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Effect of minor Sc and Zr on microstructures and mechanical properties of Al-Zn-Mg based alloys ①

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[Abstract] Two kinds of Al-Zn-Mg based alloys with and without Sc, Zr addition were prepared by ingot metallurgy. The tensile mechanical properties and microstructures of the studied alloys at different treatment conditions were studied. The results show that addition of minor Sc and Zr can remarkably improve the strength of Al-Zn-Mg based alloys, but the ductility remains on a higher level. The strength increment is mainly due to fine-grain strengthening, substructure strengthening and precipitation strengthening of $Al_3(Sc, Zr)$.

[Key words] aluminum alloy; Sc; Zr; microstructure; mechanical properties
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1 INTRODUCTION

Aluminum alloy containing minor Sc and Zr is a new group of structure materials, which has high strength, high ductility, good corrosion resistance and weldability[1~5]. It is mainly applied in aerospace, nuclear energy and ships industry. The simultaneous addition of Sc, Zr or Ti elements is a popular trend for the development of aluminum alloys. A lot of research about Al-Mg based alloys with Sc and Zr addition has been made[3~8], but research on Al-Zn-Mg based alloys containing Sc and Zr are not common[9, 10]. In this study, the effect of minor Sc and Zr on the microstructures and mechanical properties of Al-Zn-Mg alloys was studied. The purpose of this work is to find a new way to prepare new high-strength and high-ductility aluminum alloys by minor element alloying.

2 EXPERIMENTAL

The normal compositions (mass fraction, %) of the studied alloys are Al-6.2Zn-2.0Mg and Al-6.2Zn-2.0Mg-0.35(Sc+Zr). The starting materials were 99.98% Al, 99.92% Mg, 99.8% Zn, Al-Sc and Al-Zr master alloys. The alloys were melted in crucible furnace and then poured into a iron mold for casting. After homogenization at 460 ℃ for 12 h, the ingots were hot-rolled and then cold-rolled to 2 mm-thick plates. Tensile samples were taken along the rolling direction of the plates. After 465 ℃/30 min solution treatment, water quenching and 120 ℃/0~24 h aging, samples were tested on Instron-8032 tensile testing machine and the tensile ratio is 2 mm/min. Metallography samples for observing grain structure were examined on MET-2 after electrolytic polishing and anodizing membrane with water solution of HF and H_3BO_3. Metallography samples for observing crystal nucleus were etched using mixed acid. Thin foils for TEM observation were prepared by twinjet polishing with an electrolyte solution consisting of 30% HNO_3 and 70% methanol below − 25 ℃. The foils were examined on Hitachi-800 electron microscope.

3 RESULTS

3.1 Mechanical properties

The mechanical properties of the studied alloys at different treatment conditions are listed in Table 1.

At as-hot rolled condition, adding 0.35 (Sc+Zr) to Al-6.2Zn-2.0Mg alloy, the tensile strength and yield strength of the alloy increase by 30 MPa and 40 MPa, respectively; for as-solution treated sample, the strength increment are 113MPa and 129 MPa, respectively. During aging, the strength of the studied alloys increase with the increase of aging time. After aging for 24 h, the increment of tensile strength and yield strength reach 93 MPa and 104 MPa, respectively, but the plasticity remains in a higher level (10.6%). In addition, by comparing the strength increment of the studied alloys at solution treatment and aging treatment, it is suggested that adding of minor Sc and Zr mainly strengthens the solution matrix, but has little effect on the aging process.

3.2 Microstructures

3.2.1 Optical microstructure

The microstructures of different treated alloys are shown in Fig. 1.

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Table 1 Tensile properties of studied alloys (in rolling direction)

Processing	$1^{\#}$ alloy (Al-Zn-Mg)			$2^{\#}$ alloy (Al-Zn-Mg-Sc-Zr)		
	σ_b/MPa	$\sigma_{0.2}$/MPa	δ/%	σ_b/MPa	$\sigma_{0.2}$/MPa	δ/%
Hot-rolled	357	254	15.2	387	294	12.9
465 ℃/30 min solution treatment, water quenching	332	170	26.0	445	299	17.4
465 ℃/30 min solution treatment+ 120 ℃/3 h aging	416	357	15.0	490	447	13.0
465 ℃/30 min solution treatment+ 120 ℃/12 h aging	439	376	13.0	494	458	10.7
465 ℃/30 min solution treatment+ 120 ℃/24 h aging	450	405	10.0	543	509	10.6

