Influence of solidification rate on microstructure of gravity cast AZ91 magnesium alloy

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Abstract

Derivative thermal (ATD) and microstructure analyses of gravity cast AZ91 magnesium alloy are presented. The alloy was cast into cold steel and sand moulds with the same dimensions. ATD curves – solidification curves and their first derivative – are presented. The investigated alloy exhibited a strong alloying elements segregation and the presence of α solid solution and α+γ (Mg17Al12) eutectic mixture. Discontinuous precipitates of γ phase were also observed in the microstructure of AZ91 cast into sand mould.

Keywords: AZ91 magnesium alloy, gravity casting, ATD, microstructure

1. Introduction

Magnesium alloys are light metallic structural materials, which are very attractive in such applications as automobile, aerospace and electric industries. Most commercial magnesium alloys are based on Mg-Al system comprising the AZ and AM alloy series [1-9]. The most popular among these alloys is AZ91. The ternary magnesium alloy contains about 9 wt.% Al and 1 wt.% Zn, with addition of about 0.4 wt.% Mn to improve corrosion resistance. The maximum solid solubility of aluminium in magnesium (α phase with hexagonal structure) is reasonably high at 12.9 wt.% Al at the eutectic temperature of 437°C K (Fig. 1). The equilibrium concentration at 200°C K is about 2.9 wt.% Al so that a large amount of aluminium is available for precipitates [10-16]. The γ phase has a stoichiometric composition of Mg17Al12 (at 41.4 wt.% Al) and an α-Mn–type cubic unit cell.

Fig. 1. A fragment of Mg-Al binary phase diagram; intermittent line represents non-equilibrium solidification calculated by using Thermo-Calc [21]

In comparison with other binary Mg-Al alloys, in commercial ternary alloys of AZ91 type, zinc substitutes aluminium in the
precipitate \( \gamma \)-phase creating ternary intermetallic compound (\( \text{Mg}_{17}\text{Al}_{11.5}\text{Zn}_{0.5} \) or \( \text{Mg}_{17}(\text{Al,Zn})_{12} \) type) [15-20]. In this paper, the influence of solidification rate on structure of gravity cast AZ91 alloy is presented.

2. Experimental procedures

The commercial as-cast AZ91 magnesium alloy with a nominal chemical composition given in Table 1 was used in this study. Investigated material was cast into permanent mould (cold steel mould - rod samples with a 200 mm diameter) and sand mould (rod samples with a 200 mm diameter). Derivative thermal analysis (ATD) was carried out by using a Crystaldigraph PC computer recorder. DTA curves were collected from thermocouple NiCr-NiAl with a 1.5 mm diameter, located directly into moulds. Measurements were archived with a sampling time of 0.2 s for steel mould and 1 s for sand mould.

Table 1. Chemical composition of AZ91 alloy according to ASTM B93-94

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Al</th>
<th>Zn</th>
<th>Mn</th>
<th>Si</th>
<th>Fe</th>
<th>Cu</th>
<th>Ni</th>
<th>Others</th>
<th>max</th>
<th>max</th>
<th>max</th>
<th>max</th>
<th>max</th>
<th>max</th>
</tr>
</thead>
<tbody>
<tr>
<td>AZ91</td>
<td>8.5-</td>
<td>0.45-</td>
<td>0.17-</td>
<td>0.05</td>
<td>0.005</td>
<td>0.03</td>
<td>0.002</td>
<td>0.02</td>
<td>9.5</td>
<td>0.9</td>
<td>0.4</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Mg rest

Microstructure analyses were performed by means of light microscopy and scanning electron microscopy (SEM). For sample preparation a standard metallographic technique was used, namely samples were wet prepolished and polished with different diamond pastes without contact with water. To reveal microstructure, samples were etched in a 1% solution of \( \text{HNO}_3 \) in \( \text{CH}_3\text{OH} \) for about 60 seconds. Specimens were examined using a NEOPHOT-21 (Carl-Zeiss Jena) and a scanning electron microscope JSM-5400 (Joel, Japan) equipped with an energy-dispersive X-ray spectrometer (EDX).

