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Effects of Sc and Mn on microstructures and mechanical properties of Mg-Gd alloy

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Abstract: Two alloys of Mg-12.4Gd and Mg-12.5Gd-0.8Sc-1.4Mn were prepared. Hot extrusion and T5 heat treatment were conducted, and then the mechanical properties of the two alloys were tested at room and high temperatures. The effects of Sc, Mn on the microstructures of Mg-12.4Gd were investigated by optical microscopy, scanning electron microscopy and transmission electron microscopy. The results demonstrate that after hot-extrusion the alloying with Sc, Mn can efficaciously refine the grains of Mg-12.4Gd alloy; and increase the elongation at room and high temperatures after T5 heat treatment. But the strength at high temperature is not obviously improved.

Key words: Mg-Gd-Sc-Mn alloy; hot-extrusion; microstructures; mechanical properties

1 Introduction

The ultimate tensile strength and yield strength of Mg alloy at room and high temperatures can be effectively improved by the addition of rare earths[1−3]. WE54 alloy of the Mg-Y-Nd series is considered an outstanding commercial heat-resistant Mg alloy so far, and the heat-resistant temperature can reach 300 ℃[4−6]. The good heat-resistant Mg alloy used in homeland is ZM6, whose heat-resistant temperature is 250 ℃. In fact, the performance of domestic heat-resistant Mg alloys has a big gap with the foreign ones, so the research of new heat-resistant Mg alloy with high performance is necessary.

The alloys of Mg-Gd series have advantages such as high strength, good heat-resistant[7]. At the same time, the Mg alloys containing Sc and Mn elements have very high property of creep-resistance[8−12]. GROBNER et al[13] did thermodynamic phase diagram and phase amount calculations, and gave a result that the Mg-Gd-Sc-Mn system could obtain high-performance at high temperature.

For Mg alloy, the strength can be more effectively improved by grain refinement, because the *K* factor in Hall-Petch formula is more sensitive to Mg alloy, and usually is several times more than the *K* factor of Al alloy[14]. So deformation strengthening is a good way to improve Mg alloy performance. In order to improve the integrated performance of Mg-Gd alloy, the study on hot processing property is necessary. Therefore, we study the effects of Sc and Mn on microstructures and mechanical properties of Mg-Gd alloy, and get some meaningful experimental results.

2 Experimental

The chemical compositions of studied alloys were Mg-12.4Gd (MgGd) and Mg-12.5Gd-0.78Sc-1.4Mn (MgGdScMn). The addition of Gd and Sc was by Mg-Gd and Mg-Sc master alloys, and Mn was through $MnCl_2$. The melted alloy was cast into metal mould; the size of cylindrical ingots was *d* 50 mm×160 mm. After homogenized for 12 h at 520 ℃, and cut the oxidation layer, the ingots were hot extruded at 400 ℃. The ratio of extrusion was 22 and the rate of extrusion was 1 m/min. The samples were prepared from the rod extruded, and some were heat treated. The tensile tests were carried out at room or high temperatures.

The microstructures and morphology were studied by using NEOPHOT-21optical microscope, JSM-5600LY SEM and TecnaiG^{2}20 TEM. The phase

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composition was characterized by EDS. The tensile test at room temperature was performed on a CSS-44100 testing machine, and the tensile test at high temperature was on INSTRUM testing machine. The strain rate was 1.0 mm/min and the samples took 20 and 25 min to balance the temperature before tensile testing at 250 and 300 ℃, respectively.

3 Results and discussion

3.1 Microstructures of as-cast alloys

The microstructures of the studied alloys are shown in Fig.1. The grains of MgGd alloy are coarse, and there are a lot of coarse second phase particles which contain Mg and Gd (Fig.1(a), (c)). The MgGdScMn alloy consists of α-Mg matrix and some dis-continuous cluster, and the grain boundary can be clearly seen (Fig.1 (b), (d)). The results of EDS demonstrate that there are two kinds of second phase in MgGdScMn alloy: one is the skeleton-like phase containing Mg and Gd, the other is the second phase particle containing Mg, Sc and Mn (Fig.1 (d)).