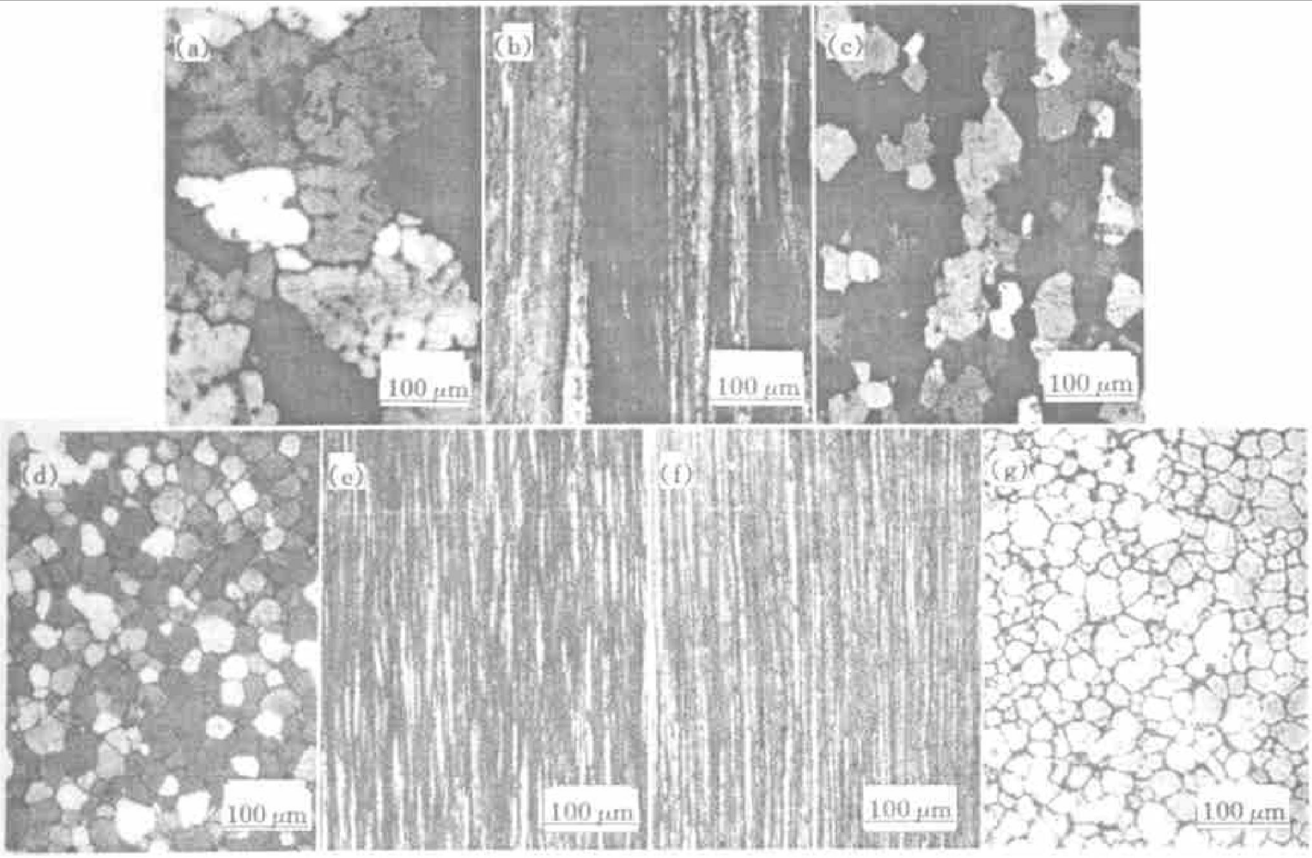

Fig. 1 Optical microstructures of different treated alloys

(a) —$1^{\#}$ alloy, as-cast; (b) —$1^{\#}$ alloy, as-hot rolled; (c) —$1^{\#}$ alloy, as-solution treated; (d) —$2^{\#}$ alloy, as-cast; (e) —$2^{\#}$ alloy, as-hot rolled; (f) —$2^{\#}$ alloy, as-solution treated; (a)~(f) —anodizing with water solution of HF and H_3BO_3; (g) —$2^{\#}$ alloy, as-cast, etched using mixed acid

