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Effects of micro-alloying with Sc and Mn on microstructure and mechanical properties of Al-Mg based alloys①

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Abstract: An extensive investigation was made on the effects of micro-alloying with small amounts of Sc and Mn on the microstructure and mechanical properties of the Al-Mg based alloys. It is found that the micro-alloying can significantly enhance the tensile strength of the alloys, and eliminate the dendritic cast structure in it. Many fine, spherical and dispersive Al_3Sc particles are found in the annealed Al-Mg-Mn-Sc alloys, which can strongly pin up dislocations and subgrain boundaries, thus strongly retarding the recrystallization of the alloys. The strengthening of the micro-alloyed Al-Mg alloys is attributed to the precipitation strengthening by the Al_3Sc particles and to the substructure strengthening.

Key words: Al-Mg alloy; Al-Mg-Mn-Sc alloy; Al_3Sc particle; microstructure; mechanical properties; micro-alloying
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1 INTRODUCTION

Aluminum alloys containing scandium have many excellent properties, such as high strength together with high ductility, good neutron-irradiation and corrosion-resistance, and superior weldability[1-4], thus can serve as high-performance structural materials. They are mainly used for manufacturing aerospace, defense and military facilities. However, a critical Sc content must be reached in the alloys in order to obtain a good performance[5-7], suggesting that a relatively large quantity of Sc must be added into the alloys. Due to the high price of Sc, and hence to the high cost of the Sc-containing aluminum alloys, the research, development and application of these alloys have been severely retarded. Thus, reducing the Sc addition while keeping the properties of the alloys unchanged has become a key point to the development of the Sc-containing aluminum alloys. Micro-alloying with elements in addition to Sc has been considered an effective way to both enhance the properties and reduce the cost of the alloys. In the present paper, the effects of micro-alloying with Sc and Mn on the microstructures and mechanical properties of Al-Mg based alloys are reported, and the mechanism by which the micro-alloying affects the properties of the alloys is elucidated.

2 EXPERIMENTAL

Four alloys for the study (marked A, B, C and D) were prepared by ingot metallurgy, using pure Al, pure Mg and Al-Sc, Al-Mn master alloys as the starting materials. Their nominal compositions are listed in Table 1. After homogenization at 460 ℃ for 13 h, the ingots were hot-rolled(at a deformation rate of 80%) and then cold-rolled (at a deformation rate of 45%) to 2.5 mm-thick plates. The specimen pieces were annealed at 340 ℃ for 1 h or at 130 ℃ for 4 h. Tensile specimens were cut along the rolling direction of the plates and tested on a CSS-44100 tensile testing machine. The microstructures of the alloys were examined using a POLYVER-Met optical microscope, with the specimens being electro-polished first, followed

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

Specimen	Mg	Sc	Mn	Al
A	5		Bal	
B	5	0.2	Bal	
C	5		0.4	Bal
D	5	0.2	0.4	Bal

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by anodizing in a water solution of HF and H_3BO_3. TEM thin foils were prepared by twin-jet polishing with an electrolyte solution composed of 30% nitric acid and 70% methanol at a temperature below − 20 ℃. The foils were examined using a HITACHI-800 transmission electron microscope at an accelerating voltage of 200 kV.

3 RESULTS AND DISCUSSION

3.1 Optical microstructures of alloys

Fig. 1 illustrates the as-cast microstructures of the alloys. It is shown that the Sc-free alloys A and C possess striking dendritic structures within the grains (Figs. 1(a) and (c)), whereas this structure is not seen in the Sc-containing alloys B and D (Figs. 1(b) and (d)). The grain sizes of the two sets of alloys are essentially unchanged. These observations indicate that addition of 0.2% Sc alone or co-addition of 0.2% Sc and 0.4% Mn into the Al-Mg based alloys can bring about an inoculation effect to the cast alloys, thus eliminating the dendritic structure in them.

