DESCRIPTION OF THE ATYPICAL STRESS-STRAIN CURVES AT FORMING OF AZ31 MAGNESIUM ALLOY

POPIS ATYPICKÝCH NAPĚŤOVÝCH KŘIVEK PŘI DEFORMACI HOŘČÍKOVÉ SLITINY AZ31

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Abstract

The axially symmetric specimens from the alloy of type AZ31 (with chemical composition as follows: 2.82 Al – 0.80 Zn – 0.37 Mn, in wt %) underwent the hot pressure tests on simulator Gleeble 3800. The experiments were implemented at temperatures $T = 250$ to $450 \, ^\circ C$ with the various strain rate $\gamma = 0.01$ to $10 \, s^{-1}$. As resulted from evaluation of the previous experiments, the deformation behaviour and especially the shape of stress curves of the alloy AZ31 are significantly different at low and high values of Zener-Hollomon parameter $Z$. The regression and statistic analysis of the experimental data confirmed unambiguously that the whole set of stress curves cannot be described by a single equation. The shape of the resulting stress-strain curves, which were recalculated from the data measured during the forming, is of a double type. The first type is a conventional one, where the changing flow stress showed the usual phases of strengthening, the subsequent decrease in strength due to the dynamic recrystallization and the steady-state. For this type of stress curves, the mathematical model, enabling the prediction of the flow stress of the investigated magnesium alloy in relation to temperature, strain and strain rate, was developed. This model is valid for values of parameter $Z \leq 2.9E+13 \, s^{-1}$. The second type of the stress curve is atypical by its concave start-up phase in the area of strengthening. It is caused by the intensive twinning, manifesting itself in higher values of parameter $Z$. We were successful in deriving an original mathematical function, describing accurately the shape of such atypical stress-strain curve, which considers also the dynamic softening.

Keywords: magnesium alloy, AZ31, flow stress, stress-strain curves

1. INTRODUCTION

One of the most frequent requirements in the current industrial production is decreasing the environmental load, first of all in the field of transport. The magnesium alloys are used, thanks to their specific properties, in state-of-the-art branches of techniques, such as in the aviation, automotive industry, military forces and biomedical engineering, but also in computers and further commodities, e.g. cell phones, cameras and DVD players, which are already quite common today.

The aim of work was to deepen the collected information on the deformation behaviour of the investigated magnesium alloy AZ31 and derive a suitable mathematical function describing its flow stress (FS) in the case of stress-strain curves with an atypical start-up phase. The topicality and significance of the given issues are documented by the recently published comprehensive work [1].

2. PLASTOMETRICKÝ TESTY

The compression tests of the axially symmetrical specimens, made of the investigated magnesium alloy, were performed on the simulator Gleeble 3800. The alloy marked as AZ31 had the following chemical
composition: 2.82 Al – 0.80 Zn – 0.37 Mn (wt %). The specimens that underwent the compression tests had the form of a cylinder with diameter 10 mm and height 12 mm. At the beginning all specimens were preheated to temperature 450 °C, cooled down to the requested temperature and only then deformed. The tests were implemented at temperatures $T = 250, 300, 350, 400$ and $450 \, ^\circ\text{C}$, with a different strain rate $\gamma = 0.01, 0.1, 1$ and $10 \, \text{s}^{-1}$.

In Fig. 1 an example of the resulting stress-strain curves, obtained from the results of plastometric tests at temperature $300 \, ^\circ\text{C}$, is shown. It is evident that the shape of the given curves is of the double type. The first type is conventional, where the changing FS in the whole deformation path shows the phases of strengthening, decrease in stress due to the dynamic recrystallization and steady-state (see the curves corresponding to $\gamma = 0.1 \, \text{s}^{-1}$ and $\gamma = 0.01 \, \text{s}^{-1}$). The second type of the stress-strain curve is atypical by its concave start-up phase – this group is represented by the curves corresponding to $\gamma = 1 \, \text{s}^{-1}$ and $\gamma = 10 \, \text{s}^{-1}$.

The experimental conditions are collectively defined by the value of Zener-Hollomon parameter $Z \, [\text{s}^{-1}]$, for calculation of which the values of the activation energy, determined before, were used [2]. The similar values of the activation energy, as well as further material constants, were achieved by other authors, which is demonstrated by some formerly published works [3, 4].

![Stress-strain curves](image)

**Fig. 1** Illustration of stress-strain curves at constant $T = 300 \, ^\circ\text{C}$ and various strain rate values

### 3. MODEL OF FLOW STRESS OF DEFORMATION RESISTANCE IN CASE OF CLASSICAL STRESS-STRAIN CURVES

The regression and statistic analysis of the experimental data performed earlier confirmed unambiguously that the whole data file (consequently the conventional and atypical stress-strain curves) cannot be described by a single equation [5]. Therefore, we worked only with the curves of the conventional shape and based on the former experience [6, 7] the well-proven model was used to describe FS of the investigated material in dependence on temperature $T \, [\text{°C}]$, true strain $\varepsilon \, [-]$ and strain rate $\gamma \, [\text{s}^{-1}]$. This model is valid for the values of parameter $Z \leq 2.9\,\text{E}+13 \, \text{s}^{-1}$. The influence of the dynamic recrystallization is represented in this model by a softening exponential term that includes the calculated value of peak strain $\varepsilon_p \, [-]$. 