Simultaneous adding of minor Sc and Zr can obviously refine as-cast grain. The hot-rolled microstructures of both alloys are fibrous unrecrystallization microstructures. After 465 ℃/30 min solution treatment, the alloy without Sc and Zr addition exhibits complete recrystallization microstructure, but the microstructure of the alloy with Sc and Zr addition remains fibrous. Fig. 1(g) indicates the microstructure of the as-cast alloy with Sc and Zr addition after etched by mixed acid, from which small square or trigonal particles of the second phases can be found within some grains, identified as Al_3(Sc, Zr) composite particles in the previous research[3].

3.2.2 TEM microstructure

Fig. 2 presents the TEM microstructures of two studied alloys at different treated conditions.

In the two studied alloys, needle and bar precipitates mainly distribute within the grains and partially exist at grain boundaries, dispersively (as shown in Fig. 2(a) ~ 2(b)). In Al-Zn-Mg-Sc-Zr alloy, some Al_3(Sc, Zr) particles coherent to the matrix, with strongly pined dislocations, can still be found (as shown in Fig. 2(d)). After solution treatment, the needle and bar precipitates existing in hot-rolled microstructure disappear (as shown in Fig. 2(c) ~ 2(d)), suggesting that the majority of precipitates have solutionized into the matrix. However, Al_3(Sc, Zr) particles coherent to the matrix still exist and these particles have strongly pinned subboundaries (as shown in Fig. 2(d)). It is the reason why the alloys

