Abstract

The magnesium alloy designated as AZ31 is alloyed by 3 % Al and 1 % Zn. Magnesium alloys distinguish themselves generally by a considerable mechanical strength and at the same time extraordinarily low density. They have also a strong resistance to corrosion. At the room temperature the formability of magnesium alloys is quite questionable and the mechanical properties unsatisfactory, while by hot processing their properties achieve already adequate values. That is why it is effective from the practical viewpoint to study plastic properties and deformation behaviour of magnesium alloys that are processed in the hot state, namely with the aim of their following commercial utilization. Magnesium alloys have already quite a long time been an integral part of the automotive and aircraft industry, but nowadays they are – thanks to their specific properties – more and more frequently implemented for manufacturing of products of everyday life, as e.g. cell phones, laptops, cameras and other small electronics.

A good deal of experiments was carried out on simulator Gleeble, implemented in a broad range of thermodynamic conditions (temperature 523 – 673 K, strain rate 0.1 – 10 s\(^{-1}\)). Pressure tests served for obtaining data that are necessary for development of the mathematical model of the static recrystallization in the case of the given magnesium alloy AZ31. The applied relaxation and metallographic methods enabled to find out that the entire recrystallization in the investigated material occurs already at temperature 523 K, and of course higher. The developed model of the static recrystallization is valuable and helpful, especially in the processes of forming which are in progress at lower temperatures, and when values of the previous deformation are relatively low.

Keywords: Magnesium alloy, AZ31, model of the static recrystallization.

1. INTRODUCTION

The magnesium alloy designated as AZ31 is alloyed by 3 % Al and 1 % Zn. In general, magnesium alloys distinguish themselves by high mechanical strength and at the same time extraordinarily low density. At the room temperature the formability of magnesium alloys is quite questionable and the mechanical properties unsatisfactory, however, by hot processing their properties reach already adequate values. Therefore it is effective from the practical point of view to study the plastic properties and deformation behaviour of magnesium alloys that are processed in the hot state, namely with the aim of their following commercial utilization, as it is noted in some already published papers [1,2]. The magnesium alloy that was investigated in the presented work underwent a series of plastometric tests and from the resulting data the constants were obtained, which supplement the mathematical models, enabling the description of kinetics of the recrystallization in the specific thermodynamic conditions. The studies [3,4] process also the data gained in a wide range of thermodynamic conditions. Magnesium alloys have already for a longer time been an integral part of the automotive and aircraft industry, but currently they are – thanks to their specific properties – more and more frequently used for manufacturing of products of everyday life, as e.g. cell phones, portable computers, cameras and other small electronics.
2. DESCRIPTION OF EXPERIMENT

The data necessary for the design of the mathematical model of the static recrystallization in the case of the investigated alloy AZ31 were obtained by means of relaxation methods carried out on simulator Gleeble 3800. The relaxation method consists in implementation of the whole progress of a specific deformation cycle on one specimen, which is held for the entire period of deformation between swages; at the same time the force decrease is continuously recorded. In the course of deformation the recrystallization of the material and the following fall of the forming force occur. The advantage of this method consists in achievement of the whole curve of softening of the material in the selected deformation terms. The axially symmetric specimens of the magnesium alloy AZ31 with the chemical composition 2.82 Al – 0.80 Zn – 0.37 Mn (in wt %) were used for the experiments. In order to provide the credibility of the achieved results a wide variety of thermodynamic conditions, as far as temperature and strain rate is concerned, was used. The temperature was changed in the range of $T = 523 – 673 \, \text{K}$ and the strain rate reached the values $\gamma = 0.1, 1.0, \text{ or } 10 \, \text{s}^{-1}$. The equivalent strain attain values $\varepsilon = 0.10 – 0.25$ and the initial grain size was 30.3, 38.2, or 45.6 $\mu\text{m}$. A summary of all these above mentioned thermodynamic parameters is given in Tab. 1.

