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Effects of rare earth elements on microstructure and tensile properties of Al-Si-Cu alloy at 250 °C

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Abstract: The effects of rare earth elements (La, Sm) on the high-temperature (250 °C) microstructure and mechanical properties of Al-Si-Cu alloys were analyzed. The experimental results show that with the addition of La and Sm, the α-Al was significantly refined, and the eutectic Si changed from acicular to rod-like and granular. XRD and SEM analysis shows that the rare earth phases in the alloy were mainly AlSiRe and AlRe. Fracture morphology observations show the fracture mode of the alloy changes from brittle and ductile fracture to ductile fracture. With the increase of La or Sm contents, the mechanical properties of the alloys at 250 °C increase at first, and then decrease. When the contents of La and Sm are 0.4wt.% and 0.2wt.%, the tensile strength of the alloy reaches maximum of 143.91 MPa and 201.48 MPa, respectively.

Key words: Al-Si-Cu; rare earth element; microstructure; mechanical properties; high-temperature stretching

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1 Introduction

Al-Si-Cu alloy is widely used in various industries for its excellent strength, corrosion resistance, and die-casting performance [1-4]. However, the high-temperature properties (strength and elongation) of traditional Al-Si-Cu alloys are generally insufficient for high-end use, which restricts the wider application of Al-Si-Cu alloys.

It has been reported that the addition of rare earth elements could change the microstructures by refining the grain size of an AlCuMgSi cast alloy, changing the acicular and laminar eutectic Si to a granular phase, and with the increased addition of the rare earth, the tensile strength and elongation of the alloy firstly increased, then decreased [5]. Huang et al. [6] showed experimentally that the α-Al and eutectic Si crystals of ADC12 Al alloy were modified with the addition of La. Qiu et al. [7] found that Sm was capable of breaking down the primary α-Al phases in the near-eutectic Al-Si alloys, giving rise to an increase in the number of dendrites, and primary Si refinement and eutectic modification were achieved by addition of Sm. Hu et al. [8] showed that the shape of iron-rich phases in an Al-Si-Cu alloy changed from Chinese script-like form to slender form and the volume fraction of iron-rich phases was decreased by the addition of Sm. However, most of these studies were conducted at room temperature, and research concerning the effects of rare earth elements on the high-temperature structure and properties of Al-Si-Cu alloys remains sparse.

In the present study, the effects of rare earth elements La and Sm on the high-temperature microstructure and mechanical properties of die cast Al-Si-Cu alloy at 250 °C were investigated.

2 Experimental procedure

The Al-Si-Cu alloy was melted at 760–780 °C using an electric resistant furnace, then, rare earth elements in the form of Al-20wt.%La and Al-20wt.%Sm were added to the molten alloy. A DV-5 photoelectric direct reading spectrometer was used to measure the composition of the alloys (Table 1). The sample was die-cast by DCC400 horizontal cold chamber die-casting machine at 720 °C. The sample sizes are shown in Fig. 1.

The metallographic samples were processed using standard procedures, and a metallographic microscope (MR200) was used to observe the changes in compounds present in the alloys with or without rare earth elements. An etchant of HF: HNO_3: H_2O=3:2:95 was used to reveal the microstructure of polished specimens. The fracture morphology and phase constitution of the specimens were characterized by SU8020 scanning electron microscopy (SEM)

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Table 1: Compositions of Al-Si-Cu alloy

Alloys	Si	Cu	Fe	La	Sm	Al
Al-Si-Cu	11.00	3.12	0.76	-	-	
Al-Si-Cu+0.2wt.%La	10.83	3.05	0.74	0.21	-	
Al-Si-Cu+0.4wt.%La	10.75	3.22	0.63	0.37	-	
Al-Si-Cu+0.6wt.%La	11.16	2.95	0.67	0.65	-	Bal.
Al-Si-Cu+0.2wt.%Sm	10.95	3.28	0.64	-	0.18	
Al-Si-Cu+0.4wt.%Sm	10.84	2.88	0.79	-	0.45	
Al-Si-Cu+0.6wt.%Sm	10.77	3.01	0.71	-	0.63	

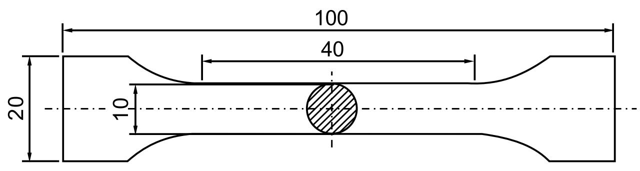

Fig. 1: Dimensions of tensile test specimen (unit: mm)

with energy dispersive spectrometry (EDS) and X-ray diffractometry (XRD). Tensile testing was conducted at a strain rate of 1 mm·min^{-1} after the specimens was heated to 250 °C and held for 20 min.

