Effects of scandium addition on microstructure and mechanical properties of ZK60 alloy

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Abstract: The effects of Sc addition on the microstructure and mechanical properties of the ZK60 wrought magnesium alloy were investigated by using optical microscope, scanning electron microscopy, X-ray diffraction and tensile testing. The experimental results show that a minor Sc addition to ZK60 alloy has an obvious effect on the refinement of the microstructure of the ZK60 alloy. During hot extrusion, incomplete dynamic recrystallization occurs in all the alloys, and the recrystallized grains become much finer with increasing Sc addition. The tensile strengths of ZK60 evidently increase with the addition of Sc, but the elongations decrease. The ZK60 alloy with 0.6% (mass fraction) Sc addition is found to have the tensile strength of about 350 MPa and the yield strength of about 280 MPa. After T6 heat treatment, the tensile strength of the alloy containing 0.6% Sc remains almost unchanged. However, the yield strength of the alloy increases up to 352 MPa, and the ratio of the tensile strength to the yield strength is close to 1.

Key words: wrought magnesium alloy; scandium; microstructure; mechanical properties

1 Introduction

Magnesium and its alloys have attracted an increasing interest in the past decade, and have been applied in motorcycles, automobiles, electric devices and so on[1–3]. However, more extensive application is limited because their mechanical properties and performance do not meet the needs of some important products yet, such as the important parts in transportation industry, aviation and aerospace industry[4]. Mg-6%Zn-0.5%Zr (ZK60) alloy is a kind of typical wrought magnesium alloys, which has a good combination of high strength, good formability and high corrosion resistance[5–6], but its yield strength is normally less than 300 MPa and the performance at elevated temperature is also unsatisfactory. It is very necessary to further improve the strength of ZK60 alloy to expand the application of ZK60 magnesium alloys.

It is found that rare earth (RE) metals are effective to improve the comprehensive properties of some magnesium alloys[7–8]. For example, PAN et al[9] found that the addition of Y refined the grain size in the as-extruded AZ31 alloy and the yield strength of as-extruded AZ31 alloys increased with the addition of Y. ZHOU et al[10] reported that the tensile properties of ZK60 alloy increased with addition of Nd and Y by grain refining during dynamic recrystallization. ZHANG et al[11] indicated that Er adding into Mg-Zn-Zr alloys improved the ductility significantly. Sc is a very important rare earth metal. It is known that the addition of Sc to Al-based alloys is an effective way to increase their mechanical properties via the formation of fine Al3Sc compounds, which pin grain and subgrain boundaries to inhibit the recrystallization[12]. It was found that Sc played an important role in the refinement of grains in pure aluminum[13–14], Al-Mg alloys[15], Al-Zn-Mg alloys[16–17], MgSc0.5Mn1 and MgSc0.5Mn1 alloys prepared by the squeeze-casting technique were also reported to show strong annealing response due to the formation of Mn2Sc precipitates, and thus showed excellent creep properties particularly at elevated temperatures and low stresses[18]. For magnesium alloys, YAO et al[19] reported that small Sc addition improved the corrosion of AZ91 alloy. However, little work was carried out on the effects of Sc on the microstructure and mechanical properties of wrought magnesium alloys[20]. In the present work, the effects of Sc addition on microstructure and tensile properties of the ZK60 wrought magnesium alloys were investigated in order to
improve the mechanical properties of the ZK60 alloy.

2 Experimental

The chemical composition of experimental alloys is listed in Table 1. The alloys were prepared in an electric resistance furnace protected by a RJ-5 flux. High pure Mg (>99.95%), Zn (>99.9%), and Mg-3Sc (mass fraction, %), Mg-30Zr master alloys were used to prepare the alloys. The melt was poured into iron molds to produce ingots with a diameter of 85 mm. The ingots were homogenized at 390 ºC for 16 h and extruded into bars with a diameter of 16 mm at 400 ºC. The solid solution treatment was performed at 450 ºC for 3 h. After that, the samples were water quenched at 25 ºC and aged at 180 ºC for 24 h (T6).

