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Microstructure and properties of Al-4Cu alloy containing Sc①

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Abstract: The effects of different contents of Sc addition on the microstructures and properties of the Al-4% Cu alloy were studied by tensile properties measurement, optical microscope, X-ray diffraction analysis, scanning electron microscope (SEM) and energy spectrum analysis. The experimental results show that rare-earth element Sc is capable of refining the dendritic structure of the Al-4% Cu alloy, the tensile strength σ_b and yield strength $\sigma_{0.2}$ just increase a little when the content of Sc is lower than 0.2%; when the content reaches 0.3%－0.4%, σ_b and $\sigma_{0.2}$ slightly decrease; but σ_b and $\sigma_{0.2}$ rise again when the Sc content is 0.5%, though both of them are lower than those of the Al-4% Cu alloy without Sc addition. However, Sc addition has little influence on the elongation of the Al-4% Cu alloy. Adding Sc to the Al-4% Cu alloy, when the amount of Sc is lower than 0.2%, Sc mostly exists in the α(Al) solid solution; when the Sc content is in the range of 0.3%－0.5%, only a part of Sc exists in the α-Al solid solution, the rest appears in two ways: one is that Sc and Al form Al_3Sc which can strengthen the alloy, and the other, Sc interacts with Al and Cu to form AlCuSc phase.

Key words: Sc; Al-Cu alloy; microstructure; mechanical properties
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1 INTRODUCTION

It is well known that the rare-earth element Sc has very positive influences on Al and its alloys. The main benefits of Sc addition can be summarized as follows: a) the Al-Sc solid solution decomposes to form a $L1_2$ type Al_3Sc phase coherent with the matrix, which can produce precipitation hardening[1－4]; b) the fine dispersed Al_3Sc particles can tightly pin up the grain boundaries and the dislocations, and also inhibit the recrystallization, so the alloy can be deforming strengthened (defects being introduced)[4,5]; c) the cast grains can be well refined[6]; d) the weldability of Al alloys can be improved[7－9]. The Al-Cu binary alloy is the base alloy of 2xxx and 7xxx alloy systems, and it is a typical kind of alloy that can be strengthened by heat-treatments. Its strong ageing strengthening effects are due to the numerous fine dispersed GP zones, θ″ and θ′ phases in the microstructure formed after the quenching and ageing treatments, and an elastic strain zone around them, which prevent the dislocation movement. The property change and mechanisms of the Al-Cu based alloy with Sc addition are mainly investigated in this paper.

2 EXPERIMENTAL

The Al-4% Cu alloys containing different additions of Sc (0.1%, 0.2%, 0.3%, 0.4% and 0.5% respectively) were prepared by ingot metallurgy with 1# commercial aluminum, the Al-33.2% Cu and the Al-3.2% Sc master alloys. Melting was carried out with a graphite crucible in a common SG2-7.5-12 type crucible resistant furnace, melting temperature being 800－820 ℃. A special aluminum alloy cover-flux, and the C_2Cl_6 gas-remover were used. The liquid alloys were cast in an iron mould with a pouring temperature of 740－780 ℃. The homogenization was carried out by two steps: first at 380 ℃ for 6 h and then 480 ℃ for 15 h. All the casts were then head-cut, surfaces milled, hot rolled and cold rolled afterwards. The hot rolling start temperature was 460 ℃ and the whole deformation ratio was about 80%. Afterwards a middle anneal process was undergone at 470 ℃ for 1 h. Subsequently the cold rolling was carried out with a whole deformation ratio of 50%. Samples for tensile properties tests were prepared according to the requests of GB6397-86. The tensile properties were tested in an Material Testing Machine (INSTRON4302) with a tensile velocity of 2 mm/min. Samples for optical microscope observation were mechanically polished and etched with mixed acid (1% HF + 1.5% HCl + 2.5% HNO_3 + H_2O), and the observation, analysis and photograph were done in an optical microscope (NEOPHOT-21). The existing states and its effects of trace Sc on the

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microstructure were investigated using the X-ray diffraction (XRD) and scanning electron microscope (SEM) (HITACHI S-3500N).

3 RESULTS AND DISCUSSION

3.1 Effects of Sc on as-cast microstructures of Al-4%Cu alloy

The as-cast microstructures of the Al-4Cu alloy, Al-4Cu-0.1Sc alloy, Al-4Cu-0.3Sc alloy and Al-4Cu-0.5Sc alloy are shown in Fig. 1. It can be seen that the size of the dendritic structure of the Al-4Cu alloy is rather big, and the grains are coarse, too (Fig. 1 (a)). For the Al-4Cu-0.1Sc alloy, the size of the dendritic structure remarkably decreases and the grains also become smaller. The dendritic structure of the Al-4Cu0.3Sc alloy almost disappears and the grains become rather small. As for the Al-4Cu-0.5Sc alloy, the dendritic structure completely disappears, and the grains are further refined. From these results one can see that the element Sc has refining and modifying effects on the microstructures of the Al-4Cu alloy, which is in agreement with the effect principles of rare earth elements on Al alloys. The causes of the refinement could be explained as follows: adding Sc to the Al-4Cu alloy, Sc accumulates in the front of the interface of the solid-liquid phase, which increases the constitutional undercooling degree on the solidification process of the alloy, and makes the breaking of the growing dendrites obvious. The fine Al_3Sc particles formed during solidification act as crystal nuclei and make the grains refined[10].