Microstructures of the hot rolled alloys are shown in Fig. 2. After hot-rolling at 450 ℃, the Al-5Mg (alloy A) is completely recrystallized, producing fine, nearly equiaxed microstructure (Fig. 2(a)), which however is not observed in the other three alloys. Instead, these alloys possess a fibrous structure along the rolling direction (Figs. 2(b), (c) and (d)), where it is the finest in alloy D. This suggests that addition of Mn or Sc could retard recrystallization of the Al-Mg alloys during hot-rolling, and the retarding effect is the best when Sc and Mn are co-added.

The annealed microstructures of the alloys are shown in Fig. 3. After annealing at 340 ℃ for 1 h, the Sc-free alloys A and C have been completely recrystallized (Figs. 3(a) and (c)), with a marked grain growth occurring in alloy A. Alloy B however still keeps the fibrous structure, with a small quantity of fine, nearly equiaxed grains formed in it (Fig. 3(b)), thus producing a partially recrystallized structure. No such recrystallization occurs in alloy D in which the fibrous structure remains unchanged. It is concluded from these observations that addition of Sc can retard recrystallization during annealing, and the retarding effect is the strongest when Sc and Mn are co-added.

3.2 TEM microstructures of alloys

Fig. 4 shows the TEM microstructures of two alloys, samples B and D, both annealed at 340 ℃ for 1 h. It is seen that many fine and dispersive particles are precipitated within grains in alloy B, which tightly pin up the dislocations (Fig. 4(a)). Such fine, dispersive and spherical particles are also found in alloy D (Fig. 4(d)). According to other investigation[7], these particles are claimed to be the secondary Al_3Sc precipitates formed during the cooling course after annealing. The dislocations and subgrain boundaries within grains of alloy D are also tightly pinned up by these particles (Figs. 4(e) and (f)).