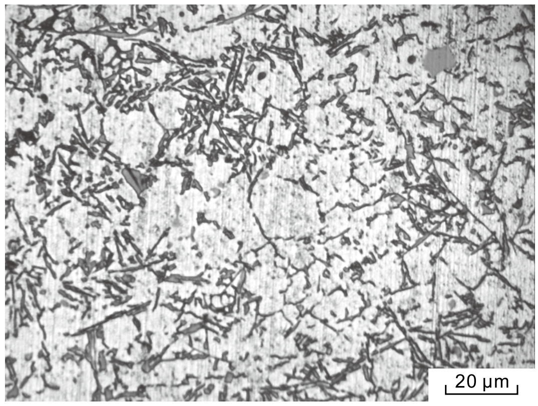

Fig. 2: Microstructure of Al-Si-Cu alloy at 250 °C

3 Results and discussion

3.1 Microstructural analysis

The metallographic structure of the unmodified alloy at 250 °C is shown in Fig. 2. The microstructure of the alloy mainly consists of α-Al, eutectic silicon, and Fe-rich phases. The α-Al is characterized by its typical dendritic shape, and the eutectic silicon morphology of the alloy is acicular with sharp edges. The Fe-rich phase, in either rod-like or strip-like forms, is distributed in a disorderly manner. Furthermore, there are some black holes in the structure, which would weaken the mechanical properties of the alloy.

The micrograph of the alloy with the addition of La is illustrated in Fig. 3. Compared with the unmodified alloy, it can be seen that, when the content of La is 0.2wt.%, the α-Al phase is refined, and the coarse dendritic α-Al dendrites are reduced, as shown in Fig. 3(a). As the content of La increases to 0.4wt.%, the α-Al in the alloy is the smallest in terms of grain size, and the secondary dendrite spacing is also the smallest [Fig. 3(b)]. When the amount of La is further increased to 0.6wt.%, the coarse α-Al appears again, as shown in Fig. 3(c). Figure 4 shows the effects of rare earth elements on the grain size of eutectic Si and α-Al in the alloy. It can be seen from Fig. 4(a) that when the La content is 0.4wt.%, the average area of the α-Al phase unit cell is the smallest, which is 54.27% lower than that in the unmodified alloy. With the addition of La, the morphology and size of the eutectic Si also change significantly. Compared with the unmodified alloy, when the La content is 0.2wt.%, the acicular eutectic Si phase decreases both in amount and size, as shown in Fig. 3(a).

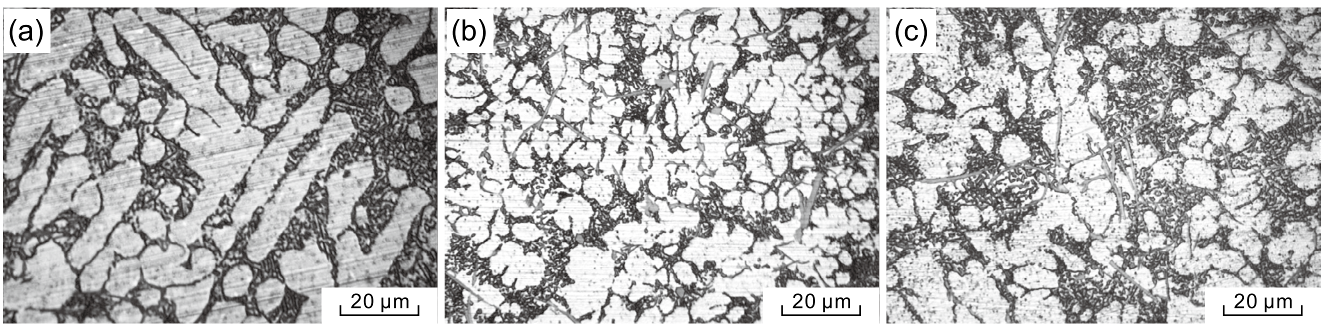

Fig. 3: Microstructures of alloys with La at 250 °C: (a) 0.2wt.%; (b) 0.4wt.%; (c) 0.6wt.%

