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Effect of scandium on superplasticity of Al-Mg alloys^①

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[Abstract] The superplastic behavior of adding 0.22% Sc into the Al-6Mg alloy was studied by simple superplastic pre-treatment process—warm rolling and cold rolling. The optimum superplastic temperature and strain rate of the alloys were defined and satisfactory results were obtained during the superplastic deformation at 811 K and initial strain rate $\dot{\epsilon}_0 = 1.67 \times 10^{-3} \text{ s}^{-1}$. The average elongation of Al-6Mg-0.22Sc alloys reaches to 1125%, and the maximum elongation is 1200%, maximum m value (strain rate sensitive index) is 0.879. But under the same condition the elongation and maximum m value for Al-6Mg alloy were only 377% and 0.595, respectively. The superplastic deforming mechanism for Al-6Mg-0.22Sc alloys was also discussed.

[Key words] Al-6Mg-0.22Sc alloy; Al-Mg alloy; superplasticity

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1 INTRODUCTION

Al-Mg-Sc alloy possesses high strength, high toughness, lower density, good weldability and corrosion resistance^[1,2]. Applying the superplasticity of these alloys to form important complex parts for the spacecraft is a significant research subject at present^[3,4]. This research has just been started around the world. Russia is ahead of other countries, the second one is USA, while China is still vacant^[2].

2 EXPERIMENTAL

The prepared procedure of a specimen was as follows. The Al-6Mg-0.22Sc alloy obtained through adding 0.22% Sc into molten Al-6Mg alloy was cast to slabs in the water cooling copper modes; then the slabs were warm rolled at 288 °C, and cold rolled to the plate with thickness of 1.5 mm, and the superplastic tensile specimens of 1.5 mm × 6 mm × 15 mm were made and stamped along rolling direction; finally the tensile test was conducted by AG-10TA Universal Electronic Machine made in Japan, of which the specimens were held at a constant temperature for 15 min in a furnace at temperature of 350, 400, 450, 518 and 580 °C respectively, with correspondingly moving velocity of machine cross-head being 0.2, 0.5, 1.0, 2.0, 3.0, 5.0, 10.0 mm/min respectively. In addition m values were measured by Backfen Sudden Changed method of speed.

3 RESULTS AND DISCUSSION

3.1 Superplastic behavior of Al-6Mg-0.22Sc alloy

Useful superplasticity was obtained among 787~811 K for this alloy. The optimum deformation temperature is 811 K for this alloy. Test results are shown in Fig. 1 and Fig. 2.

As shown in Fig. 1 and Fig. 2, the average elongation reaches to 1125% at initial strain rate of $1.67 \times 10^{-3} \text{ s}^{-1}$ and 811 K (538 °C). However the elongation for the Al-6Mg alloy only reaches to 377% under the same condition. Obviously the superplasticity of the Al-6Mg alloy is improved markedly with the addition of scandium.

The relationship between $\lg \dot{\epsilon}_0$ and m value is shown in Fig. 3. It can be seen that the strain rate sensitive index m of Al-6Mg-0.22Sc alloy is reached to its peak value of 0.879 at the initial strain rate of $1.67 \times 10^{-3} \text{ s}^{-1}$. However m value of Al-6Mg alloy is lower than that of the alloy adding Sc, it is only 0.595. This indicates that after adding Sc to

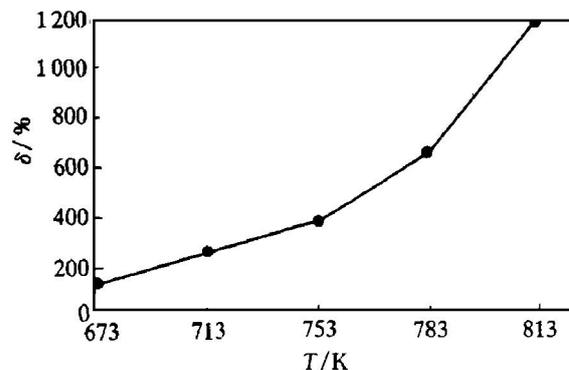


Fig. 1 Relationship between elongation and temperature of superplastic deformation ($\dot{\epsilon}_0 = 1.67 \times 10^{-3} \text{ s}^{-1}$)