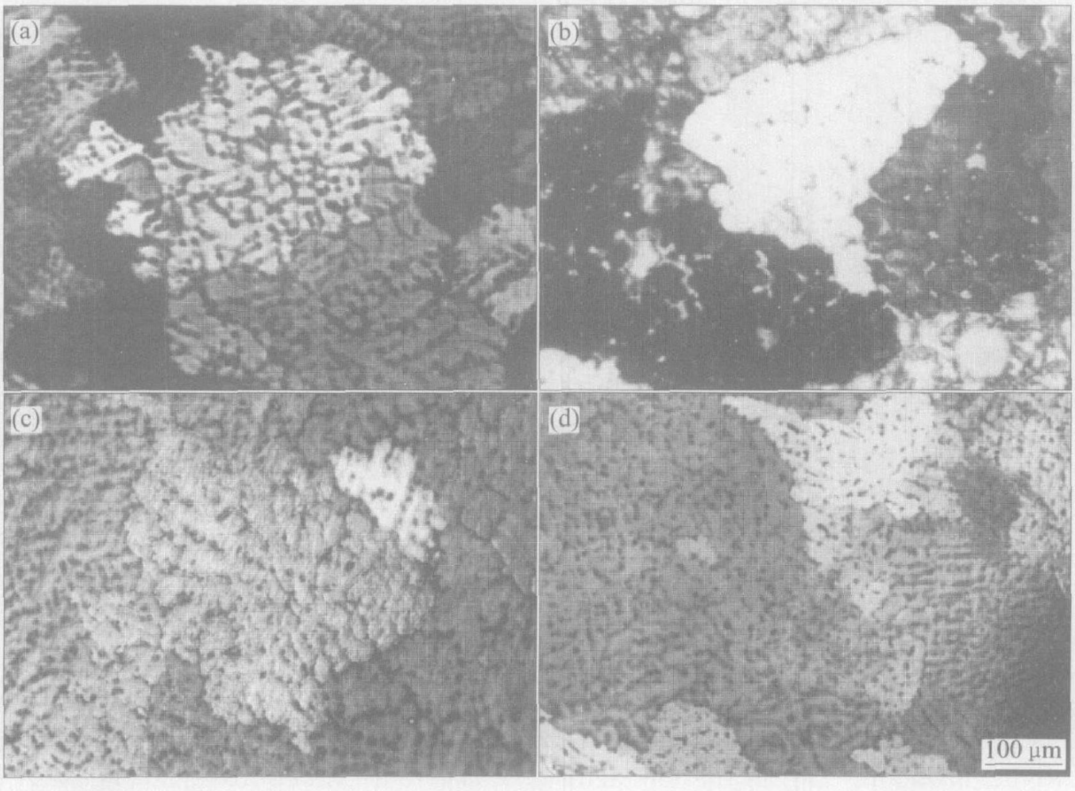

Fig. 1 Optical microstructures of alloys (as-cast)
(a) —Alloy A; (b) —Alloy B; (c) —Alloy C; (d) —Alloy D

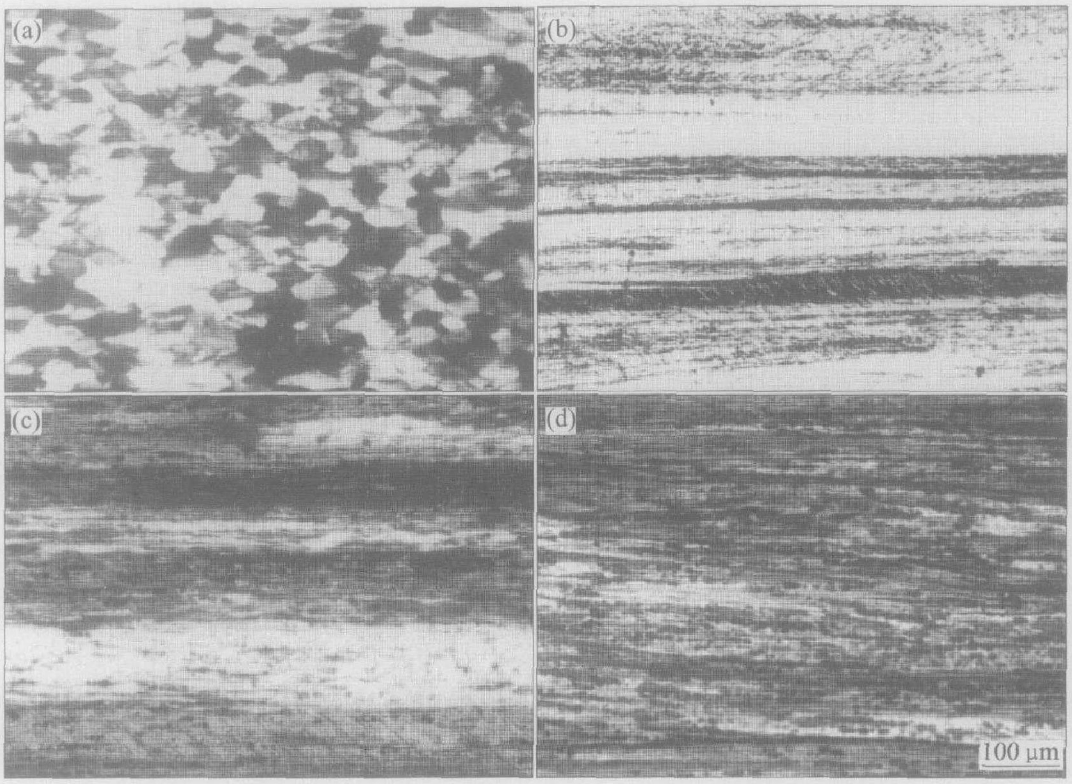

Fig. 2 Optical microstructures of studied alloys (hot-rolled)
(a) —Alloy A; (b) —Alloy B; (c) —Alloy C; (d) —Alloy D

