Influence of initial state on forgeability and microstructure development of magnesium alloys

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Abstract

The paper is focused on magnesium alloys with different initial states – cast or extruded – for forging operations at the example of a wheel hub. The different initial microstructures have an influence on the deformation behaviour and therefore on the final mechanical properties of the components. The forming process of this component was designed with a numerical simulation tool (temperature of the billet, temperature of the die, velocity of the press ram), which need the sensitive material specific parameters for the description of the temperature depending deformation and recrystallization behaviour. All this parameters are necessary for a correct simulation of the whole process. The required parameters (flow stress, dynamic recrystallization kinetic) were determined in a deformation simulator. The models were developed considering preferentially the chemical composition of the AZ system. The content of aluminium is combined with the activation energy for the hot deformation process in the Zener-Hollomon parameter. After the experimental and numerical simulation the wheel hubs were forged on a 10 MN universal oil-hydraulic press at the Institute of Metal Forming for the validation of the laboratory results.

Keywords: Magnesium alloys; Forging; Microstructure evolution; Experimental simulation

1. Introduction

Over the last decades light-metal design has received a high priority in the modern automotive industry. Thereby the focus is on the use of lightweight materials and the substitution of component materials. The application of die-forged structural parts made of aluminum offer a significant reduction of the construction weight. However, the use of magnesium would result in greater weight savings. Although magnesium is the metallic

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construction material with the lowest density and hence exhibits a high application potential, the current state of
research is still in the initial state.

For dimensioning of technological process steps up to complete process chains computer engineering including
appropriate software tools is preferably used. Accurate simulation requires adequate models to regarding the real
conditions. Precise results can only be achieved if thermo-physical properties as well as material- and forming-
specific parameters are available. Implementing of the whole material data in the FEM-software of entire process
chains demand the consideration of the process description on the one hand as well as inhomogeneous material
properties within a process step and changing material conditions along the process chain on the other hand.

Resulting from these requirements, the determination of material-specific values needs to be adjusted to special
deformation processes as well as correlations and interactions of forming material and kinetic of the plant must be
modeled in several process steps. Realizing a high-precision process modeling (> 95 % accuracy), experimental
data, for example strain, strain rate, temperature or friction, determined under realistic conditions, have to be
observed and supplied for numerical simulation.

2. Experimental details

2.1. Testing material

Appropriating the influence of several initial conditions in dependence of the chemical composition, cast and
extruded rods of the magnesium alloys AZ31, AZ61 and AZ80 are investigated. Their chemical compositions are
summarized in Table 1.

<table>
<thead>
<tr>
<th>Material</th>
<th>Al</th>
<th>Zn</th>
<th>Mn</th>
<th>Fe</th>
<th>Cu</th>
<th>Si</th>
<th>Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td>AZ31 cast</td>
<td>2.83</td>
<td>1.22</td>
<td>0.33</td>
<td>0.0026</td>
<td>0.001</td>
<td>0.11</td>
<td>0.00041</td>
</tr>
<tr>
<td>AZ31 extruded</td>
<td>2.8</td>
<td>0.88</td>
<td>0.39</td>
<td>0.003</td>
<td>-</td>
<td>0.02</td>
<td>0.0005</td>
</tr>
<tr>
<td>AZ61 cast</td>
<td>6.4</td>
<td>0.89</td>
<td>0.25</td>
<td>0.0046</td>
<td>0.0011</td>
<td>0.12</td>
<td>0.00065</td>
</tr>
<tr>
<td>AZ61 extruded</td>
<td>5.96</td>
<td>0.74</td>
<td>0.22</td>
<td>0.0024</td>
<td>0.0018</td>
<td>0.029</td>
<td>0.0009</td>
</tr>
<tr>
<td>AZ80 cast</td>
<td>8.76</td>
<td>0.65</td>
<td>0.18</td>
<td>0.0024</td>
<td>0.0018</td>
<td>0.015</td>
<td>0.00043</td>
</tr>
<tr>
<td>AZ80 extruded</td>
<td>9.2</td>
<td>0.8</td>
<td>0.5</td>
<td>0.005</td>
<td>0.05</td>
<td>0.10</td>
<td>0.005</td>
</tr>
</tbody>
</table>

The representative microstructures of the AZ31 and AZ80 alloys in the cast and extruded condition are shown
in Table 2.