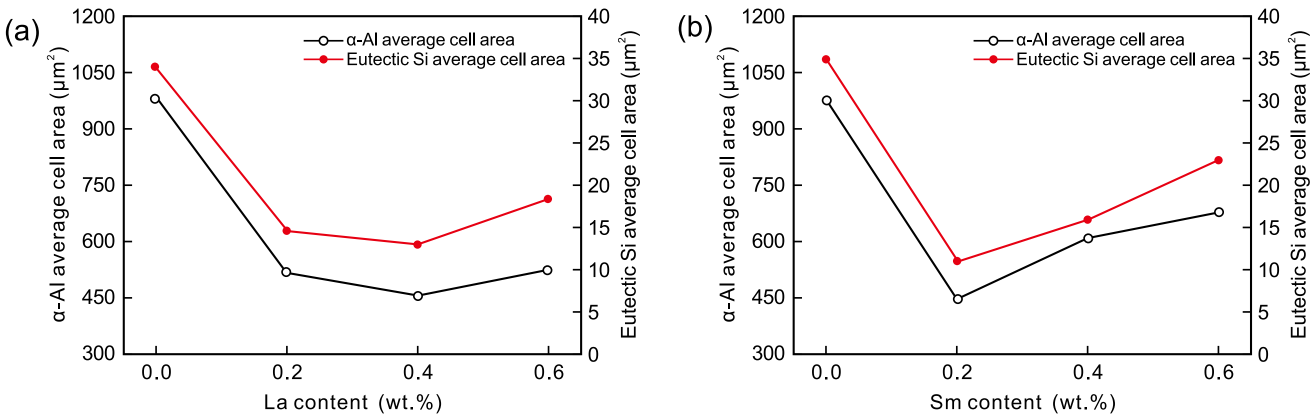

Fig. 4: Effects of rare earth elements on grain size of alloys with La (a) and Sm (b)

When the amount of La increases from 0.2wt.% to 0.4wt.%, the bulk of the primary silicon disappears, and the eutectic Si changes from acicular to rod-like or even granular. It can also be seen from Fig. 4(a) that, when the La content is 0.4wt.%, the average area of eutectic Si is 61.67% lower than that in the unmodified alloy.

Figure 5 shows the metallographic structure of the alloy with Sm. Compared with the alloy without RE modification, the morphology and size of α-Al and eutectic Si in the alloy with Sm modification are significantly changed. When the content of Sm is 0.2wt.%, the secondary dendrite spacing in the α-Al phase decreases significantly, and fine equiaxed grains appear; the eutectic Si phase is refined, and distributes uniformly in the form of fibers or short rods, as shown in Fig. 5(a). As the content of Sm is increased, the amount of coarse α-Al gradually increases, and that of the acicular eutectic Si also increases. It could be seen from Fig. 4(b) that when Sm content is 0.2wt.%, the average cell area of α-Al and eutectic Si is the smallest. Compared with the unmodified alloy, the average cell area of α-Al and eutectic Si is reduced by 57.27% and 70.21%, respectively.

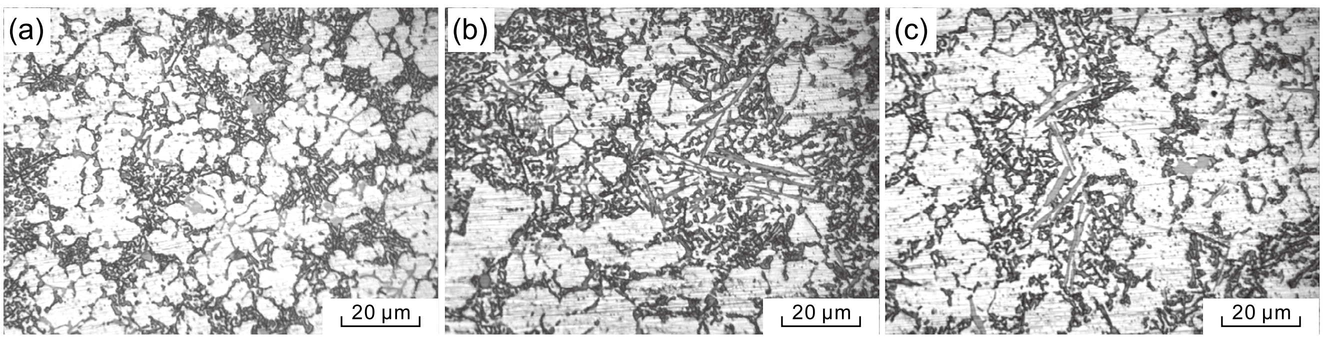

Fig. 5: Microstructures of alloys with Sm at 250 °C: (a) 0.2wt.%; (b) 0.4wt.%; (c) 0.6wt.%