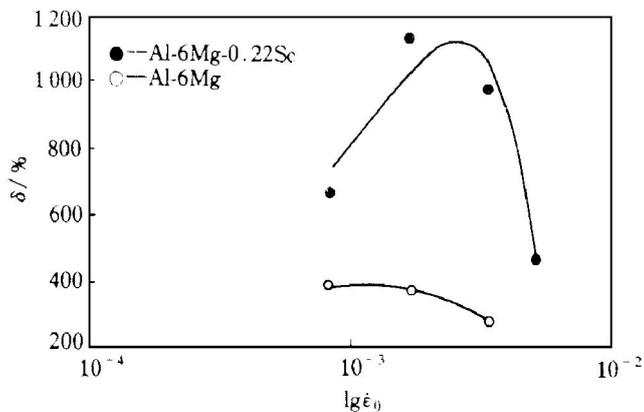


Fig. 2 Relationship between initial strain rate and elongation

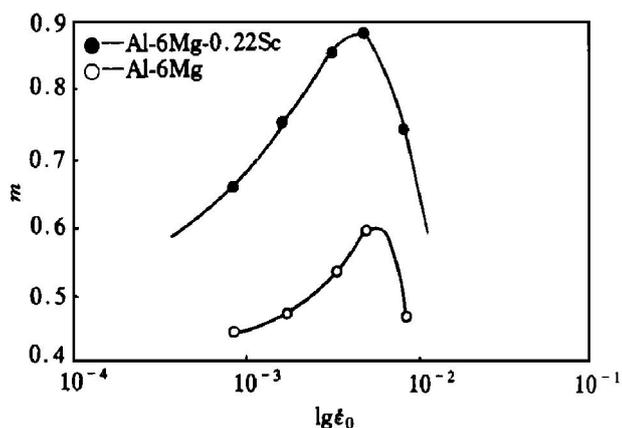


Fig. 3 Curves of strain rate and *m* value

the alloy, the anti-necking ability of the alloy is enhanced significantly.

3.2 Effect of simple pretreatment on grain size of alloys

Generally the grain of most alloys has grown greatly before it is heated to the superplastic deforming temperature. A fundamental problem of obtaining superplasticity of aluminum alloys is how to get fine

grain and controls of grain coarsening. Specimens are pretreated by the combination of warm rolling and cold rolling for Al-6Mg alloy and Al-6Mg-0.22Sc alloy, then the superplastic tension tests are conducted at a given temperature.

The recrystallization condition is provided by the warm rolling deformation. It is characteristic to form a strong deforming zone around the hard precipitant phase particles and to possess dislocation cells with minimum size in the deforming regions. TEM micrographs of two alloys are shown in Fig. 4 and Fig. 5 respectively. As shown in Fig. 5(a), the dislocation density of Al-6Mg-0.22Sc alloy at cold rolling is increased further than that at warm rolling and the dislocation tangle in which second phase is precipitated is formed. Those particles in the second phase that dispersed in the matrix are very small. The cold rolling structure of Al-6Mg is shown in Fig. 5(b). The dispersed particles are not discovered in the structure. Obviously, a lot of dispersive particles precipitated from solid solution at cold rolling in the Al-6Mg-0.22Sc alloy are Al₃Sc phase particles whose sizes are 15~45 nm. The growth of recrystallization grain is hindered by Al₃Sc particle to form equiaxial fine grain, and it is the condition of producing high superplastic structure.

3.3 Superplastic mechanism for Al-6Mg-0.22Sc alloy

After adding Sc into Al-6Mg alloy its superplasticity is greatly increased. There are two changes evidently in the microstructure of adding Sc into Al-6Mg alloy. Firstly the cast structure is strongly fined; secondly, the structure stability is apparently enhanced during the deforming process. The acting mechanism of scandium should be studied. It is necessary to make the scandium distribution clear in the alloy.