<table>
<thead>
<tr>
<th>Material</th>
<th>Microstructure</th>
</tr>
</thead>
<tbody>
<tr>
<td>AZ31 cast</td>
<td>Typical cast microstructure with a coarse, network-like eutectic Mg17Al12-phase non-uniformly distributed in the interdendritic zones. With higher aluminium contents (6 and 8 wt%) the amount of second-phases increases in both conditions (cast and extruded). All extruded materials exhibit a relatively rough, deformed microstructure with grains. Most of the grains are equiaxed; however, some grains are elongated in the extrusion direction, which increases material inhomogeneity. In addition, the elongated grains in the AZ61 and AZ80 alloys were less observed than in AZ31 as these were retarded by larger volume fractions of the phase in AZ61 and AZ80.</td>
</tr>
</tbody>
</table>
2.2. Experimental procedure

2.2.1. Experimental simulation at the servo-hydraulic hot deformation simulator

The evaluation of the flow curves was carried out by cylindrical compression tests under process-oriented conditions at the servo-hydraulic hot deformation simulator at the Institute of Metal Forming. Isothermal flow curves result from the recorded force-displacement data considering the correction of the measured values with regard to dissipation energy and friction.

Previous to deformation the samples were heated up to the final forming temperature (250 to 450 °C) in a circulating air furnace with a low heating rate. Subsequently the samples were compressed continuously to an effective strain of $\varphi_v=1$ using several deformation rates (1 bis 10 s$^{-1}$).

2.2.2. Forging tests at the 10 MN oil-hydraulic forming press

Supplementary die-forging operations by producing a real wheel hub as testing component (for e.g. microstructure, yield strength, notched-bar impact value) were carried out to complete the experimental and numerical investigations. On the one hand these investigations enable ascertaining the potential of magnesium alloys for forging under industrial conditions. Otherwise the mechanical properties, relevant for application, of the forged wheel hubs are determined. The samples for forging with initial dimensions of 90 mm in diameter and a height of 59 mm are heated up to forming temperature (250 °C to 450 °C) in a circulating air furnace. After heating the magnesium samples were pressed at the 10 MN oil-hydraulic forming press using a forging die, heated up to 200 °C, and a ram speed of 1 and accordingly 10 mm/s.

3. Experimental simulation to determine coefficients for modeling

The flow curves provide a basis to describe hardening and softening procedure in the material. Furthermore, flow curves enable the determination of energy requirements as well as the estimation of microstructure. The derived data are directly integrated into the numerical simulation.

3.1. Flow curves

The flow curves indicate the well-known dependency of the flow stress on forming temperature and strain rate as well as between materials condition and alloy composition.

Fig. 1 shows the influence of the materials condition (cast or extruded) by the example of AZ31 at 350 °C considering the effect of the strain rate.

The shape of the flow stress curves can be indicative of microstructural changes that material undergoes during deformation (Barnett 2003, Ion 1982). Every flow curve of the extruded material exhibits compared to cast condition a discontinuity at low strains. This is due to the formation of twins. Therefore the flow curve of the extruded condition is classified in three areas, in order to apply semi-empirical models. Table 2 contains a composition of the determined maxima of the flow stress depending on materials conditions and testing parameters.

The overview in Table 3 indicates a higher strength with increasing aluminum content of the magnesium alloy due to the formation of aluminum-containing phases. Commonly the extruded material offers higher flow stress maxima compared to the cast condition. The reason for these phenomena are the refined grains in the extruded material.
3.2. Dynamic recrystallization (model approaches and results)

Dynamic recrystallization is the predominant mechanism for magnesium alloys (Sit 2001). Thus, subsequently the processes of the dynamic recrystallization are focused. In order to model a dynamic microstructure development, semi-empiric approaches are used whereas process conditions will be correlated to the characteristics of the material. The coupled influence of strain rate and thermal activation of hot forming is described with the help of the Zener-Hollomon parameter \( Z = \frac{\varphi \cdot \exp \left(\frac{Q}{R \cdot T}\right)}{A \cdot \sinh \left(\alpha \cdot k_{\text{max}}\right)^{m}} \). In this connection the dependency of the activation energy on the aluminum content has to be considered (Table 4).

A parameter fit is performed to the experimental results of the materials flow behavior. Thereby, the characteristic of the flow curve reveals information on the particular softening mechanism. Describing the kinetics of primary recrystallization the approach under Johnson, Mehl, Avrami and Kolmogorow is used (Kern, 1997). The recrystallization kinetics provides the correlation between material condition and alloy composition. Initiation of grain formation during deformation requires higher energy in cast condition compared to the extruded magnesium. Additionally, increasing aluminum content leads to a decrease of the activation energy, in order to initiate dynamic recrystallization in magnesium materials (Slooff et al., 2010). In general, the AZ-alloys with higher aluminum content, particularly AZ61 and AZ80, offer a significant lower critical strain. The models of dynamic recrystallization provide the basis for the numerical simulation.
4. Numerical simulation of die-forging

For the numerical simulation of the forging process the required technological and system-dependent conditions were generated in the software package Simufact.forming 12.0. Afterwards the material coefficients for describing the hardening and softening processes were implemented. Further the incorporation of thermo-physical specific values of the materials were necessary to map the thermal conditions during deformation. Fig. 2 shows exemplarily the adjusting effective strain and the temperatures during forging of an extruded AZ31 rod to a wheel hub as well as the calculated grain size distribution.