Through the above analysis, it is found that La and Sm can refine the grains of the Al-Si-Cu alloy at 250 °C. The refinement of La and Sm is generally considered to be caused by undercooling. Huang et al. [6] pointed out that La was enriched at the front of solid-fluid interface during the solidification process, thereby forming constitutional supercooling, however, when the content of La was too high, the excess La would form intermetallic compounds in the alloy. These compounds would weaken the constitutional supercooling. Qiu et al. [7] showed that, when Sm was added to the alloy, the eutectic temperature declined which would increase the undercooling in such a binary Al-Si system; with the increase of undercooling, both the primary α-Al nucleation rate and the grain growth rate of the alloy increased, but the nucleation rate of α-Al was greater than that of grain growth, leading to an increase in the number of crystal nuclei in the alloy, thereby achieving grain-size refinement.

Figure 6 shows the diffraction pattern of the Al-Si-Cu alloys modified with different amounts of La and Sm addition. It can be seen from Fig. 6(b) that, compared to the alloy without modification, $Al_{11}Si_4La_2$ phase and $Al_{11}La_3$ phase appear in the alloy modified by 0.4wt.% La, while Al_4Sm and $Al_{13}Si_6Sm_2$ phases appear in the alloy with 0.2wt.% Sm.

The SEM micrographs of the Al-Si-Cu alloy with 0.4wt.% La and 0.2wt.% Sm at 250 °C are shown in Fig. 7. It can be seen from Fig. 7(a) that the α-Al grains of the unmodified alloy are light-grey blocks. The size of primary Si is relatively large, and the long acicular Al-Fe phase is coarse. In the alloy with 0.4wt.% La, the sizes of the light-grey blocky α-Al and the dark-black primary Si are much smaller, and the Al-Fe phase also changes from an acicular to a rod-like form, as shown in Fig. 7(b). In the alloy modified by 0.2wt.% Sm, the grain