3.2 Existing states of trace Sc

The XRD patterns of the as-cast alloys are shown in Fig. 2. Analyzing the peak values of these curves, one can see that only α(Al) and θ($CuAl_2$) phase can be observed in the Al-4Cu alloy when the Sc content is lower than 0.3% (curves 1 and 2). But when the Sc content is higher than 0.3%, the Al_3Sc phase and a ternary compound AlCuSc can be observed besides α (Al) and θ($CuAl_2$) phase (curves 3 and 4). According to Refs. [11, 12], in Al alloys containing Sc, Al_3Sc particles were coherent with the matrix, which precipitated during the warm rolling, hot rolling and annealing process, indicating that element Sc can enter the cast Al matrix during solidification. Furthermore, according to the Hume-Rothery experiential law which demonstrates the effect factors of the solid solubility of elements, a qualitative analysis about the existing states of Sc in the Al matrix was done and a conclusion can be drawn that Sc can enter the Al matrix. This is because that the atom radius difference between Al and Sc is 14.7% (matching number = 12, atom radius being 0.143 nm, 0.164 nm, respectively), and the electron negative difference between Al and Sc is 0.2 (matching number= 12, the electron negative difference of Al and Sc being 1.5, 1.3, respectively). But when the addition of Sc is higher than 0.3%, an AlCuSc phase forms during the crys-

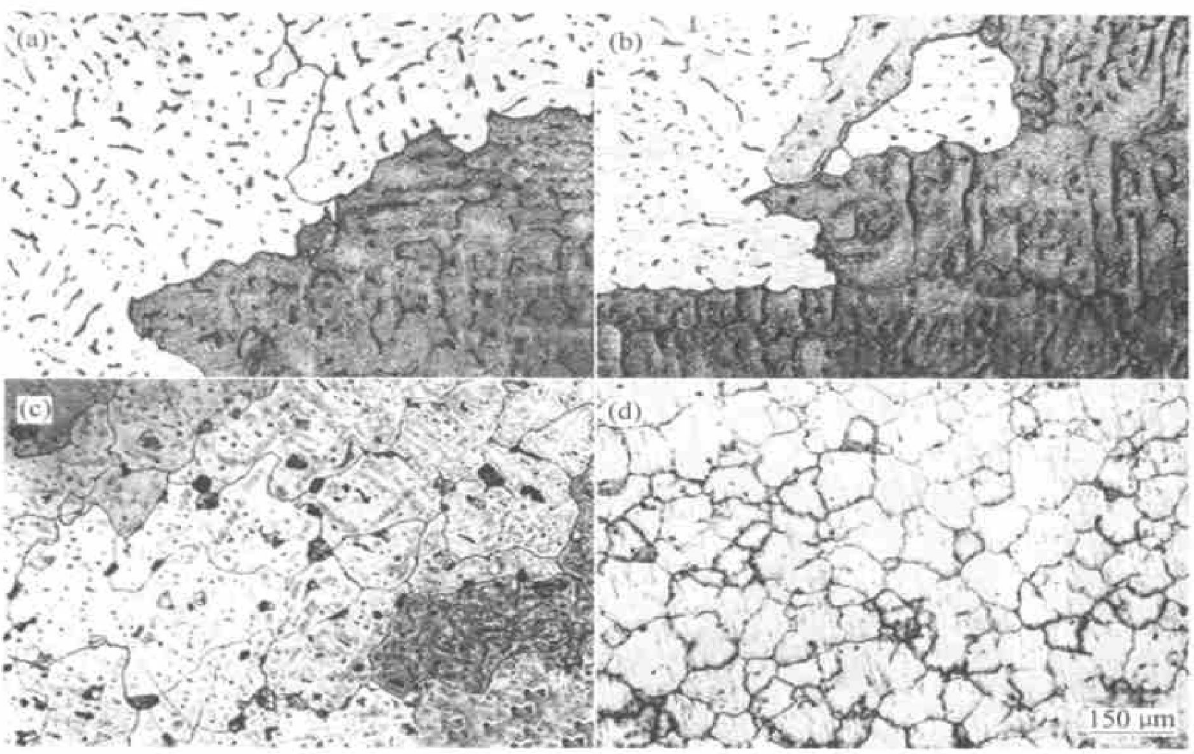

Fig. 1 Optical micrographs of as-cast alloys
(a) —Al-4Cu; (b) —Al-4Cu-0.1Sc; (c) —Al-4Cu-0.3Sc; (d) —Al-4Cu-0.5Sc