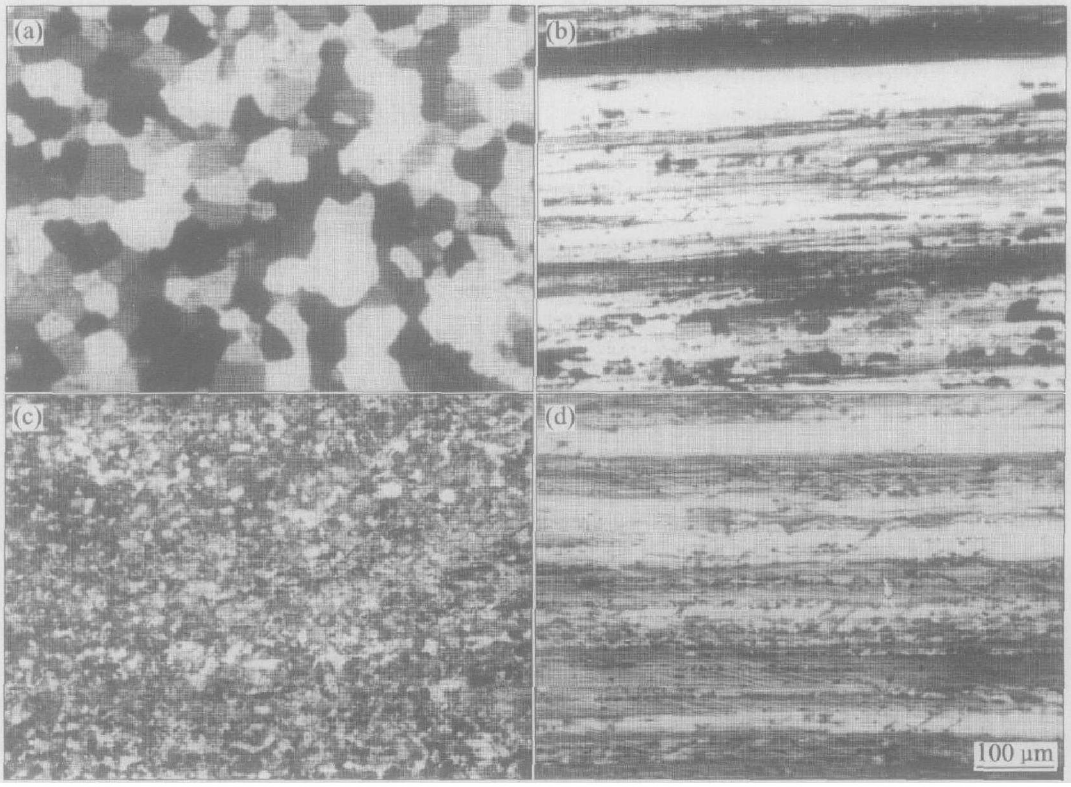

Fig. 3 Optical microstructures of alloys (annealed at 340 ℃ for 1 h)
(a) —Alloy A; (b) —Alloy B; (c) —Alloy C; (d) —Alloy D

In addition, cubic particles are observed in alloys C and D (Fig. 4(b)). These particles are analyzed by TEM (the diffraction spot in the top right corner in Fig. 4(b)) and EDAX (Fig. 4(c)) which, in combination with other investigations[8, 9], confirm the cubic phase to be (Fe, Mn)Al_6. Some other investigators[10-12] however claimed this cubic phase to be $MnAl_6$ instead. The latter conclusion is plausible if high-purity materials and precisely controlled casting process are available. In this study, however, no such conditions are guaranteed, and trace Fe is inevitably brought into the alloys during smelting, which can react with Mn and Al to form $(Fe, Mn)Al_6$.