![Effective strain, Temperature in °C, Recrystallized volume fraction in %](image)

Fig. 2. (a) Adjusting effective strain and (b) temperature during forging of the wheel hub as well as (c) recrystallization distribution.

According to the results in Fig. 2 the grain size distribution and the volume fraction of recrystallized grains were calculated considering forging conditions (temperature and ram speed), alloy composition (aluminum content) and the initial state (cast or extruded material). In conformity with the numerical simulation, the extruded condition is the most appropriate for forging tests. The characterization of the microstructure revealed a finer grain structure of the extruded material compared to the cast condition. Moreover, the cast material offers regardless of the alloy composition casting defects, such as micro-porosity or micro-segregation. The following assessment is therefore focused on the extruded condition.

5. Forging test for validation of numerical simulation

In accordance with the numerical simulation the microstructure evolution (e.g. grain size) significantly depend on temperature and ram speed. Fig. 3 shows this dependency exemplarily for the extruded magnesium alloy AZ31, considering several positions of the wheel hub. Due to the unequal distribution of the strain, different volume fractions of recrystallized grains are observed – complete recrystallization (e.g. A) and partial recrystallization (e.g. G). Areas of partial recrystallization are a result of insufficient strain, so that a recrystallization cannot occur completely.

![Microstructure evolution in the wheel hub](image)

Fig. 3. Microstructure evolution in the wheel hub after deformation (left: starting temperature 350 °C, ram speed 1 mm/s; right: starting temperature 450 °C, ram speed 10 mm/s) of extruded AZ31.

Grain size and volume fraction of recrystallized grains increase with rising temperatures as expected. Higher temperatures adjust the initiation and the completion of the recrystallization to lower strains. In addition grain growth is promoted. Finally, these changes of the microstructure influence the mechanical properties, such as ultimate tensile strength, yield strength and notched bar impact-value.
The investigations have shown that AZ31 is the least suited alloy for die-forging regarding to the tested conditions. High ram speeds, comparable to industrial conditions, can only be realized at high temperatures due to the recrystallization processes of this alloy require increased temperatures and strain. However, these conditions result in a coarse structure. Thus, the property potential of AZ31 cannot be achieved completely by forging.

Die-forging enables the production of almost flawless parts of AZ61 – even at high ram speeds. By further optimization of testing parameters, particularly the die temperatures, the production of wheel hubs without cracks is expected. Most important of all is the high utilization of the materials potential, because of a satisfactory microstructure at high ram speeds. The experiences in the field of microstructure evolution of the AZ61 alloy enable the adaptation of the process parameters in order to induce a fine grain by the formation of precipitations even at high temperatures. This requires a specific heat treatment previous to deformation, which leads to a microstructure with minor volume fraction of Mg17Al12-phase, undissolved when forming temperature is reached. The Mg17Al12-phase acts as nucleation site and effect a grain refinement. Hence, the structure of AZ61 exhibits homogeneously distributed precipitations, which impede undesirable grain growth, in combination with a fine grained structure.

With increasing aluminum content (AZ80) the ability for forging is improved. Even at low die temperatures of about 350 °C, which lead to the formation of cracks for AZ31 and AZ61, the production of wheel hubs was possible (Table 5).

6. Conclusion

Basic idea of this work was the investigation of the forming behavior during die-forging depending on the initial condition of semi-finished products (Graf et al. 2013). Initial conditions of semi-finished products are formed, more precisely rolled, drawn or extruded, and cast. These various materials offer differences in microstructure influencing forming parameters (e.g. required forming force), development of finished part properties as well as the forming behavior of the material. The evaluated flow curves of the AZ-alloys in the cast and extruded initial state provide the basis for the description of the forming behavior in dependency of process parameters and materials condition. This enables conclusions regarding recrystallization behavior as well as the estimation of the grain size. The results show a good correlation between the calculated and the experimentally determined grain size.

The investigations show, that the tested magnesium alloys of the AZ system are considered suitable for the forging under specified process parameters. Concerning forgeability magnesium alloys with higher aluminum contents enable the production of high quality finished products even in the lower range of the process parameters. Homogeneously distributed precipitations and a small grain size have a beneficial effect on the mechanical properties. Furthermore, the extruded initial state offers under equal conditions an improved property profile compared to cast condition.

References