Table 1 Chemical compositions of investigated alloys (mass fraction, %)

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Mg</th>
<th>Zn</th>
<th>Zr</th>
<th>Sc</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZK60</td>
<td>Bulk</td>
<td>5.83</td>
<td>0.52</td>
<td>–</td>
</tr>
<tr>
<td>ZK60-0.2Sc</td>
<td>Bulk</td>
<td>5.56</td>
<td>0.47</td>
<td>0.22</td>
</tr>
<tr>
<td>ZK60-0.4Sc</td>
<td>Bulk</td>
<td>5.67</td>
<td>0.55</td>
<td>0.40</td>
</tr>
<tr>
<td>ZK60-0.6Sc</td>
<td>Bulk</td>
<td>5.56</td>
<td>0.53</td>
<td>0.56</td>
</tr>
</tbody>
</table>

Microstructures of the investigated alloys were observed by using optical microscope (OM) and scanning electron microscopy (SEM). X-ray diffraction (XRD, D/MAX-2500PC) was utilized for phase analysis. The phase diagram for Mg-Zn-Zr system at 25 ºC was calculated by “Thermo-calc” software. The tensile samples of 8 mm gauge diameter and 56 mm gauge length were taken from the center of the extrudate. The tensile testing was carried out on a CMT5105 material test machine parallel to the extrusion direction. The tensile fracture surfaces were observed by using scanning electron microscope (SEM, TESCAN VEGAII LMU). The DSC cures were measured by NETZSCH-STA.

3 Results and discussion

3.1 Microstructures

Fig.1–3 show the microstructures of the as-cast ZK60 alloys with different Sc contents. The as-cast ZK60 alloy is composed of α-matrix and eutectic compounds, in which the eutectic compound has a skeleton-shaped morphology. When Sc is added in the ZK60 alloy, the dentrite microstructure is refined, and the morphology and size of the as-cast compounds are changed. With the increase of Sc addition, the size of eutectic compounds decreases and the skeleton-shaped eutectic compounds gradually change to granular compounds or divorced eutectic compounds. A dark band is observed along the dentrite boundaries in the ZK60 alloy (Fig.2), which is due to the segregation of Zn element. With the addition of Sc, the dark band in the tested alloys disappears.

In the ZK60-Sc alloys, the compound containing Sc is found. When Sc addition is less than 0.6% (mass fraction), the composition of the compound containing Sc is not easily measured due to the small size. In order to measure the composition of the compounds, the

Fig.1 Optical microstructures of as-cast alloys: (a) ZK60; (b) ZK60-0.2Sc; (c) ZK60-0.4Sc; (d) ZK60-0.6Sc
ZK60-1.0Sc alloy was also prepared. Figure 4 shows SEM images and EDS spectra of the as-cast ZK60 and ZK60-1.0Sc alloys. In the ZK60-1.0Sc alloy, the big compound containing Sc is found clearly by optical microscopy. The compound identified by the composition measurement is Sc$_3$Zn$_{17}$, which is in agreement with the XRD analysis results as shown in Fig.5. Fig.5 shows the XRD patterns of the as-cast ZK60...
alloys containing different amount of Sc element. α-Mg, MgZn and Zn<sub>2</sub>Zr are identified in the ZK60 alloy, and MgZn<sub>2</sub> is also found. Because most of the as-cast compounds are found to have a mole ratio of Mg to Zn near to 1, the main compound is MgZn phase, which is in agreement with the calculated phase diagram for Mg-Zn-Zr system in Fig.6.

The DSC curves (Fig.7) show that Sc addition increases the temperature of solidification reaction in the ZK60 alloy. The results show that the reaction occurring at about 330 °C for the formation of non-equilibrium eutectic compounds almost disappears when 0.6%Sc is added to the ZK60 alloy, which is in agreement with the investigation results on the as-cast microstructure (Fig.2) and suggests that Sc can inhibit the low melt eutectic compounds.

Fig.8 shows the microstructures of the ZK60 alloys containing different Sc contents at vertical cross sections of the extruded bars after hot extrusion at 400 °C. The dynamic recrystallization with different degrees happens in the alloys under the experiment condition. The micro-

![Figure 5](image)

**Fig.5** XRD patterns of as-cast alloys: (a) ZK60; (b) ZK60-0.4Sc; (c) ZK60-0.6Sc

![Figure 6](image)

**Fig.6** Calculated phase diagram for Mg-Zn-Zr system at 25 °C

![Figure 7](image)

**Fig.7** DSC curves for ZK60-Sc alloys during cooling: (a) ZK60; (b) ZK60-0.4Sc; (c) ZK60-0.6Sc

structure of the as-extruded ZK60 alloy containing Sc is comprised of stripe grains which represent the unrecrystallized grains and very fine recrystallized grains. With the increase of Sc content, the recrystallized grains become much finer, which suggests that Sc addition suppresses the growth of recrystallized grains. It is known that the valence electron structure of alloys can be changed by the addition of rare earth elements[21]. Hence, the addition of Sc can change the bond-energy between atoms and enhance the stability of the alloys so as to restrict the growth of recrystallized grains in the tested alloys during hot deformation. After hot extrusion, the undissolved compounds in all the tested alloys are broken up, however, the size of undissolved compounds in the ZK60-Sc alloys is found to be less than that in the ZK60 alloy.