3.3 Effect of Sc and Mn on tensile properties of Al-Mg based alloys

Table 2 lists the tensile properties of the alloys annealed at 130 ℃ for 3 h or at 340 ℃ for 1 h. It is clear that co-addition of small amounts of Sc and Mn into Al-Mg alloys can appreciably improve the tensile strength (σ_b) and yield strength ($\sigma_{0.2}$) of the alloys subjected to annealing treatments, while still keep their ductility (δ) at a high level (> 10.9%). Specifically, σ_b increases by 54 − 67 MPa and $\sigma_{0.2}$ by 64 − 67 MPa, as compared with the Al-Mg alloys; and σ_b increases by 25 − 45 MPa and 20 − 48 MPa respectively, $\sigma_{0.2}$ increases by 32 − 48 MPa and 39 MPa, respectively, as compared with the Al-Mg-Sc and Al-Mg-Mn alloys. It is also clear from Table 2 that a better combination of strength and ductility is obtained when annealed at 130 ℃

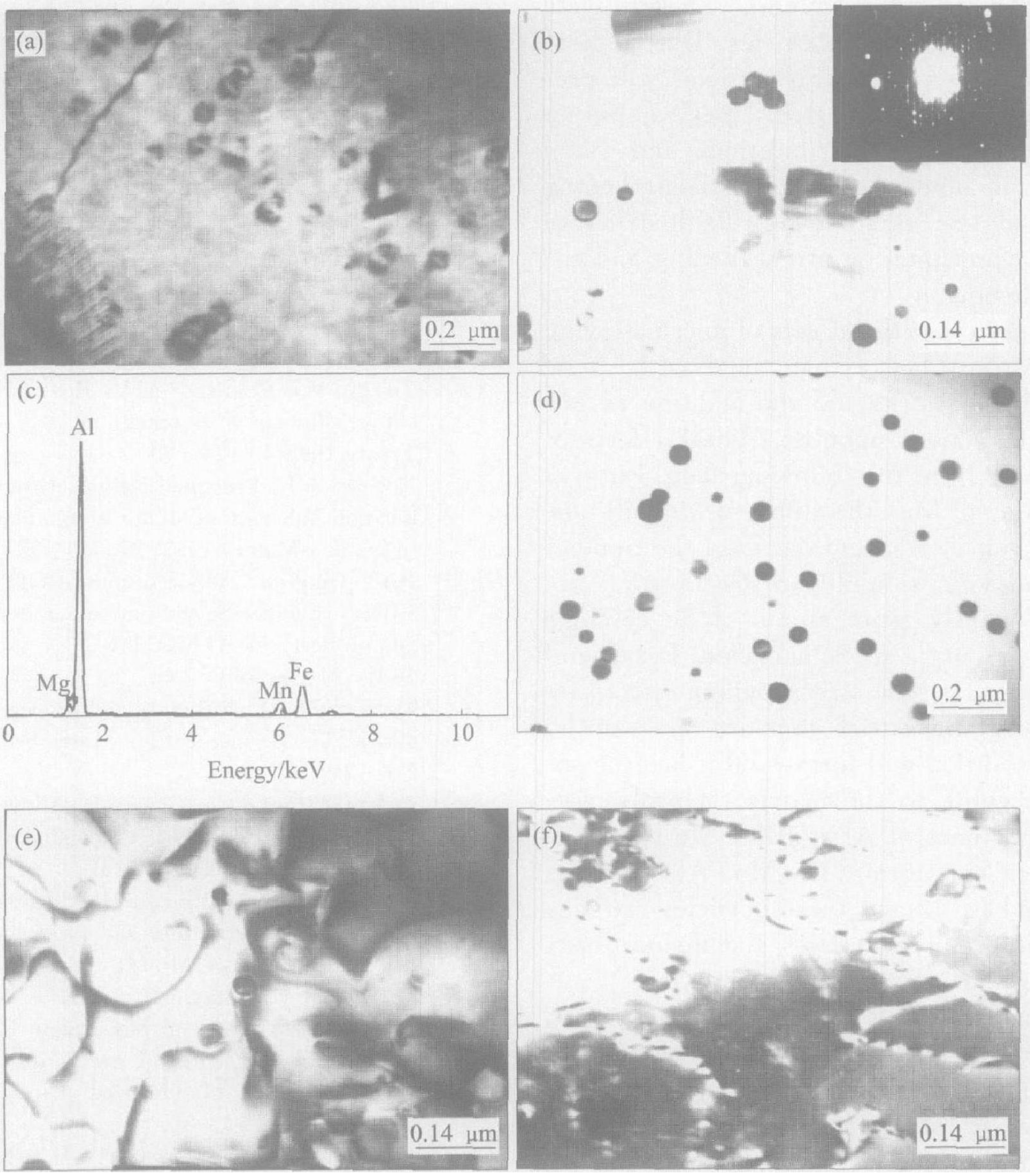

Fig. 4 TEM micrographs of alloys annealed at 340 ℃ for 1 h (alloy B and D)
(a) —Al_3Sc particles pinning dislocations in alloy B;
(b) —Spherical Al_3Sc particles and cubic $(Fe, Mn)Al_6$ particles formed in alloy D;
(c) —EDS spectrum of cubic particle in alloy D; (d) —Fine, spherical and dispersive secondary Al_3Sc particles in alloy D;
(e) and (f) —Secondary Al_3Sc particles pinning up dislocations and subgrain boundaries in alloy D

Table 2 Tensile properties of four annealed alloys

Heat treatment	σ_b/MPa				$\sigma_{0.2}$/MPa				δ/%			
	A	B	C	D	A	B	C	D	A	B	C	D
130 ℃, 3 h	329	348	371	396	240	265	284	304	19.3	15.4	10.9	11.4
340 ℃, 1 h	282	304	291	336	124	152	143	191	25.4	21.0	20.1	15.5

for 3 h than at 340 ℃ for 1 h.

3.4 Discussion

According to the observation of microstructures and measurement of tensile properties above, it can be known that the micro-alloying with Sc and Mn has good effects on the retarding recrystallization and strengthening to the Al-Mg alloys. However lots of studies[13-15] have been done on the influence mechanism of Sc addition to the Al-Mg alloys. Their works show that Sc addition can take significant strengthening effect on the alloys. But the Sc must reach a given amount. These effects mainly come from the Al_3Sc particles. During casting and heating process, Al_3Sc particles will precipitate and disperse in the matrix, they can pin up the grain boundaries and dislocations and, stop their moving and annexation. So the strengthening mechanisms of Sc are mainly sub-structure strengthening, precipitation strengthening and solution strengthening.

