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Microstructure and mechanical properties of Gd-modified A356 aluminum alloys

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Abstract: The effect of Gd modification on the microstructure and mechanical properties of A356 aluminum alloys was investigated using the metallurgical microscopy, scanning electronic microscopy, X-ray diffraction and mechanical testing. The addition of 0.2 wt.%–0.4 wt.% Gd had an excellent refining effect on primary α-Al grains and a modification effect on Si phases in its as-cast state. The needle-like Si phases were adjusted into fine particles and uniformly distributed in the matrix by the T6 treatment, especially for the 0.2 wt.% Gd-modified alloy. The Gd additions introduced the Fe-containing $GdAl_2Si_2$ compounds, which precipitated in the forms of flakes and bulks. The $GdAl_2Si_2$ and β-Al_5FeSi phases were also refined by the T6 treatment. The mechanical properties of the Gd-modified alloys were very poor in as-cast state; however, the highest strength and elongation were obtained for the 0.2 wt.% Gd-modified alloy by the T6 treatment.

Keywords: rare earths; modification; aluminum alloy; microstructure; mechanical property

A356 aluminum alloy is increasingly used in the fields of automotive, military and aerospace industries. To improve its mechanical property, the grain refinement and Si modification techniques were used. The refining effect of the Al-Ti, Al-Ti-B and Al-Ti-C master alloys[1,2] and the modification effect of the Al-Sr master alloy were substantially reported[3,4].

The effects of rare earth (RE) elements on the Al-Si-Mg alloys have received great attention. Tsai et al.[5,6] found that the addition of La less than 1.0 wt.% resulted in a full modification of the eutectic Si phases; however, the tensile strength was not improved because of the introduced brittle Al-Ti-La-Mg and Al-Si-La compounds; the addition of 1.0 wt.% Ce made the plate-like eutectic silicon transform into small and nodular shapes and resulted in the best modification and properties. Zhu et al.[7] observed that 0.1 wt.%–1.0 wt.%Ce-rich mischmetal modification made the α-Al grains coarsen; more than 0.3 wt.% additions yielded the full modification effect, however, the tensile strength and ductility were decreased because of the coarsened α-Al grains and the RE-containing compounds. Dong et al.[8] noticed that the Y addition increased the size of α-Al grains due to the precipitated Al_3Y compounds. Patakham et al.[9] confirmed that the Sc addition refined the α-Al grains because the precipitated Al_3Sc can act as heterogeneous nucleation sites; however, it has a much weaker effect on the eutectic silicon morphology. Hu et al.[10] and Gao et al.[11] found the refining effect of Er-modification for the die-cast ADC12 Al-Si-X alloy and the pure aluminum respectively; because the Al_3Er particles that precipitated in the grain boundaries inhibited the growth of the α-Al grains. Xing et al.[12] found that the addition of 0.3 wt.% Er refined the microstructure, changed the size and shape of the eutectic Si, and improved the anti-wear properties of the Al-12.6 wt.%Si alloys. Xu et al.[13] concluded that the Nd addition can modify the primary and eutectic silicon in a hypereutectic Al-Si alloy.

The RE elements have different physicochemical properties to some extent. It has been found that the gadolinium (Gd) addition has a reefing effect on the primary α-Al grains and modifying the eutectic Si[14]. The present work was to further investigate the effects of Gd modification on the microstructure and mechanical properties of the A356 aluminum alloy in as-cast and T6 states.

1 Experimental

A356 aluminum alloy ingot (7.1 wt.%Si, 0.45 wt.%Mg, 0.12 wt.%Fe) and master alloy (Al-10 wt.%Gd) were used as raw materials. The ingot (10 kg) was melted in an induction furnace at 760 ºC. Different amounts of the master alloys were added to form samples with different Gd contents (0.1 wt.%, 0.2 wt.%, 0.3 wt.% and 0.4 wt.%). An N_2 gas purification technique was used to eliminate gases and inclusions in the melts for 5 min. When the temperature decreased to 730 ºC, the melts were stewed

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for 5 min and then poured into a preheated steel mold (250 ºC, wall thickness 20 mm) through a pre-heated porous ceramic filter with a pore size of 1 mm. The size of the formed ingots is 20 mm(thickness)×120 mm (height)×150 mm(width). The ingots were cooled to room temperature in the mold. The samples were then treated with a standard T6 schedule. The ingots were cut along the longitudinal symmetric plane by an electric spark cutting method and machined into standard tensile bars with a working diameter of 10 mm.

The microstructure was observed with a metallurgical microscope (OLYMPUS-GX51), and the average size of the grains and the average aspect ratio of the Si phases were statistically calculated by quantitative analysis software against 20 fields. The composition of phases was detected by a scanning electronic microscope (SEM, S3400-N, Hitachi) with an energy dispersive spectrometer (EDS, 7021-H, HORIBA). The surfaces of the samples used for the observation were polished and etched by an HF (5 wt.%)-alcohol solution. The phase composition was analyzed by an X-ray diffractometer (XRD, D/MAX-2500/PC, PIGAKV) using copper Kα radiation at 40 kV, 200 mA and at a scanning speed of 1(°)/min. The mechanical properties were examined using a material test machine (Jinan SHT4605) with a loading speed of 5.0 mm/min. The hardness (HV) was tested by a hardness tester (HVS-30Z\LCD, Huayin); five samples for each group were measured to obtain the average values.