According to the values of Table 1 and the alloy

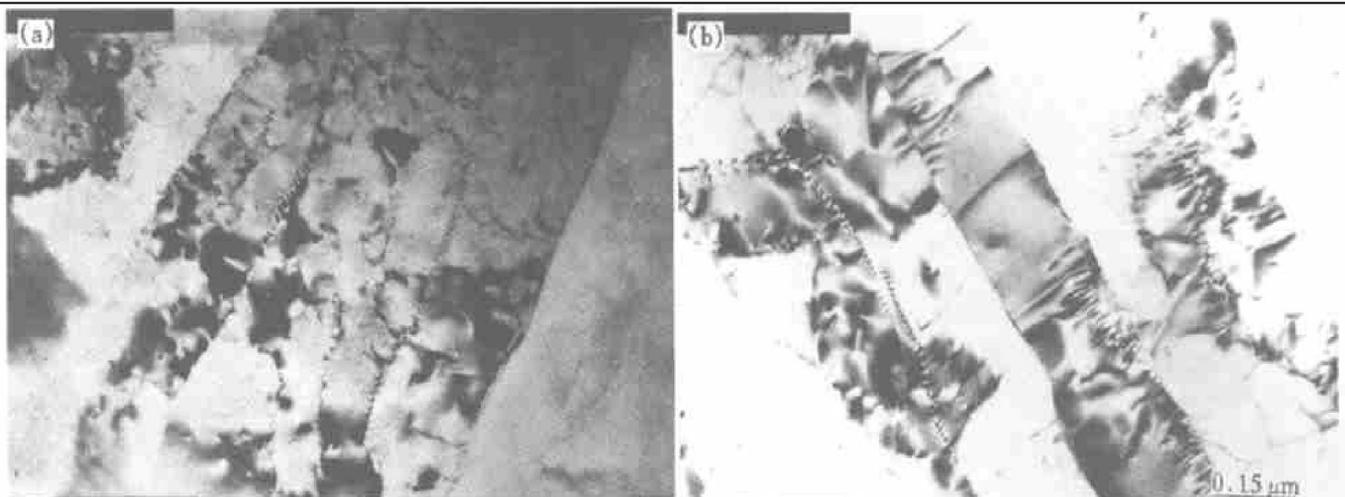


Fig. 4 Dislocations and subcells formed after warm rolling (a) —Al-6Mg-0.22Sc alloy; (b) —Al-6Mg alloy

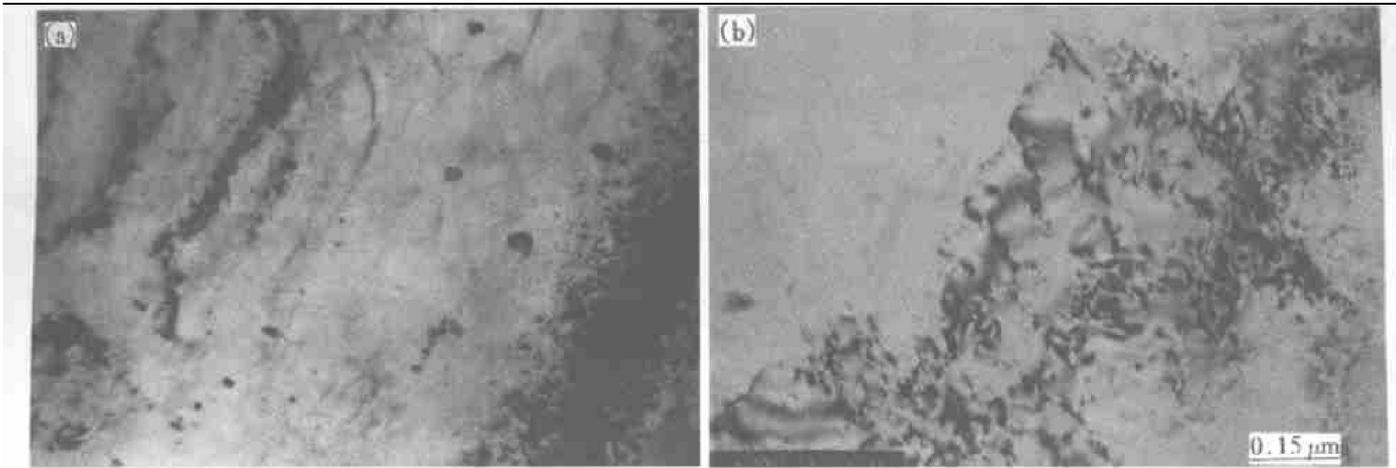


Fig. 5 TEM micrographs of cold rolling alloy dislocation tangle and precipitated particles
(a) —Al-6Mg-0.22Sc alloy; (b) —Al-6Mg alloy