Fig.2 shows the microstructures of alloys homogenized at 520 ℃ for 12 h. The grain boundaries of MgGd alloy become clear, the average size of grains is about 270 μm and the quantity of coarse second phase particles obviously decreases. The average size of MgGdScMn alloy grains is about 160 μm, and some coarse second phase particles can be seen. There are a large quantity of fine second phase particles in grains (Fig.2(d), (e)). These particles are the phase containing Mg, Sc and Mn by the composition analysis of EDS, and the quantity of particles containing Mg and Gd decreases. There are a lot of particles which precipitate in grains and grain boundary, and these particles are phase containing Mg, Sc and Mn by EDS analysis. From Fig.2 (b) the uneven structure distribution can be found. The uneven composition distribution can also be found by the EDS linear scanning.

3.2 Microstructures of alloys after hot-extrusion

The microstructures of two alloys after hot extrusion at 400 ℃ are shown in Fig.3. The dynamic re-crystallization of two alloys has completely taken place and the grains are fine, but it can be obviously found that the average size of MgGd grains is much bigger than that of MgGdScMn. The average size of MgGd grain is about 24 μm and that of MgGdScMn is about 8 μm.

Fig.4 shows the TEM image of extruded MgGdScMn rod. There are a lot of dislocations enwinding fine second phase particles containing Mg, Sc and Mn.

3.3 Mechanical properties

The tensile tests of the two alloys after hot-extrusion and hot extrusion plus heat treatment were carried out at room and high temperatures. The ultimate tensile strength and elongation at room temperature are increased by adding Sc and Mn in MgGd alloy, the

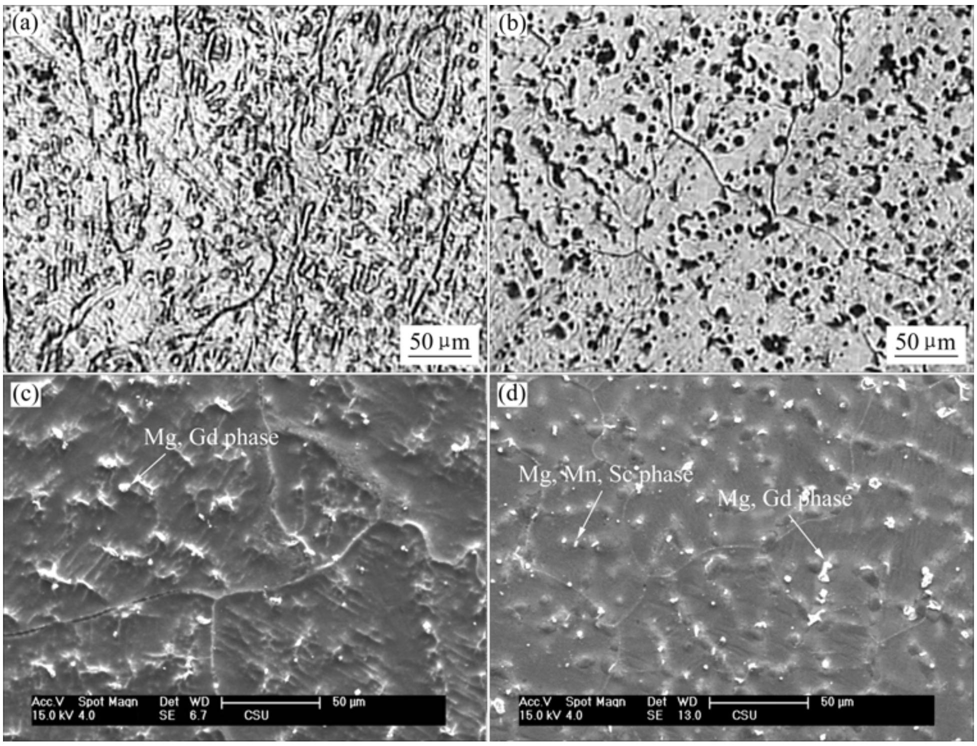

Fig.1 OM and SEM images of as-cast Mg-12.4Gd (a), (c) and Mg-12.5Gd-0.78Sc-1.4Mn (b), (d) alloys