3. Results

Figs. 2 and 3 show ATD curves obtained for AZ91 magnesium alloy solidified in steel and sand moulds, respectively. In a steel mould the investigated alloy solidified only about 15 seconds whereas in sand mould (at the same dimension) about 680 seconds.

According to the equilibrium phases diagram, in AZ91 alloy after solidification process only one \( \alpha \)-phase should occur. Non-equilibrium solidification condition cause the formation of large crystal of the primary \( \alpha \)-phase, depleted in alloying elements, and pushing the Al admixture away into interdendritical spaces. At the last stage of solidification the \( \alpha + \gamma \) semi divorced eutectic is formed. The equilibrium eutectic temperature is 437°C. Differences in characteristic temperatures obtained during solidification of AZ91 alloy in cold steel and sand moulds are given in Figs. 2 and 3.

Fig. 2. ATD result: solidification curve \( T(t) \) and their first derivative \( dT/dt \) obtained for AZ91 alloy solidified in a steel mould

Fig. 3. ATD result: solidification curve \( T(t) \) and their first derivative \( dT/dt \) obtained for AZ91 alloy solidified in a sand mould

1 - temperature of solidification start - 596°C
2 - temperature of maximum over-cooling of primary phase - 526°C
3 - average temperature of eutectic solidification - 418°C
4 - solidus temperature - 405°C
The segregation of alloying elements is typical for the majority of magnesium alloys. In this case a non-uniform distribution of aluminium in dendrite arms was observed.

Figs. 4 and 5 show microstructure of AZ91 magnesium alloy solidified in steel and sand moulds, respectively. The dendritical microstructure is characterised by the presence of $\alpha$ solid solution and the binary $\alpha+\gamma$ eutectic. Central areas of dendrites were strongly depleted in aluminium whereas near eutectic regions aluminium concentration was higher (Fig. 6). Such aluminium distribution is very often observed in gravity cast AZ91 alloy. Differences in alloying elements distribution in microstructure were presented in Fig. 7 as the results of SEM+EDX analysis.

The presence of a small amount of manganese in the investigated AZ91 alloy caused also formation of $\text{Al}_8\text{Mn}_5$ intermetallic compound (Fig. 6).

In the case of the alloy solidified in a sand mould, dark areas observed in Fig. 5 constitute regions of $\gamma$-phase discontinuous precipitates. Discontinuous precipitates ($\gamma_D$) formed from supersaturated solid solution (like areas marked as 2 in Fig. 7) due to slow cooling down of casts below the solvus temperature. Discontinuous precipitates are typical for AZ91 magnesium alloy gravity casts into sand moulds, where cooling of cast is slow. Unfortunately, ATD analysis is not sensitive for this phase change. The discontinuous precipitation is the cellular growth of...
alternating layers of a secondary phase and a near-equilibrium matrix phase at the high angle boundaries. This heterogeneous reaction leads to the formation of a lamellar structure behind a moving grain boundary. Characteristic lamellar structure of plate-like γ-phase is shown in Fig. 8.

![Microstructure of AZ91 magnesium alloy, a sand mould; light microscopy (γD – discontinuous precipitates)](image)

Fig. 8. Microstructure of AZ91 magnesium alloy, a sand mould; light microscopy (γD – discontinuous precipitates)

4. Summary

After non-equilibrium solidification of AZ91 magnesium alloy, it exhibited the diphase structure characterized by the presence of α solid solution (with strong segregation of alloying elements) and α+γ semi-divorced eutectic. Additionally, a small amount of Al₉Mn₃ intermetallic compound can also observed.

During cooling of AZ91 alloy cast into sand mould, discontinuous precipitates of γ phase were formed from supersaturated solid solution below a solvus temperature.

References