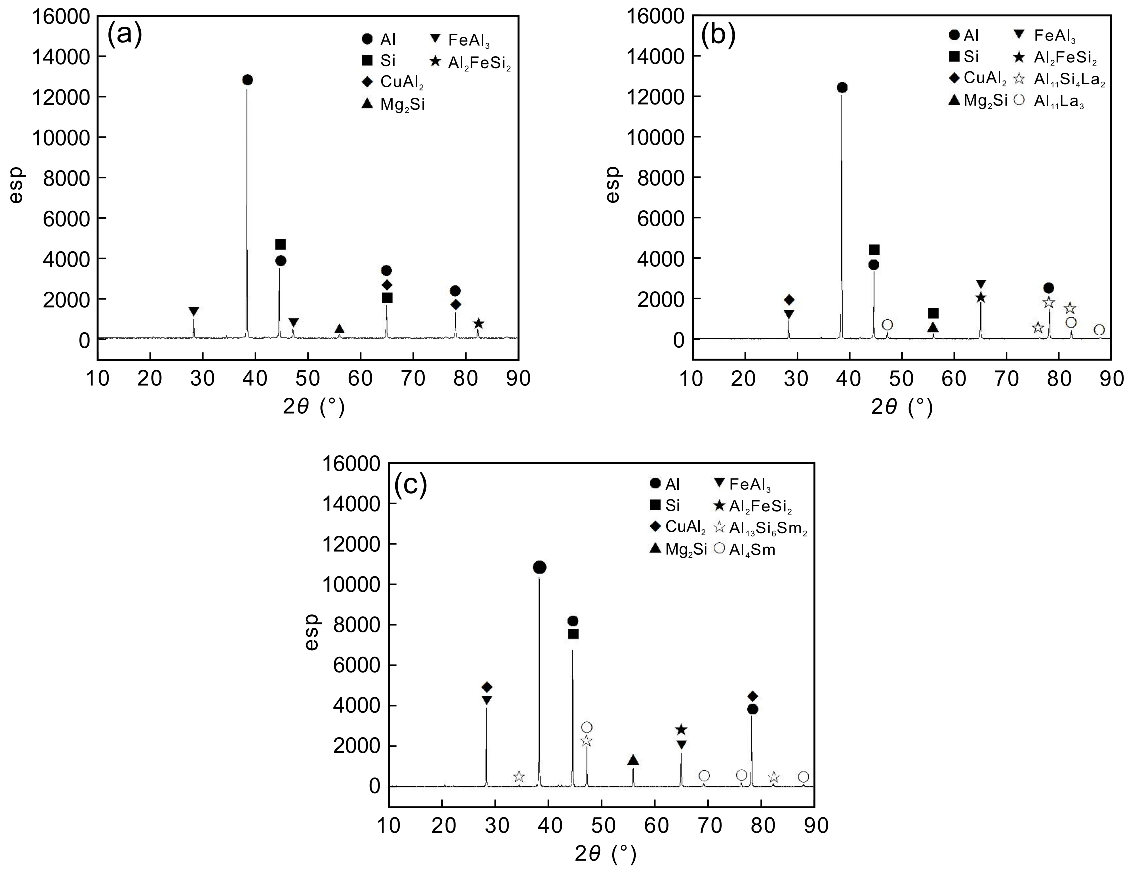

Fig. 6: XRD patterns of Al-Si-Cu alloy: (a) without modification; (b) 0.4wt.% La; (c) 0.2wt.% Sm