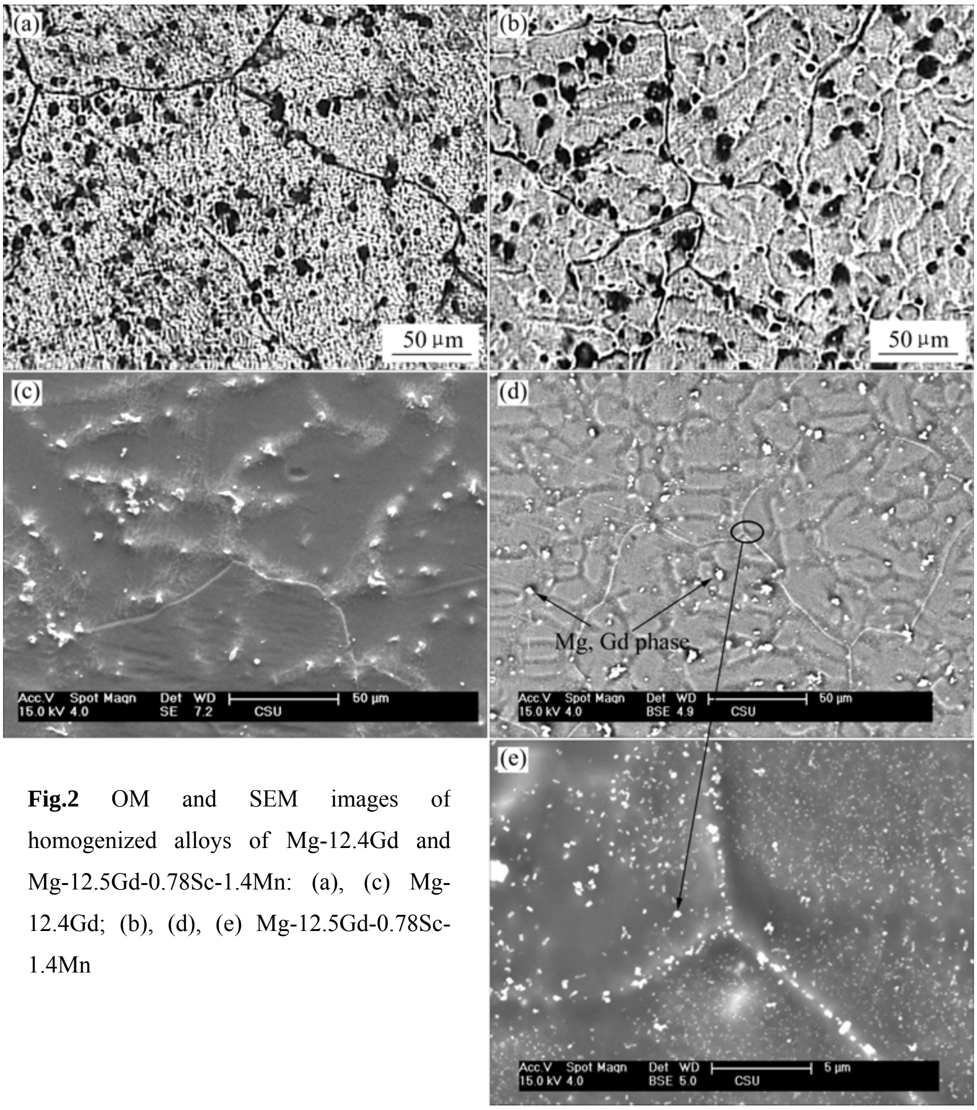

Fig.2 OM and SEM images of homogenized alloys of Mg-12.4Gd and Mg-12.5Gd-0.78Sc-1.4Mn: (a), (c) Mg-12.4Gd; (b), (d), (e) Mg-12.5Gd-0.78Sc-1.4Mn

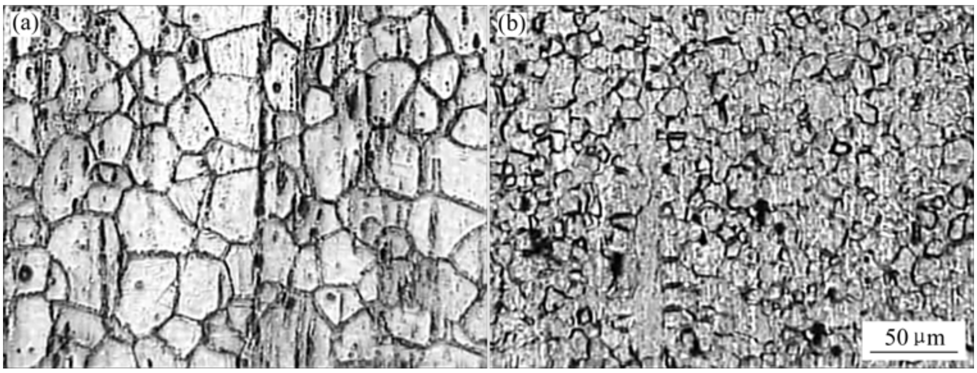

Fig.3 OM microstructures of alloys extruded at 400 ℃: (a) Mg-12.4Gd; (b) Mg-12.5Gd-0.78Sc-1.4Mn (vertical section)