2 Results

2.1 Microstructure of Gd-modified alloys

Fig. 1 shows the microstructure of different contents of Gd-modified A356 alloys in the as-cast state. It can be observed that additions of 0.2 wt.%–0.4 wt.% Gd refined the α-Al grains and yielded the short rods and particles of eutectic Si (Fig. 1(b–d)). The refinement effect was gradually enhanced with an increase of the Gd content. By the T6 treatment, the fraction of the fine particles of Si phases was greatly increased for the 0.2 wt.%Gd-modified alloys (Fig. 2(b)). However, further increase in the content up to 0.3 wt.%–0.4 wt.% made the Si phases coarsen again.

Table 1 shows the statistical results of the size and morphology of the α-Al grains and Si phases. It can be observed that 0.2 wt.%Gd-modified alloy has the smallest size of the α-Al grains and Si phases; the roundness of the Si phases is the best for the 0.2 wt.%Gd-modified alloys in the T6 state.

The Gd-modification introduced the $GdAl_2Si_2$ phases (Fig. 3), which are present in the form of bulks and flakes (bright phases) as shown in Fig. 4(a) and they were changed into small bulks and short flakes by the T6 treatment (Fig. 4(b)). According to the EDS analysis (Fig. 5), it was found that the Si elements dissolved little in the α-Al matrix; Gd could not dissolve in α-Al and Si phases. Moreover, the Gd-containing β-Al_5FeSi phase (position D) was identified (Fig. 4(a)) and it was changed into the very fine and dispersive particles (position H) by the heat

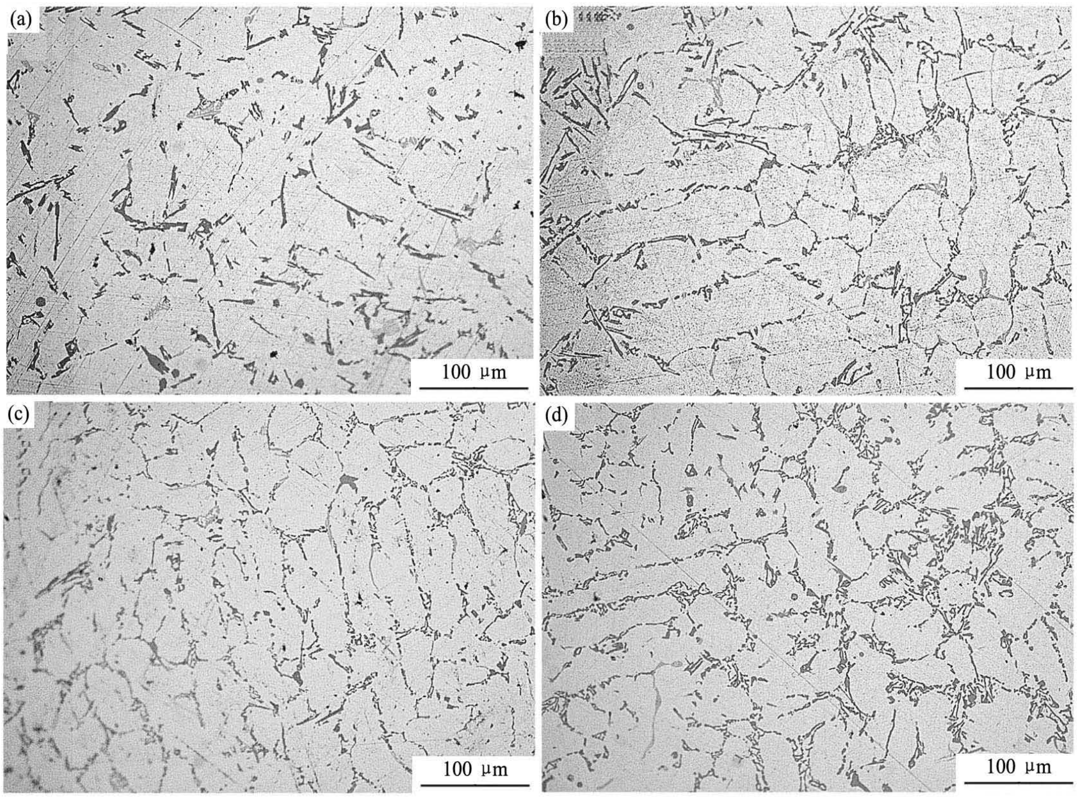

Fig. 1 Microstructure of Gd-modified A356 alloys in as-cast state
(a) 0.1 wt.%; (b) 0.2 wt.%; (c) 0.3 wt.%; (d) 0.4 wt.%