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Effects of ultrasonic vibration and manganese on microstructure and mechanical properties of hypereutectic Al–Si alloys with 2%Fe

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The effects of ultrasonic vibration (USV) on the microstructure and mechanical properties of Al–17Si–2Fe–2Cu–1Ni (mass %) alloys with 0.4% or 0.8% Mn were studied. The results show that the average grain size of primary Si in the alloys treated by USV could be refined to 21–24 μm, whether with or without P modification. The P addition has no further refinement effect on the primary Si in the case of the combined use of USV with P addition. Without USV, the alloy with 0.4%Mn contains a large amount of long needle-like β-$Al_5(Fe,Mn)Si$ phase and coarse plate-like δ-$Al_4(Fe,Mn)Si_2$ phase. Besides, the alloy with 0.8% Mn contains a small amount of coarse dendritic α-$Al_{15}(Fe,Mn)_3Si_2$ phase. With USV treatment, the Fe-containing compounds in the alloys are refined and exist mainly as δ-$Al_4(Fe,Mn)Si_2$ particles with average grain size of about 18 μm, and only a small amount of β-$Al_5(Fe,Mn)Si$ phase is remained. With USV treatment and without P modification, the ultimate tensile strengths (UTS) of the alloys containing 0.4% and 0.8% Mn are 271 MPa and 289 MPa respectively at room temperature, and the UTS are 127 MPa and 132 MPa at 350 °C. The Brinell hardness of the alloys are 131 HB and 139 HB respectively. It is considered that the modified morphology and uniform distribution of the Fe-containing intermetallic compounds and the primary Si phases, which are caused by USV process, are the main reasons for the increase of the tensile strength and hardness of these two alloys.

1. Introduction

Iron is the most common and detrimental impurity element in aluminum casting alloys. The coarse needle-like or plate-like Fe-containing intermetallic compounds, which are very hard and brittle and have a relatively low bond strength with the matrix, are detrimental to the mechanical properties [1,2]. Iron is usually unintentionally added to the molten metal through the use of iron tools during melting and casting or through the use of scrap materials containing iron. The raw materials such as aluminum and silicon used for the preparation of alloys also contain a certain unavoidable amount of iron [3].

Hypereutectic Al–Si alloys are widely used for making light-weight components such as engine blocks, pistons and cylinder liners, because of their good wear resistance, low thermal expansion coefficient and high heat resistance [4,5]. Adding alloy elements such as Cu and Mg to hypereutectic Al–Si alloys can only improve the room mechanical properties through forming the precipitation hardening phases. It has been reported that the Fe-containing intermetallic compounds such as δ-Al_4FeSi_2 and β-Al_5FeSi phases are relatively stable at temperature up to 300 °C [6]. Therefore, the Fe-containing intermetallic compounds with high melting point formed in hypereutectic Al–Si alloys can improve the mechanical properties at elevated temperature. The morphology of the Fe-containing intermetallic compounds plays a most important role in determining the mechanical properties of the alloys. Thus, if the Fe-containing intermetallic compounds can be refined into fine particles, the scrap of aluminum alloy containing large amounts of iron can be used as a raw material, and the full potential of hypereutectic Al–Si alloys with high Fe content will be exploited.

Numerous researches have focused on the refinement of iron-rich phases in A1–Si alloys. Investigations show that the Fe-containing intermetallic compounds can be modified by rapid solidification process [7] and melt superheating [3]. However, applications of these processing are limited because of the costly equipment and complicated process. Mn is the most common alloying element, which is used to modify the morphology of Fe-containing intermetallic compounds in high Fe cast Al–Si alloys. The Mn is often added at a Mn:Fe ratio of at least 0.5, but some β-Al_5FeSi still form, even when %Mn>%Fe [1]. Furthermore, the use of Mn to neutralize the effect of Fe will lead to continual increase of

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transition metals in scrap materials. Thus, for sustainable recycling of aluminum casting alloys, addition of neutralizing elements should be as low as possible.

