Keys to improving the strength and ductility of the AZ64 magnesium alloy

Y.Q. Ma, R.S. Chen, En-Hou Han

Abstract

The effects of 0.5 wt.% Sb addition and carbon inoculation with magnesite on microstructures and tensile properties of AZ64 (Mg–6Al–4Zn) magnesium alloy have been studied, and excellent tensile properties (Yield Tensile Strength ≈ 158 MPa, Ultimate Tensile Strength ≈ 308 MPa, and Elongation ≈ 7.0%) have been observed in this AZ64–0.5%Sb–C magnesium alloy. These excellent tensile properties are proposed to be attributed to significant refinement in grain size and secondary phases achieved by carbon inoculation together with small quantity of antimony addition.

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1. Introduction

Although AZ91 magnesium alloy has good mechanical properties, a lot of attempts about the effects of antimony (Sb) [1,2] on the possibility of further promotion in its ductility and/or strength have been made. It has been concluded from these attempts that antimony addition can refine both grain size and Mg17Al12 phase of AZ91 alloy, which results in significant increase in room temperature tensile strength, especially when antimony content is around 0.3–0.6 wt.%. In addition to the beneficial effects of antimony in grain refinement of Mg–Al based magnesium alloys, carbon inoculation using carbon-contained agents, such as C2Cl6, was also proposed to be a good way to refine grain size in this alloy as recently reviewed in Ref. [3]. Magnesite, as a carbon inoculation agent, decomposes into MgO and CO2 when being introduced to magnesium alloy melt, the whole process has no pollution, and thus is both cost effective and eco-friendly [4].

Recently, some researchers began turning their interests to medium aluminum and medium zinc content Mg–Al–Zn casting magnesium alloys, where aluminum and zinc contents vary from 4 wt.% to 8 wt.%. But most of these works are focused on microstructure analysis of these alloys [5–7] except for the work of Z. Zhang et al. [8], who reported unexpected tensile properties of ZA8x (x = 2, 4, 6) alloys in as-cast condition and found that the elongation was less than 3% while UTS was less than 150 MPa. However, tensile properties of these alloys should have been much higher than those obtained by Zhang, if we consider that these alloys contain so much high Zn or Al content, especially, if they were alloyed with minor element addition and/or carbon inoculation. Therefore, our present work chooses AZ64 magnesium alloy as an example to clarify how strong and ductile, in nature, the medium aluminum and medium zinc content Mg–Al–Zn alloys are. Meanwhile, the purposes of this work are dual as follows: first, to study the effects of antimony addition and carbon inoculation with magnesite particles on its microstructure and tensile properties; secondly, to develop a new alloy with excellent tensile properties superior or equal to that of AZ91 alloy.

2. Experimental procedure

Three alloys were prepared in a mild steel crucible using commercial high purity raw materials. Smelting process was carried out in an electrical resistance furnace with 15 kg capacity. The magnesite particles, with a size of about 0.5 mm and wrapped up with aluminum foil, were introduced in a bell...
jar to the melt after the refining procedure. The content of MgCO₃ in magnesite particles was more than 98 wt.% and the addition of magnesite particles to the melt accounts for 1.5 wt.% of the total weight of raw materials. Alloying elements contents were analyzed by using ICP-AES method and carbon content was analyzed by using CS-444LS apparatus. Chemical analyses results are given in Table 1.

Most microstructural observation specimens were etched with 2 vol.% nitride acid ethanol solution and/or 2 vol.% tartaric acid ethanol solution after mechanical polishing. Electrochemical polished microstructure specimens were prepared with 5 vol.-% perchloric acid ethanol solution at −20 to −30 °C environment after mechanical polishing. Observations of microstructure were conducted on a Philips XL30 ESEM-FEG/EDAX scanning electron microscope (SEM). X-ray Diffraction (XRD) experiments were carried out on a Rigaku D/max 2400 X-ray diffractometer with monochromated CuKα radiation.

Tensile samples were prepared with a gauge dimension of 36×10×3 mm. Tensile tests were conducted on a Z050 testing machine at the analyzing and testing department of the Institute of Metal Research, Chinese Academy of Sciences. The head displacement rate was 2 mm/min.

The T6 treatment process was as follows: the samples first went through a solid solution treated at 300 °C×2 h+345 °C×12 h+370 °C×4 h, and then an artificial aging at 180 °C holding for 16 h was given to the solid solution treated samples.

### Table 1

<table>
<thead>
<tr>
<th>Alloys</th>
<th>Al</th>
<th>Zn</th>
<th>Mn</th>
<th>Sb</th>
<th>C</th>
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<tbody>
<tr>
<td>AZ64</td>
<td>5.87</td>
<td>3.75</td>
<td>0.52</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>AZ64–0.5%Sb</td>
<td>5.89</td>
<td>3.65</td>
<td>0.50</td>
<td>0.50</td>
<td>–</td>
</tr>
<tr>
<td>AZ64–0.5%Sb–C</td>
<td>5.66</td>
<td>3.57</td>
<td>0.35</td>
<td>0.52</td>
<td>0.015</td>
</tr>
</tbody>
</table>

Fig. 2. The XRD of AZ64 alloy with and without 0.5 wt.% Sb addition.