It can be seen that the effects of micro-alloying with Sc and Mn are better than those with single Sc from the above works, so the addition of Mn can improve the actions upon Sc. These effects of Mn mainly come from the following fact. Firstly, after the addition of Mn, the atoms of Mn will take up the lattice gap of Al, and decrease the number of gap, so the solid solubility of Sc in Al is reduced. Consequently more atoms of Sc combine with Al and form more Al_3Sc particles. Because of more Al_3Sc particles, the strengthening effects are better. Secondly, the lattice gaps are taken up by Mn, so solid solution will form, and it has the solution strengthening to the matrix. Thirdly, because of the existence of Al and Fe, Mn can combine with them and form (Fe, Mn) Al_6 particles (Figs. 4(b) and (c)), and these particles can also pin up the sub-grain boundaries and dislocations, so have the sub-structure strengthening.

Sc is expensive, and this is the main reason that the aluminium alloys containing Sc cannot develop fast. But Mn is cheap. When put it into the alloys with Sc, it can reduce the consumption of Sc, in the same time the effects on the alloys are not decreased. This will reduce the manufacturing cost and give one way to develop the aluminium alloys containing Sc.

4 CONCLUSIONS

1) Micro-alloying Al-Mg alloys with small amounts of Sc and Mn can considerably increase the strength of the alloys, while still keep their ductility at a high level. And the strengthening mainly results from sub-structure strengthening and precipitation strengthening.

2) Co-addition of small amounts of Sc and Mn into the Al-Mg alloys brings about an inoculation effect on their cast microstructure, thus eliminating the dendritic cast structures in them.

3) Co-addition of small amounts of Sc and Mn can retard the recrystallization of the alloys during hot-rolling and annealing, thus stabilizing their deformation structures.

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