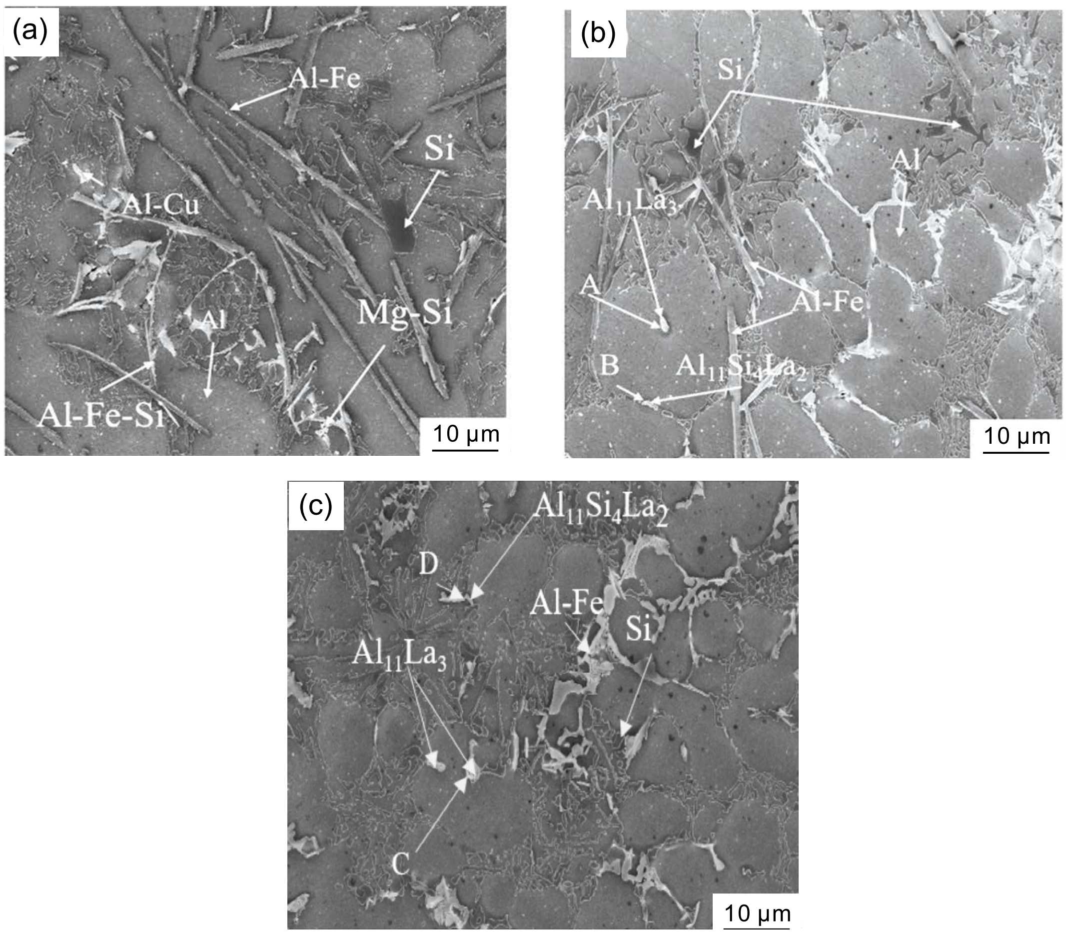

Fig. 7: Morphologies of Al-Si-Cu alloy at 250 °C: (a) without modification; (b) 0.4wt.% La; (c) 0.2wt.% Sm

refinement of α-Al is more obvious, and the primary Si is fine block-like, and granular. The coarse acicular Al-Fe phase is refined into short rods [Fig. 7(c)]. Compared with the Al-Si-Cu alloy without modification, bright white round or strip-like $Al_{11}La_3$ and grey strip-like $Al_{11}Si_4La_2$ appear in the alloy containing 0.4wt.% La. Similarly, the new phases in the alloy modified with 0.2wt.% Sm are bright white granular Al_4Sm and light-grey blocky $Al_{13}Si_6Sm_2$. Points A, B, C, and D in Fig. 7 were quantitatively studied by EDS, and the results listed in Table 2 are found to be consistent with the XRD. It was worth mentioning here that similar $Al_{11}La_3$ phases were observed in ADC12 alloy by Huang et al. [6], in which $Al_{11}La_3$ cannot only affect the mechanical properties of the alloy at room temperature, but also at high temperature, due to its thermal stability. Hu et al. [8] observed the Al_8SiSm phase in their study of the effects of Sm on the structure and properties of Al-Si-Cu alloys. Similarly, Tsai et al. [9] observed an AlSiLa phase in their report on the influence of La on the microstructures and mechanical properties of A356 alloy. It can be found that the rare earth phases in the alloy are relatively small, and most of them are distributed at the grain boundaries. Wang et al. [10] pointed out that the rare earth phase at the grain boundary could hinder the growth of crystal grains, thereby achieving grain refinement.

3.2 Fracture morphology analysis

Figure 8 shows the fracture morphology of the unmodified alloy after fractured at 250 °C. The fracture morphology shows dimples of different sizes and uneven distribution, but there are still large cleavage planes and coarse tearing ridges, accompanied by trans-crystalline rupture. The fracture is mainly ductile fracture accompanied by brittle fracture.

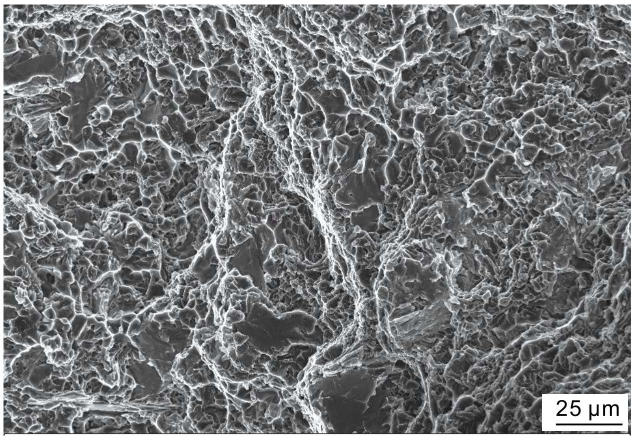

Fig. 8: Fracture morphology of Al-Si-Cu alloy after fracture at 250 °C

Figures 9 and 10 show the fracture morphologies of the alloys modified with different amounts of Sm or La. With the addition of La or Sm, the number of dimples and tearing edges in the fracture surface increase, and the cleavage surface almost disappears. Only in the alloy with 0.6wt.% Sm, does a few smooth sliding platform steps appear, at this time, the fracture mode is the combination of ductile fracture and brittle fracture, as shown in Fig. 9(c). When the Sm content is 0.2wt.% and 0.4wt.%, the fractures are completely composed of torn edges and dimples, which are typical of ductile fracture. When the Sm content is 0.4wt.%, the fracture morphology of the sample is the optimal, torn edges are uniformly distributed in the shape of short rods, and the dimples are deep, uniformly distributed circles, as shown in Fig. 9(b). It can be seen from Fig. 10 that the number of torn edges and dimples in the modified alloy increases with the increasing La content, and when the La