**Tab. 1** Survey of data used for obtaining model of static recrystallization and determined values $t_{0.5}$

<table>
<thead>
<tr>
<th>$T$</th>
<th>$\gamma$</th>
<th>$\varepsilon$</th>
<th>$d_0$</th>
<th>$t_{0.5}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>[K]</td>
<td>[s$^{-1}$]</td>
<td>[-]</td>
<td>[µm]</td>
<td>[s]</td>
</tr>
<tr>
<td>523</td>
<td>0.1</td>
<td>0.2</td>
<td>38.2</td>
<td>2.3</td>
</tr>
<tr>
<td>523</td>
<td>0.1</td>
<td>0.2</td>
<td>45.6</td>
<td>3.7</td>
</tr>
<tr>
<td>523</td>
<td>0.1</td>
<td>0.25</td>
<td>38.2</td>
<td>3.7</td>
</tr>
<tr>
<td>523</td>
<td>1</td>
<td>0.15</td>
<td>38.2</td>
<td>2.4</td>
</tr>
<tr>
<td>523</td>
<td>10</td>
<td>0.1</td>
<td>38.2</td>
<td>4.1</td>
</tr>
<tr>
<td>523</td>
<td>10</td>
<td>0.15</td>
<td>38.2</td>
<td>2.3</td>
</tr>
<tr>
<td>573</td>
<td>0.1</td>
<td>0.1</td>
<td>38.2</td>
<td>2.1</td>
</tr>
<tr>
<td>573</td>
<td>0.1</td>
<td>0.1</td>
<td>30.3</td>
<td>1.6</td>
</tr>
<tr>
<td>573</td>
<td>0.1</td>
<td>0.1</td>
<td>45.6</td>
<td>2.7</td>
</tr>
<tr>
<td>573</td>
<td>1</td>
<td>0.1</td>
<td>38.2</td>
<td>1.5</td>
</tr>
<tr>
<td>623</td>
<td>1</td>
<td>0.1</td>
<td>38.2</td>
<td>1.4</td>
</tr>
<tr>
<td>623</td>
<td>1</td>
<td>0.15</td>
<td>38.2</td>
<td>1.0</td>
</tr>
<tr>
<td>623</td>
<td>10</td>
<td>0.15</td>
<td>38.2</td>
<td>1.0</td>
</tr>
<tr>
<td>673</td>
<td>10</td>
<td>0.15</td>
<td>38.2</td>
<td>0.5</td>
</tr>
</tbody>
</table>

In Tab. 1 also the particular graphically determined values of time needed for reaching a 50% share of recrystallization, designated as $t_{0.5}$ [s], can be seen. An example of the values determined in such a way is shown in Fig.1.
3. MODEL OF STATIC RECRYSTALLIZATION

To create a model of static recrystallization is important mainly in the case of processes in which the deformation is implemented under lower temperatures and its amount is small. From the beginning the deformation of the material causes an increase in the dislocation density, which raises the deformation resistance of the material and leads to a change of the plastic properties of the material.

Based on the analysis of the references and previous experience [5,6] the following equations were used and experimentally enumerated with the aim to describe kinetics of the static recrystallization. Using the non-linear regression analysis, performed by means of the statistic software Unistat 5.6, the equation defining the variable \( t_{0.5} \) was successfully described. Using a next regression the value 0.70 of the constant in equation (1), describing the recrystallized share \( X \) in relation to the annealing time \( t \) [s], was gained. The specific forms (after expression in numbers) of both equations are as follows:

\[
X = 1 - \exp\left[-\ln(2) \frac{t}{t_{0.5}}\right] \tag{1}
\]

\[
t_{0.5} = 6.8 \cdot 10^{-4} \varepsilon^{-0.35} \gamma^{-0.04} d_0^{0.24} \exp\left(\frac{29950}{RT}\right) \tag{2}
\]

4. DISCUSSION OF RESULTS

For the graphic evaluation of conformity between the experimentally found and according to equation (2) calculated values \( t_{0.5} \), Fig. 2 may be used. In spite of the fact that scattering of experimental values \( t_{0.5} \) is relatively considerable (see Table 1), we succeeded in gaining the model \( t_{0.5} = f(\varepsilon, \gamma, d_0, T) \) of the investigated alloy AZ31 with a comparatively good accuracy.
In Fig. 3 we can see examples of the achieved conformity between the data measured in the course of the plastometric tests and the curves representing the newly developed model, describing kinetics of the static recrystallization – equations (1) and (2).