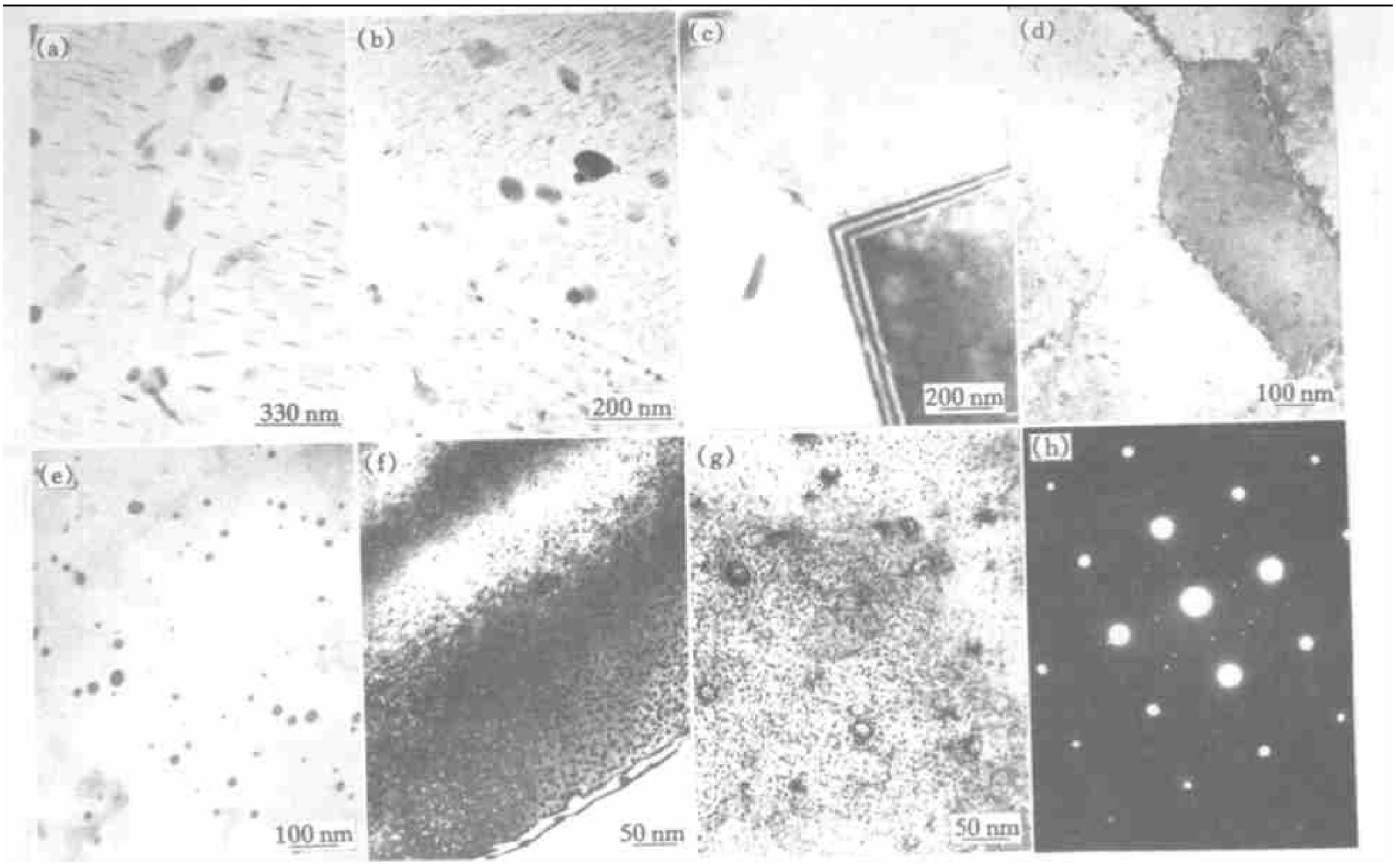

Fig. 2 TEM microstructures of different treated alloys
(a) —1# alloy, as-hot rolled; (b) —2# alloy; as-hot rolled; (c) —1# alloy, as-solution treated;
(d) ~ (e) —2# alloy, as-solution treated; (e) —(001) dark field image of $Al_3(Sc, Zr)$; (f) —1# alloy, 120 ℃/12 h aging;
(g) —2# alloy, 120 ℃/12 h aging; (h) —diffraction pattern of Fig. 2(g) showing that besides
[001] diffraction spots of matrix, there exist those of $Al_3(Sr, Zr)$ and Mg_2Zn precipitates

still remain the fibrous microstructures after solution treatment. During aging, $MgZn_2$ precipitates from the matrix. With increasing aging time, $MgZn_2$ phase is coarsened, and discontinuous secondary phase particles precipitate at the boundaries. After 120 ℃/12 h aging, the size of $MgZn_2$ precipitates is about 10 nm (as shown in Fig. 2(f) ~ 2(g)).

4 DISCUSSION

The author's previous researches[5,7] suggest that in Al-Mg based alloy, minor Sc and Zr mainly exist in two forms of $Al_3(Sc, Zr)$ intermetallic compound particles. One is primary $Al_3(Sc, Zr)$ precipitated from the melt during solidification. Primary $Al_3(Sc, Zr)$ is an ideal crystal nucleus[5] and can greatly refine the grain size of as-cast alloys. The other is secondary $Al_3(Sc, Zr)$ precipitated during homogenization[1,7], which is small, dispersive, and coherent to the matrix. In this study, primary $Al_3(Sc, Zr)$ can be seen in Fig. 1(g) and Fig. 2(d) and refined grains of as-cast alloy in Fig. 1(d). The secondary $Al_3(Sc, Zr)$ has strongly pinned dislocations and subboundaries, which can produce precipitation strengthening and effectively restrain recrystallization (as shown in Fig. 1(e) ~ (f)). However, the alloy without Sc and Zr addition has completely recrystalliated after solution treatment (as shown in Fig. 1(c)). Comparing Fig. 2(f) with Fig. 2(g), except $Al_3(Sc, Zr)$ precipitates within the matrix of alloy with Sc and Zr addition, characteristics of $MgZn_2$ precipitates have little difference, suggesting that minor Sc and Zr have little effect on the aging process. Therefore, strengthening produced by adding of minor Sc and Zr mainly comes from fine-grain strengthening, substructure strengthening and precipitation strengthening. Minor element alloying which can increase the strength by such a high level is rarely discovered in the history of aluminum alloys and opens up a new way of preparing high-strength and high-ductility aluminum alloys.

5 CONCLUSIONS

1) Simultaneous adding of minor Sc and Zr to Al-Zn-Mg alloys can obviously increase the strength of alloys, but the ductility can remain on a higher level.

2) Strengthening caused by adding of minor Sc and Zr mainly comes from fine-grain strengthening,

$Al_3(Sc, Zr)$ particle precipitation strengthening and substructure strengthening caused by restraining recrystallization.

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