theory, the atomic radius and negative electricity of aluminum and scandium are between forming solid solution and intermetallic compounds. The solubility of scandium in aluminum are 0.186% and 0.033% at 640 °C and 470 °C respectively. If the Sc content added into Al is over the solubility enriching Al phase containing Sc, i. e. Al_3Sc is formed and then the eutectic is formed with aluminum^[5]. The frame is formed in the boundary by these eutectics under casting state or some other conditions. Because the melting point of the Al_3Sc phase is very high and it is stronger at high temperature than aluminum, the grain growth and grain boundary slip at high temperature were inhibited by the eutectics due to the strengthening of the grain boundary and the alloy strength at high temperature^[6].

Table 1 Atomic radius and negative electricity of aluminum and scandium

Element	Atomic radius/nm	$\frac{r_{\text{Sc}} - r_{\text{Al}}}{r_{\text{Al}}}$ / %	Negative electricity
Al	0.1429	14.7%	1.5
Sc	0.1640		1.3

It is discovered by electronic microscope that the size, the shape and distribution of Al_3Sc phase are different under various conditions. The precipitation and growth of Al_3Sc phase in the casting state is shown in Fig. 6 after aging 8 h at 288 °C. The fine dispersive precipitation of Al_3Sc spherical particles before tension at constant temperature is shown in Fig. 7, with size about 0.03~ 0.08 μm. This dispersion phase is characteristic of the coherence with the matrix under microscope observation^[7]. It is discovered that spherical particles of Al_3Sc has grown further after observing under elongation of 50%, 100% and 200%, respectively. As shown in Fig. 8, the particles are characteristics of the dispersion distribution in the matrix and their sizes are only about several nanometers. The heat stability of Al_3Sc particles is

still very high and the particles are coherent with the matrix.

Obviously Al_3Sc particles are existent under different conditions. It is most advantageous to the superplasticity of the alloys to precipitate at a constant

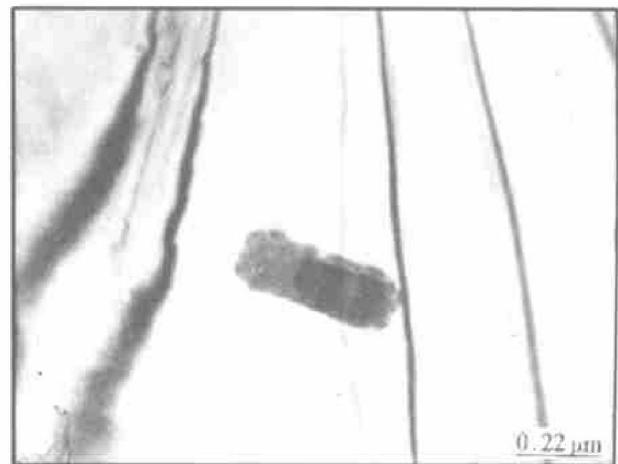


Fig. 6 Microstructure of precipitated Al_3Sc casting state after aging 8 h



Fig. 7 Microstructure of precipitated Al_3Sc before alloy tension at constant temperature for 15 min