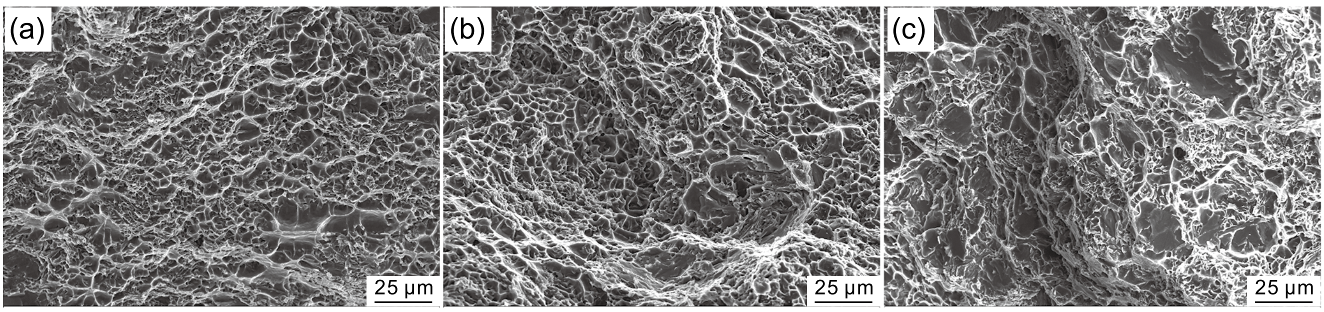

Fig. 9: Fracture morphologies of alloys with different Sm contents at 250 °C: (a) 0.2wt.%; (b) 0.4wt.%; (c) 0.6wt.%

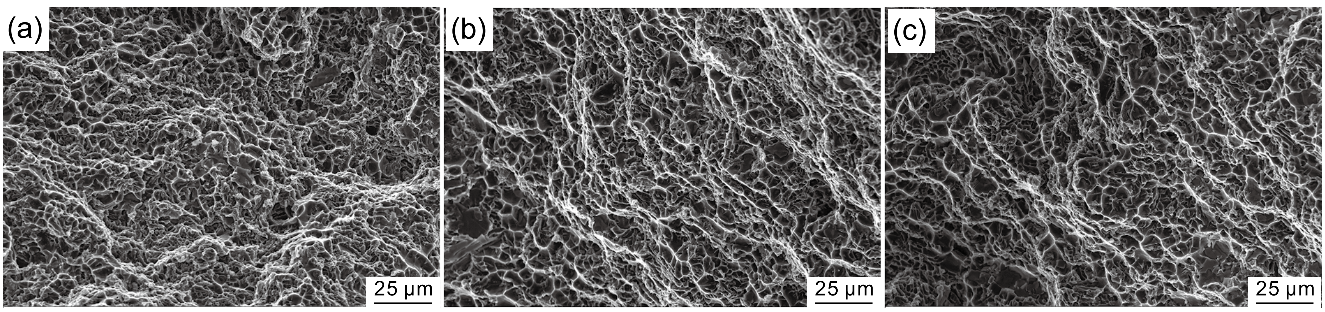

Fig. 10: Fracture morphologies of alloys with different La contents at 250 °C: (a) 0.2wt.%; (b) 0.4wt.%; (c) 0.6wt.%

content is 0.6wt.%, the number of dimples and torn edges is the maximum and their distribution is the most uniform, as shown in Fig. 10(c). In conclusion, La and Sm can improve the fracture morphology of the alloy. When the added amounts of Sm or La are 0.4wt.% or 0.6wt.%, respectively, the fracture morphology of the alloy is optimized, and the macroscopic performance affords greater elongation and an improved plasticity. It can be seen that La and Sm can refine the grains in the alloy and improve the plasticity of the alloy; however, when the content of rare earth elements is too high, the second phase would agglomerate, causing stress concentration. So, the effects of rare earth elements on the fracture of the alloy are quite different under high temperature and room temperature. It is inferred that, at high temperature, the unstable rare earth phases which are formed by rare earths and alloying elements are recombined to form stable and fine rare earth phases, such as $REAl_2$, RE_3Al_{11}, $REAl_4$. Dispersion of these stable rare earth phases in the alloy structure played a role in pinning dislocations, thereby enhancing the ability of the alloy to resist plastic deformation, and weakening the plasticity of the material [11-12].