After T6 heat treatment, the recrystallized grains grow apparently, as shown in Fig.9. It is shown that the grain size of Sc-containing ZK60 alloys is much smaller than that of ZK60 alloy, and the grain size continues to decrease with the increase of Sc content. The average grain size in the ZK60 alloy after T6 treatment is about 50 μm, while 0.6% Sc is added to the alloy, the average grain size decreases to about 20 μm.

### 3.2 Tensile properties

Fig.10 shows the mechanical properties of the as-extruded and as-T6 alloys at room temperature. The ultimate strength and yield strength of the alloys increase and the elongation remains unchanged with addition of 0.2% Sc to ZK60 alloy. After that, the ultimate strength and yield strength of the experimental alloys continue to increase but the elongation to decrease. After extrusion, the ultimate strength and yield strength of the ZK60 alloy are found to increase by about 20 MPa with the addition of 0.6% Sc. After T6 heat treatment, Sc addition is found to increase the yield strength very apparently, and the
maximum increment of yield strength is up to 55 MPa. It should be noted that the addition of 0.2% Sc does not decrease the elongation of the alloy, while the yield strength is increased by about 35 MPa. After T6 heat treatment, the ultimate strength and yield strength of the ZK60-0.6Sc alloy increase to 360 and 352 MPa, respectively, higher than that of ZK60 alloy by about 25 and 55 MPa, respectively. In the ZK60-0.6Sc alloy after T6 treatment, the ratio of ultimate strength to yield strength is close to 1, which suggests that Sc element can
be used to develop the new types of wrought magnesium alloys with high yield strength.

The improvement of the strength of the ZK60 alloy by the addition of Sc may be attributed to three factors. Firstly, Sc addition results in the grain refinement of the ZK60 alloy. With addition of Sc, the microstructure of the as-cast alloys is refined and the growth of recrystallized grains is suppressed during hot extrusion. After T6 treatment, the grain refinement caused by the addition of Sc is more obvious and the grain size is decreased by about 60% with addition of Sc to the ZK60 alloy. According to the Hall-Patch formula[22] and related work[21, 23], the grain refinement is very helpful to improve the yield strength of wrought magnesium alloys. Another factor is the high solid solubility and low diffusion of Sc in Mg alloys[18, 24–26]. The other one is possibly related to the precipitates containing Sc occurring during aging treatment. The detailed investigations on precipitation behaviors during aging treatment will be reported in another paper. The decrease of elongation in the ZK60-Sc alloys can be attributed to the formation of some coarse compounds containing Sc (Fig.2 and Fig.3).

The fracture types of the magnesium alloys mainly include cleavage fracture, quasi cleavage fracture and intergranular fracture[27–28]. Due to the limited slip systems in magnesium alloys, the appearance of dimples needs to activate multi-slip. Fig.11 shows the fractural

**Fig.10** Tensile properties of ZK60-Sc alloy: (a) As-extruded; (b) As-T6

**Fig.11** Fractural micrographs of as-extruded alloys: (a) ZK60; (b) ZK60-0.2Sc; (c) ZK60-0.4Sc; (d) ZK60-0.6Sc
micrographs of the as-extruded alloys. The fracture surface of the ZK60 alloy is composed of tearing ridges, quasi-cleavage steps and a small amount of dimples. The fracture behavior is between ductile fracture and brittle fracture. In the Sc-containing ZK60 alloys, the cleavage planes and steps are observed clearly, which suggests that the brittle fracture feature is more obvious in the ZK60-Sc alloys. The above results indicate that the ductility decreases with the addition of Sc, which are concordant with the results of tensile testing.

4 Conclusions

1) The dendrite microstructure of the ZK60 alloy is refined by the addition of Sc. The size of eutectic compounds decreases, and the skeleton-shaped eutectic compounds change to granular compounds or divorced eutectic compounds.

2) Sc addition increases the temperature of solidification reaction in the ZK60 alloy. The compounds containing Sc in the as-cast ZK60-Sc alloys are identified as Sc3Zn17, and the compounds of the alloy mainly are determined to be MgZn, Zn3Zr, and Sc3Zn17 phases.

3) The tensile strength and yield strength in the as-extruded ZK60 alloys increase with the increase of Sc content, but the elongation decreases. After T6 treatment, Sc addition results in an obvious improvement on the yield strength of the alloy. 0.2% Sc addition increases the yield strength of the as-T6 treated alloys by about 35 MPa and the elongation remains unchanged. The yield strength of the ZK60-0.6Sc alloy increases up to 352 MPa, which is close to the tensile strength of the alloy.

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References