**Fig. 2** Graphic depiction of experimentally found and according to model (2) calculated values $t_{0.5}$

**Fig. 3** Recrystallized share $X$ [-] in relation to time $t$ for the measured and according to model (1) predicted data

a) $T = 623\, \text{K}$, $\varepsilon = 0.15$, $\gamma = 10\, \text{s}^{-1}$, $d_0 = 38.2\, \mu\text{m}$

b) $T = 523\, \text{K}$, $\varepsilon = 0.25$, $\gamma = 0.1\, \text{s}^{-1}$, $d_0 = 38.2\, \mu\text{m}$
In Fig. 4 two chosen examples of the fully recrystallized structure of the magnesium alloy AZ31 after carrying out the plastometric tests and accomplishment of the static recrystallization under various conditions are shown. The resulting recrystallized grain has a different size, which depends on the conditions of plastic working and annealing. For the time being, we did not succeed in deriving a sufficiently exact mathematical model describing the size of the resulting recrystallized grain.

Lee et al. [7] have recently been concerned with the description of the dynamic and static recrystallization of the magnesium alloy AZ31 as well. The high temperature compressions and load relaxation tests were conducted at various temperatures (523 – 773 K) and strain rates ($10^{-4}$ – $10^2$ s$^{-1}$). The artificial neural networks method was used to derive the accurate amounts of thermal softening by deformation heating. As it results from the graph in Fig. 5, for the ranges of the previous deformation and the annealing temperatures which we selected the authors of work [7] determined the time values $t_{0.5} = 1.3 – 2.2$ s. This represents a good accordance with the experimental data stated in Tab. 1, with regard to the applied strain rates that were by an order of magnitude lower.

Fig. 4 Microstructure of magnesium alloy AZ31 after static recrystallization under selected thermodynamic conditions

Lee et al. [7] have recently been concerned with the description of the dynamic and static recrystallization of the magnesium alloy AZ31 as well. The high temperature compressions and load relaxation tests were conducted at various temperatures (523 – 773 K) and strain rates ($10^{-4}$ – $10^2$ s$^{-1}$). The artificial neural networks method was used to derive the accurate amounts of thermal softening by deformation heating. As it results from the graph in Fig. 5, for the ranges of the previous deformation and the annealing temperatures which we selected the authors of work [7] determined the time values $t_{0.5} = 1.3 – 2.2$ s. This represents a good accordance with the experimental data stated in Tab. 1, with regard to the applied strain rates that were by an order of magnitude lower.

![Fig. 5 Time $t_{0.5}$ as function of pre-strain and temperature [7]](image-url)
5. SUMMARY

By means of the relaxation method a large quantity of experiments was performed, which led to gaining the model of the static recrystallization. The compression tests carried out on the simulator Gleeble 3800 were performed under the wide variety of thermodynamic conditions (temperature 523 – 673 K, strain rate 0.1 – 10 s\(^{-1}\)) and the obtained results, though burdened with relatively great scattering, helped to design the model \(\tau_{0.5} = f(\varepsilon, \gamma, d_0, T)\) of the studied alloy AZ31 with relatively good accuracy. So, after the successfully implemented previous experiments with the dynamic recrystallization and activation energy [8] we managed to replenish our research with the model describing the static recrystallization. In the next step it would be suitable to carry out a more detailed metallographic investigation of the microstructures and a description of size of the resulting recrystallized grain in dependence on the previous conditions of plastic working and annealing.

ACKNOWLEDGEMENTS

This work was conducted in the framework of solution of the projects MSM 6199810015 (financed by the Ministry of Education of the Czech Republic), CZ.1.05/2.1.00/01.0040 "Regional Materials Science and Technology Centre" within the frame of the operation programme "Research and Development for Innovations" financed by the Structural Funds and from the state budget of the Czech Republic, and 2016/T02/2006/31 (MNSW, Poland). Financial support of Structural Funds in the Operational Programme - Innovative Economy (IE OP) financed from the European Regional Development Fund - Project "Modern material technologies in aerospace industry". Nr POIG.01.01.02-00-015/08-00 is gratefully acknowledged.

REFERENCES