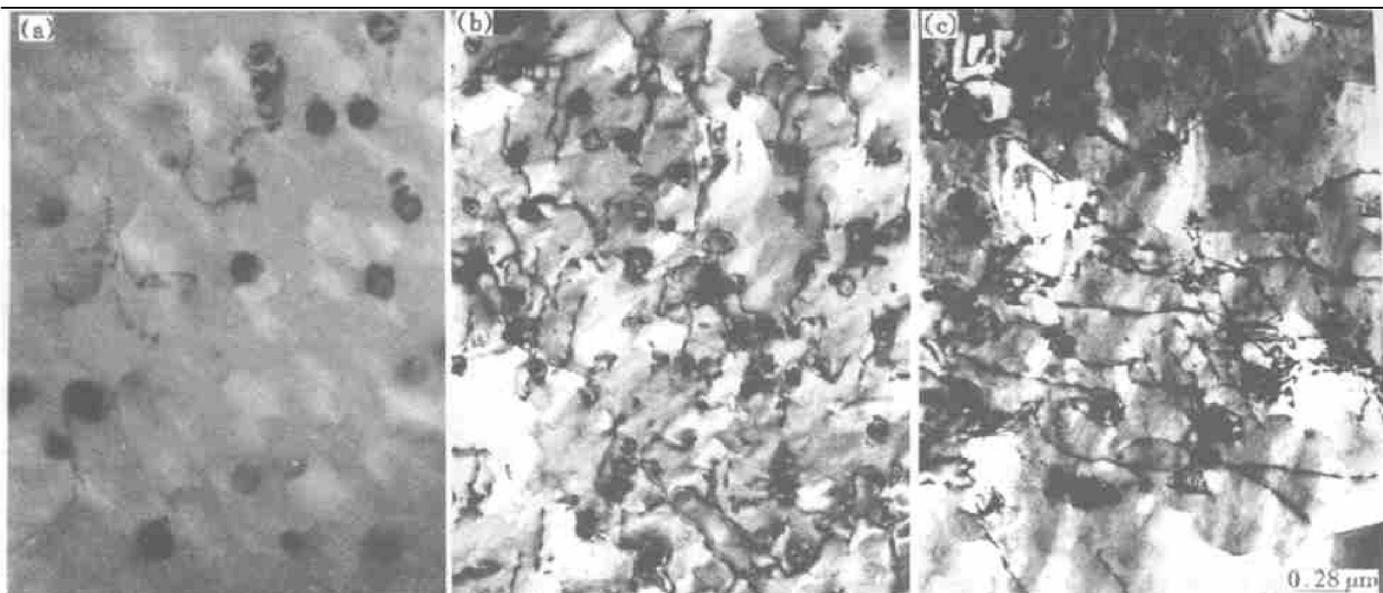


Fig. 8 TEM micrographs of precipitated Al_3Sc of Al-6Mg-0.22Sc alloy after different deforming reductions (a) —50%; (b) —100%; (c) —200%

temperature. Because Al_3Sc phase is characteristic of spherical dispersion to the matrix and coherence with the matrix, therefore a pretreatment is used at 288 °C before warm and cold rolling.

As shown in Fig. 9, Al_3Sc particles are not only able to fine grain but also able to pin the grain boundary and fix grain size. Even during the final period of superplastic tension, Al_3Sc particles are still capable of effectively pinning the grain boundary. Scandium is able to increase the heat stability of Al-6Mg alloy. The dispersity of Al_3Sc particles is extremely high. It is an effective barrier of dislocation motion and inhibitor of recrystallization^[8,9]. If recrystallization is produced, the equilibrium Al_3Sc phase still keeps up with the matrix. Therefore continuous recrystallization is inhibited by the Al_3Sc phase in the deforming

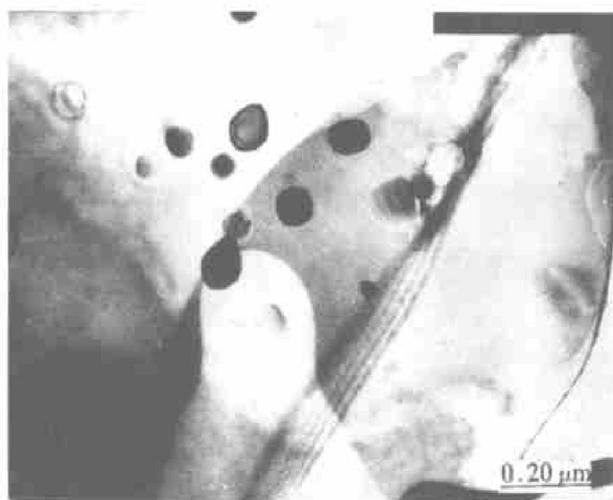


Fig. 9 Pinning of Al_3Sc particles in grain boundary

process at high temperature, thus the grain growth is inhibited. It plays an important role for stabilizing deformation structure at high temperatures, therefore a structure stability for Al-6Mg-0.22Sc alloy is increased in the superplastic deformation.

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