3. Results and discussion

The as-cast microstructures of AZ64 with and without antimony addition are shown in Fig. 1. It can be seen from Fig. 1.a and b that 0.5 wt.% antimony can refine the secondary phases of AZ64 alloy. The secondary phases in as-cast AZ64 are distributed almost in bulk form along grain boundaries. On the other hand, the secondary phases in as-cast AZ64–0.5%Sb, which were also mainly distributed along grain boundaries with a few exceptions in the grain interior, were finer than those in AZ64.

Fig. 2 gives the X-ray diffraction pattern of the as-cast AZ64 and AZ64–0.5%Sb alloys, which characterized the main secondary phases as γ-Mg₁₂(Al, Zn)₁₇ phase and Φ-Mg₂₁(Zn, Al)₁₇ phase. The γ-Mg₁₂(Al, Zn)₁₇ phase contains less Zn contents than Φ-Mg₂₁(Zn, Al)₁₇ phase according to our EDX analyses. As a result, the dark secondary phases in Fig. 1.a and b are identified as γ-Mg₁₂(Al, Zn)₁₇ phase, and the bright ones are mainly Φ-Mg₂₁(Zn, Al)₁₇ phase, based on principles of back-scattering spectrometry (BSE). As shown in Figs. 1.b and 2, it is also observed that antimony addition to this alloy results in a formation of the Mg₃Sb₂ phase, which is in accordance with the results reported by other researchers [1,2].

Significant refinement was obtained by antimony addition together with magnesite particles as carbon inoculation agent. Fig. 3.a gives an image of the as-cast microstructure of AZ64–0.5%Sb–C, where suffix –C indicates carbon inoculation. To characterize grain boundary, the specimen was electrochemically polished. It can be seen that the carbon inoculation combined with Sb addition has resulted in a much more homogeneous and finer grain size with an average grain size less than 50 μm.

The grain refinement mechanism of magnesite particles should be attributed to the Al₂CO nucleus which formed by a reaction between aluminum and CO₂ released by decomposition of magnesite as
suggested by many researchers [3,4,9]; and as shown in Fig. 3.b, the observation of the Al–C–O nucleus in our present study seems to support this proposed mechanism. Moreover, antimony also gave its contribution to the grain refinement. Because the solid solubility of antimony in magnesium was very low [2], most of the antimony addition would generate constitutional undercooling in a diffusion layer ahead of the advancing solid/liquid interface during solidification. The aggregation of antimony to grain boundaries was also reported by G. Y. Zhang et al. [10]. According to GRF (grain growth restriction) theory [3], the aggregated antimony would restrict primary grain growth since the diffusion of antimony occurs slowly, thus limiting the rate of crystal growth. So, the grain refinement in AZ64–

0.5%Sb–C should be a synergic effect of the foreign nucleus mechanism of Al–C particles and the GRF mechanism of the antimony element.

T6 treatment was given to AZ64–0.5%Sb–C so that maximum strength could be obtained. Fig. 3.c shows the microstructure of AZ64–0.5%Sb–C in T6 condition. It can be seen that T6 treatment turned almost all of the coarse secondary phases in the as-cast condition into much finer ones. A few bright secondary phases in Fig. 3.c can still be observed even after T6 treatment, which are characterized by EDX analyses as Mg3Sb2 phases and/or Al–Mn phases.

The tensile stress–strain curves are shown in Fig. 4, and it can be seen that the strength and ductility of AZ64 have been improved by 0.5 wt.% antimony addition, and these tensile properties would be improved even further by carbon inoculation with magnesite. After T6 treatment, the tensile properties of AZ64–0.5%Sb–C alloy can reach its maximum, i.e. YTS ≈ 158 MPa, UTS ≈ 308 MPa, and Elongation ≈ 7.0%. Whereas the tensile properties of the most widely used magnesium alloy AZ91 in T6 condition are as follows: YTS ≈ 145 MPa, UTS ≈ 275 MPa, and Elongation ≈ 6.0% [11], suggesting that the strength and ductile obtained in AZ64–0.5%Sb–C are even better than those of AZ91, this means that an option between this new alloy and AZ91 alloy could be made for application in the cases that require high strength and high ductility. Based on the present work, the excellent tensile properties of the AZ64–0.5%Sb–C are proposed to be strongly determined by solid solution strengthening together with dispersion strengthening by finer secondary phases; a further, and possibly the largest contribution comes from the decreasing grain size due to Hall–Petch effect. Much more work should be done to clarify the ambiguous mechanisms responsible for the excellent tensile properties of AZ64–0.5%Sb–C.

4. Conclusions

Small quantity of antimony addition to the AZ64 alloy can significantly refine secondary phases. Carbon inoculation with magnesite on AZ64 with an addition of 0.5 wt.% Sb can significantly refine its grain size. A homogeneous and dispersive microstructure has been obtained after T6 treatment, and excellent tensile properties have been observed in AZ64–0.5%Sb–C alloy after T6 treatment.
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References