a temperature of 250 °C and a rate of 0.01 s^{-1}. For higher compression temperatures new grains nucleate on the grain boundaries, corrugated as a result of migration. An increase in the deformation intensifies the dynamic recrystallization process, which, in consequence; leads to a full refinement of the structure. A dependence of an exponential nature was obtained between the average recrystallized grain size, d, and parameter Z.

The obtained examination results will be used to develop a comprehensive model of changes in the structure of a hot deformed magnesium alloy. However, there is a necessity for the diversified deformation mechanisms taking place in the analyzed alloy to be taken into account in the model, depending on the process parameters, which will enable a correct design of the rolling technology and extrusion of products from this alloy.

5 Conclusions

On the basis of the experimental observation we can make the following conclusions:

1) The alloy was characterized by a single-phase structure with a grain size dependent on the annealing. This process leads to grain coarsening and an intense decrease in the amount of twins in the microstructure.
2) On the basis of the compression tests carried out for the investigated alloy, two types of deformation mode were observed. A classical, where the dominant mechanism in the microstructure was a slip (for a parameter around $Z < 5{,}3\times10^{11}$), as well as a characteristic curve, where twinning dominated in the microstructure (for a parameter around $Z > 5{,}3\times10^{11}$).
3) After deformation with high value of Zener-Hollomon parameter, a course of the plastic flow curve, disparate from the classical one, was observed. The initial stage of the flow is connected with the twinning effect, which has an impact on the flow curve's shape, as the twins make the transition of dislocation within the area of the grains difficult.
4) For low value of Zener-Hollomon parameter , the processes occurring in the microstructure take place in a classical manner, which affects the course of changes in stress. New grains nucleate on the grain boundaries, corrugated as a result of migration. An increase in the deformation intensifies the dynamic recrystallization process. An exponential dependence was obtained between the dynamic recrystallized grain size and parameter Z.

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