elongation at high temperature also increases. The results are shown in Table 1. And sample in T5 state (at 200 ℃ for 78 h) is peak-aging.

At room temperature, both in the extrusion and T5 state, the integrated performance of MgGdScMn alloy is better than that of MgGd alloy (Table 1). The strength of Mg alloy strongly depends on the size of grains[14]. The size of MgGdScMn grains is much smaller than that of MgGd from above results, so there is fine strengthening at room temperature. The morphologies of as-cast and hot-extrusion alloy demonstrate that the addition of Sc and Mn leads to a lot of rare earth phase precipitate (Fig.1 and Fig.2). These fine second phase particles containing Mg, Sc and Mn strongly pin the dislocations

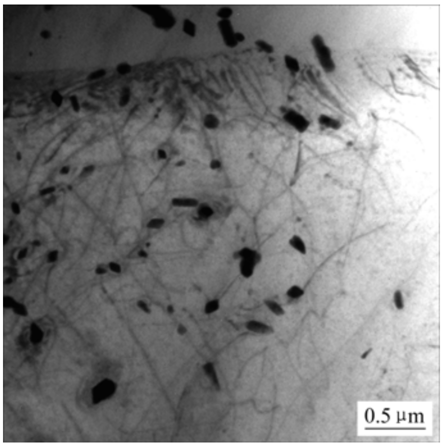

Fig.4 TEM image of extruded rod of Mg-12.5Gd-0.78Sc-1.4Mn alloy

Table 1 Mechanical properties of alloys

Alloy and state	σ_b/MPa	δ/%	Temperature/℃
MgGd−F	240.9	17.3	RT
MgGd –T5-1	343.7	5.0	RT
MgGd –T5-2	254.0	14.1	250
MgGd –T5-3	158.5	21.0	300
MgGdScMn-F	269.9	24.6	RT
MgGdScMn –T5-1	374.8	8.0	RT
MgGdScMn –T5-2	248.1	18.0	250
MgGdScMn –T5-3	153.9	37.7	300

F: The state after extrusion; T5: The state after extrusion and heat-treatment; RT: Room temperature.

during hot-extrusion (Fig.4), leading to much more nucleation sites and increasing the driving force of dynamic re-crystallization. So MgGdScMn alloy has finer grains than MgGd alloy. From the TEM image of MgGdScMn alloy after hot-extrusion (Fig.4), we can find a lot of fine second phase particles, which is beneficial to improving the strength of alloy by second phase pinning dislocations. Fine strengthing and second phase strengthing lead to the increase of mechanical strength at room temperature, but only an increase of 30 MPa. The reason might be the result of uneven composition distribution. At high temperature, because fine grains are not good for heat-resistant performance, so the effect of fine grains counteracts the second phase strengthing. Finally, the ultimate tensile strength of MgGdScMn alloy does not increase compared to MgGd alloy. For the addition of Sc and Mn leads to fine grains, the elongation of MgGdScMn alloy remarkably increases.

The addition of Sc and Mn into MgGd alloy obtains fine grains and leads to a large quantity of fine second phase particles in grain and boundary. These particles effectively influence the performance of alloy. If there is a long homogenization time after hot extrusion, the uneven composition may be eliminated and the fine grain of MgGdScMn alloy will grow up. And then the heat treatment is carried out, the performance at high temperature may be better. The research work is going on.

4 Conclusions

1) The addition of Sc and Mn in Mg-Gd alloy lead to the precipitation of particles containing Sc and Mn, and these particles have the effects of second phase strengthening.

2) The addition of Sc and Mn in Mg-Gd alloy can effectively fine the grains after hot-extrusion.

3) The Mg-Gd-Sc-Mn alloy exhibits higher ultimate tensile strength and elongation at room temperature, and higher elongation at 250 ℃ and 300 ℃.

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