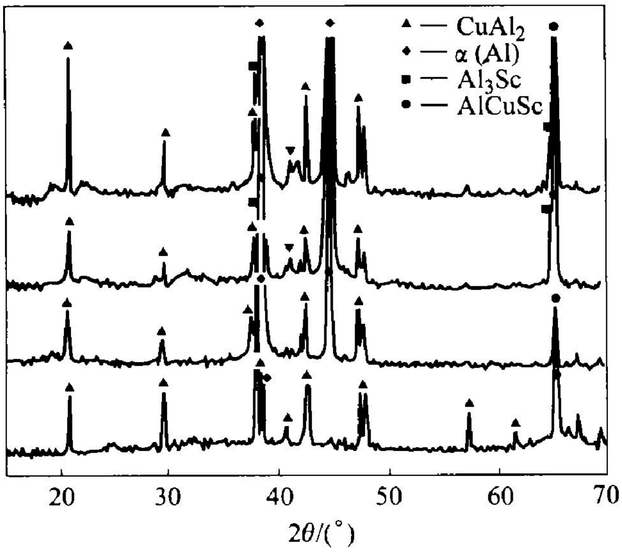

Fig. 2 XRD patterns of as-cast alloys
1 —Al-4Cu; 2 —Al-4Cu-0. 1Sc;
3 —Al-4Cu-0. 3Sc; 4 —Al-4Cu-0. 5Sc

tallizing process. This phase has influence on the properties of the alloys, but its structure is not clear yet[13, 14].

The results of SEM observation and point-located energy analysis of the as-cast Al-4Cu-0. 5Sc are shown in Fig. 3. It can be seen that there are small shining block-like phases at the boundaries (Fig. 3, labeled 1) and some shining particles within the grains of the alloy (Fig. 3, labeled 2). Through the energy analysis, it can be known that there are three elements, Al, Cu, and Sc in the small block-like phase, but only Al and Sc in the shining particles. Combined with the X-ray diffraction analysis results, it can be confirmed that the small block-like phase is AlCuSc phase and those shining particles are Al_3Sc phase, and the plate-like phase distributing at the interfaces and dendrite boundaries is the main strengthening phase of the Al-4Cu alloy, i. e. $CuAl_2$.

3. 3 Effects of Sc on tensile properties of alloys

The experimental data of the tensile properties of cold-rolled Al-4Cu and Al-4Cu-Sc alloys is shown in Table 1. The relationships between Sc addition and the strength of the alloys are illustrated in Fig. 4.

From Table 1 and Fig. 4, it can be known that adding Sc to the Al-40Cu alloy, the tensile

Table 1 Tensile properties of as-cold rolling Al-4Cu and Al-4Cu-Sc alloys

Properties	Al-4Cu	Al-4Cu-0. 1Sc	Al-4Cu-0. 2Sc	Al-4Cu-0. 3Sc	Al-4Cu-0. 4Sc	Al-4Cu-0. 5Sc
σ_b/MPa	229. 2	236. 0	249. 4	212. 4	199. 5	220. 6
$\sigma_{0.2}$/MPa	207. 7	216. 9	224. 5	202. 3	183. 1	198. 6
δ/ %	5. 7	6. 2	6. 3	5. 8	5. 7	5. 6