3.3 Tensile properties

Figure 11 shows the effects of La and Sm on the tensile properties of the alloy at 250 °C. It could be seen from Fig. 11 that La and Sm significantly improve the mechanical properties of Al-Si-Cu alloys. The tensile strength of the alloy reaches maximum of 143.91 MPa and 201.48 MPa when the La content is 0.4wt.% and Sm is 0.2wt.%, respectively, which are 27.87% and 79.01% higher than that of the unmodified alloy. It is well known that the tensile properties of Al-Si alloys mainly depend on the size and morphology of α-Al and eutectic Si in the alloy [13]. Through the above experiments and analysis, it can be found that when the La and Sm contents are 0.4wt.% and 0.2wt.%, respectively, the morphology and size of α-Al and eutectic Si in the alloy are optimal. The addition of La or Sm in the alloy cannot only reduce the degree of supercooling of the alloy, but also form rare earth phases at the solid-liquid interface to hinder the growth of the grains, ultimately leading to grain refinement. In general, as the content of La or Sm increases, the tensile strength and elongation of the alloy increase at first, and then decrease. When the rare earth elements present in excessive amounts, the resulting rare earth compounds could not form a crystal nucleus to prevent grain growth in the subsequent crystallization process, but form transgranular and intergranular mixed distribution brittle phases [9,14].

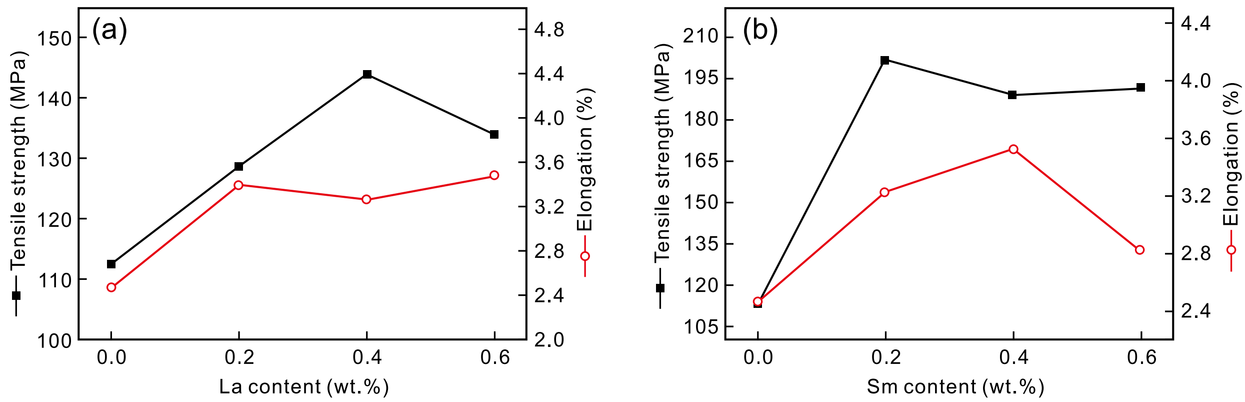

Fig. 11: Effects of La and Sm on tensile properties of alloys at 250 °C

4 Conclusions

The effects of La and Sm on the high-temperature microstructure and tensile properties of Al-Si-Cu alloys were investigated. The following conclusions can be drawn:

(1) At 250 °C, La and Sm could improve the morphology and decrease the size of α-Al and eutectic Si phases. When the contents of La and Sm are 0.4wt.% and 0.2wt.%, respectively, the grains in the alloy are the finest. SEM and XRD test results show that the rare earth phases in the alloy are dominated by AlSiRe and AlRe.

(2) Appropriate additive doses of La and Sm could change the fracture mode of the alloy from ductile and brittle mixed fracture to ductile fracture. When the added amounts of La and Sm are 0.6wt.% and 0.4wt.%, respectively, the fracture edges are evenly distributed in the shape of short rods, the number of dimples is the maximum, and the fracture morphology of the alloy is optimized (the plasticity of the alloy is also the optimal).

(3) La and Sm can significantly improve the tensile properties of the alloy at 250 °C. As the additive content increases, the tensile strength of the alloy at 250 °C firstly increases, and then decreases. When the amounts of added La and Sm are 0.4wt.% and 0.2wt.%, respectively, the tensile strength reaches maximum of 143.91 MPa and 201.48 MPa, respectively.

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