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\[ \sigma = A \cdot \varepsilon^B \cdot \exp\left(-B \cdot \frac{\varepsilon}{\varepsilon_p}\right) \cdot \gamma^C \cdot \exp(-D \cdot T) \]  

(1)

where \( \sigma \) [MPa] is predicted (calculated according to the developed model) FS; \( A = 743, B = 0.33, C = 0.0095 \) and \( D = 0.0045 \) are the material constant, determined by methods of the multiple non-linear regression, with utilization of the static program Unistat 5.5. The equation (1) describes the experimental data in the wide range of deformation conditions, but not in the area of steady-state.

4. DESCRIPTION OF ATYPICAL STRESS-STRAIN CURVES

The atypical course of stress-strain curves with the concave start-up phase was caused in the case of high values of parameter Z by the massive twinning [2]. The mathematical description of the character of stress-stress curves was not a simple matter. It was obvious that it should be a complex mathematical function, but the physical essence of the given dependence had to be maintained.

First proposals were focused on the sum function, which would respect a different course of the dependence up to the point of inflexion on the start-up part of the curve and after exceeding this point. The function was designed, the first term of which (up to reaching the point of inflexion) corresponded to the exponential dependence and the second term (after reaching the point of inflexion) corresponded to the function for description of this dependence without the concave start-up phase. The designed sum function described very well the experimental data, which is demonstrated by the high correlation index, reaching the value 0.999. However, a disadvantage from the viewpoint of the practical use of this function was the fact that first of all the position of the point of inflexion had to be defined and that a turning point on the curve in the vicinity of the point of inflexion was noticeable in the case of small changes of stress values.

To remove these shortcomings, further types of combined functions were designed and tested in the next stage of work. For description of the atypical course of the stress-strain curves, the function (2) showed to be the most suitable. This function is able to describe the atypical course of the stress-strain curves both in the start-up phase up to reaching the point of inflexion, and in the successive phase:

\[ \sigma = F + \frac{G}{1 + \exp(1 + H \cdot \exp(-J \cdot \varepsilon))} \cdot \exp(-K \cdot \varepsilon) \]  

(2)

where \( F, G, H, J, K \) are the material constants, or parameters of the function.

For evaluation of parameters of the function the non-linear regression analysis was used, with the utilization of the statistic programs Statgraphics Plus v. 5.0 and Unistat. A special attention was dedicated to the initial estimates of the parameters of the function. The achieved results are discussed on examples of two stress-strain curves, obtained at various temperatures and strain rates.

The values of parameters \( F \) to \( K \), listed in Table 1, were determined by processing of the experimental data gained at temperature 200 °C and strain rate 0.01 s\(^{-1}\), or at temperature 350 °C and strain rate 10 s\(^{-1}\).

The progression of the determined regression functions, in comparison with measured data, is demonstrated in Fig. 2. It is evident that the determined functions describe very well the experimental data. This is confirmed also by values of the correlation index, which are in both cases higher than 0.998.

Testing the statistic significance of the determined parameters of the regression function was carried out. It was found that all determined parameters are on the significance level \( \alpha = 0.05 \) statistical significant and
therefore they should be left in the function. Further it was verified that the stress-related residues values of FS show in both monitored examples homoscedasticity (see Fig. 3). Therefore, the designed regression model can be used without any modifications for the description of the experimentally determined data.

Table 1: Parameters of the function, determined for different experimental conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$T = 200 , ^\circ\text{C}, , \gamma = 0.01 , \text{s}^{-1}$</th>
<th>$T = 350 , ^\circ\text{C}, , \gamma = 10 , \text{s}^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F$</td>
<td>52.93</td>
<td>54.71</td>
</tr>
<tr>
<td>$G$</td>
<td>737.8</td>
<td>642.2</td>
</tr>
<tr>
<td>$H$</td>
<td>3.735</td>
<td>4.484</td>
</tr>
<tr>
<td>$J$</td>
<td>12.34</td>
<td>11.89</td>
</tr>
<tr>
<td>$K$</td>
<td>1.280</td>
<td>2.310</td>
</tr>
</tbody>
</table>

Fig. 2 Comparison of the experimentally found and recalculated (calc.) FS values based on the model, with selected values of strain rate and temperature

![Graph showing stress-strain curves](image)

Fig. 3 Relative deviations of flow stress of deformation resistance, recalculated according to equation (2) from values experimentally determined in dependence on strain

a) at $T = 200 \, ^\circ\text{C}, \, \gamma = 0.01$

b) at $T = 350 \, ^\circ\text{C}, \, \gamma = 10 \, \text{s}^{-1}$

5. CONCLUSIONS

The deformation behaviour and especially the shape of the stress-strain curves of the investigated alloy AZ31 are significantly different with various values of Zener-Hollomon parameter $Z$. The atypical shape of the curve with the concave start-up phase in the region of strengthening, caused by the intensive twinning at $Z > 2.9E+13 \, \text{s}^{-1}$, resisted the satisfactory mathematical description for the time being. We succeeded in
deriving the original mathematical function, which accurately describes the shape of such curve, considering the dynamic softening. The values of the pertinent parameters for two selected atypical stress-strain curves were calculated. The significance of the particular parameters of the regression function, as well as homoscedasticity, were evaluated by the statistic processing and by means of the relative deviations of measured and recalculated FS values. In such a way the foundation was laid for deriving a complex mathematical model, describing FS of the alloy AZ31 in the wide range of temperatures and strain rates.

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LITERATURA