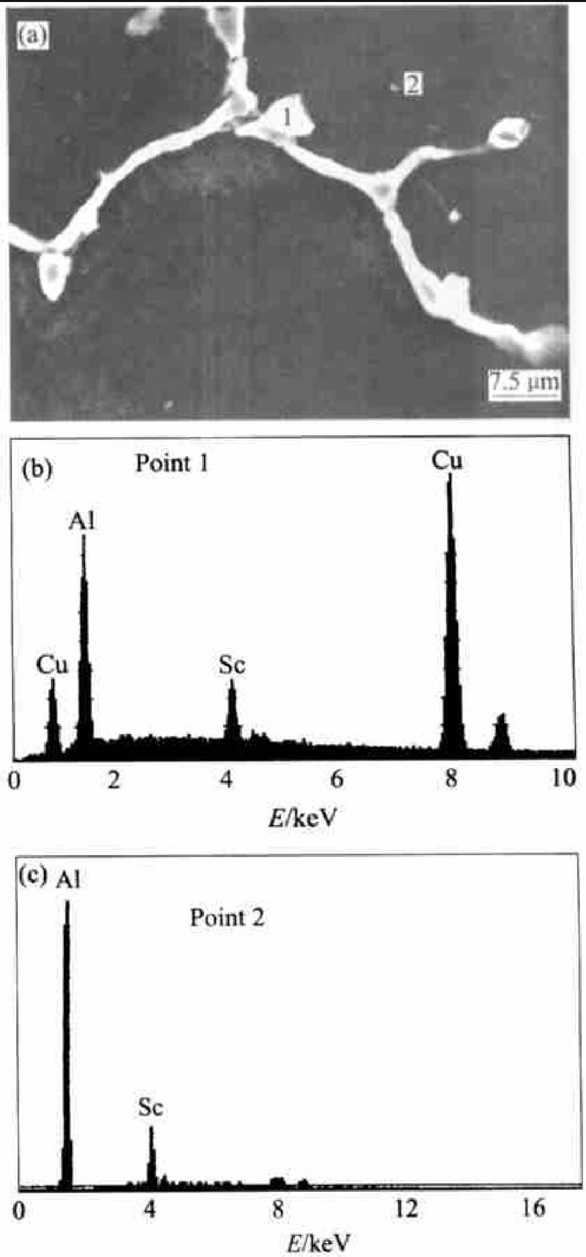

Fig. 3 SEM surface micrograph of as-cast Al-4Cu-0. 5Sc alloy and energy spectrum analysis

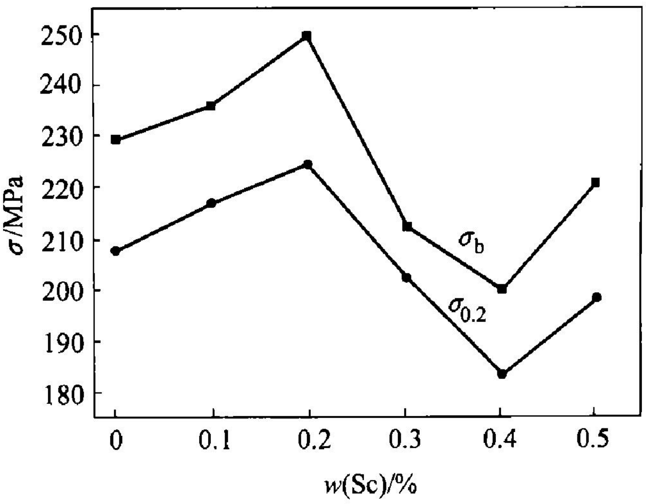

Fig. 4 Effect of Sc on tensile properties of as-cold rolling Al-4Cu alloys

strength σ_b and the yield strength $\sigma_{0.2}$ improve a little when the Sc content is lower than 0.2% ($\Delta\sigma_b$ being about 20 MPa); when the Sc content is in the range of 0.3%−0.4%, the tensile strength σ_b and the yield strength $\sigma_{0.2}$ of the alloys decrease a bit, but σ_b and $\sigma_{0.2}$ rise again when the Sc content reaches 0.5%, though both of them are lower than those of the Al-4Cu alloy without Sc addition. However, Sc addition has little influence on the elongation of the Al-4Cu alloy. This is because that when the Sc content is lower than 0.2%, element Sc does not form the Al_3Sc phase with element Al, and has no interaction with element Al and Cu to form the AlCuSc phase, but only enter the Al matrix(see Fig. 2), so it can strengthen the alloy at a certain degree. When the Sc content is 0.3%−0.4%, only a part of Sc enter the Al matrix, most of the Sc exists in the form of Al_3Sc and interacts with element Al and Cu to form the AlCuSc phase, which forms during the solidification and will not decompose in the subsequent heating treatment. Although the Al-4Cu alloy can be strengthened by the Al_3Sc phase, the main strengthening phase $CuAl_2(\theta)$ is relatively reduced due to the formation of AlCuSc which consumes element Cu in the alloy. Therefore, the strength of the alloy decreases. Comparing these two sides, the strength loss caused by the reduced main strengthening phase $CuAl_2(\theta)$ is bigger than the strength increment caused by the formation of Al_3Sc phase, so the tensile strength of the alloy decreases. When the Sc content reaches 0.5%, the strength of the alloy rises again because the strength increment caused by the formation of Al_3Sc phase is bigger than the strength loss caused by the formation of AlCuSc resulting in the decrement of the main strengthening phase $CuAl_2(\theta)$. As there is almost no necking in the samples during tensile tests, on the whole, only homogeneous plastic deforming(ε_B), little or no centralized deforming (ε_U) occurs in the range of standard space. According to Refs. [14, 15], ε_B mainly lies on the matrix phase state in metals, reflects the strengthening degree of the matrix phase, and is not sensitive to the secondary phase as well as not affected by the size of the grains. Adding Sc or not has little influence on the elongation of the studied alloy because the effect of grain refinement on the flow-change strain is almost the same as on the deforming strengthening.

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