The treatment of molten aluminum and its alloys using ultrasonic vibration (USV) is a relatively new environmentally safe technology with uncomplicated process and low cost. It has been proved that USV can effectively modify the primary α-Al and Si in hypoeutectic and hypereutectic Al–Si alloys respectively [8–10]. Recently, Osawa et al. [11] studied the effect of USV on the morphological changes of Fe-containing intermetallic compounds of the Al–xSi–4Fe (x = 6,12,18 mass%) alloys, and the results show that the Fe-containing intermetallic compounds are refined after USV treatment, with the average equivalent diameter ranging from 59 μm to 77 μm. However, the mechanical properties of the Al–xSi–4Fe alloys treated by USV have not been investigated yet. Zhong et al. [12] studied the effect of USV on the morphology of Fe-containing intermetallic compounds of high silicon alloy with 2%Fe, the results show that the Fe-containing phases are refined to rectangle shape particles with a size of 20–30 μm. And the tensile strengths of the Al–20Si–2Fe–2Cu–0.4Mg–1.0Ni–0.5Mn alloy produced by rheo-casting at the room temperature and 300 °C are 230 MPa and 145 MPa, respectively [13]. Nevertheless, the tensile strength of the alloy at room temperature still cannot meet the application requirement.

The present study aimed to investigate the effects of USV on the microstructure and mechanical properties of Al–17Si–2Fe–2Cu–1Ni (mass %) alloys with 0.4% or 0.8% Mn. And a comparative study between the effect of USV and Mn addition on the Fe-containing intermetallic compounds was also performed. In addition, the mechanism of the effect of USV on the morphology of Fe-containing intermetallic compounds was also discussed.

2. Experimental procedure

The installation of USV in reference [9] was employed in this experiment. It consists of ultrasonic generator, ultrasonic vibrator composed of firmly connected transducer and amplitude transforming rod, vibrator holder, heating furnace, PID temperature controller, metal cup, etc. The vibrating time, rest-work ratio in a vibration cycle, and power of the ultrasonic vibrator could be adjusted by the ultrasonic generator. The rest-work ratio R_t of vibration was defined as the ratio of interval resting time T_r to ultrasonic time T_w in an ultrasonic vibration cycle, i.e., $R_t = T_r/T_w$. $T_r = 1.0$ s and $T_w = 1.0$ s were selected in this study. The ultrasonic vibrator was made with titanium alloy. The metal cup, with a diameter of 71 mm and a height of 130 mm, was made with stainless steel. The preheating and isothermal holding temperatures were controlled by the PID temperature controller. The temperature of the melt in the metal cup was measured with a thermocouple. The applied ultrasonic power in this study was 1.6 kW, and the frequency of USV was 20 kHz.

The chemical compositions of the Al–17Si–2Fe–2Cu–1Ni alloys with different Mn additions were listed in Table 1. The alloys used were prepared with raw materials of Al-25.8%Si (mass%, the same in the following) and Al-10% Mn master alloys, commercial pure aluminum (99.8%), pure Fe (99.9%), pure Cu (99.99%), pure Ni (99.99%) and pure Mg (99.9%). The liquidus and the solidus temperatures of A1 alloy which were determined by DSC, are about 653 °C and 543 °C respectively.

The materials were melted in a resistance furnace at 820–850 °C with modification of 0.08% P in the form of Cu-14%P. And the melt was degassed for 10 min with argon gas through a graphite lance. The melt was cooled down to a temperature of 750–780 °C after degassing. In order to study the effect of USV on primary Si, the melt without P addition was also prepared with the same process. The metal cup was preheated to 530–550 °C by the heating furnace. Subsequently, about 600 g liquid metal was poured into the preheated metal cup. The USV was then applied on the melt with the ultrasonic vibrator immersed into the melt 15–20 mm in depth when the liquid metal cooled down to the predetermined temperature. The starting temperature of USV was 665 °C, and ending temperature was 640 °C. The USV treatment time was 1.5 min. After the melt was treated with USV for a certain time, the semi-solid slurry with a certain solid fraction was obtained. The slurry was immediately poured into a cast iron mold preheated at 200 °C to get tensile samples with diameter of 8 mm. The schematic of casting and tensile samples is shown in Fig. 1. For comparison, conventional casting samples were also made without USV treatment under a pouring temperature of 750 °C. Half of the samples were heat treated with T6 process (solution treatment at 510 °C for 7 h, followed by water quenching, then artificial aged at 190 °C for 10 h).

Specimens for the metallographic examination were cut from the ends of tensile test samples, then grinded, polished and etched by solution with 5% sodium hydroxide. The microstructures were examined using an Axiovert 200MAT optical microscope. Micrographs of the specimens were analyzed using a quantitative metallographic analysis software. Phase constitution and composition of different phases were studied by Quanta 200 Environmental Scanning Electron Microscope (SEM) fitted with an Energy Dispersive X-ray Spectroscopy (EDX). X-ray diffraction (XRD) analysis was carried out with an X'Pert PRO diffractometer. The room temperature tensile tests were conducted on a WDW3200 tester while the elevated temperature tests were performed on an SHIMADZU AG-IC tester. The average ultimate tensile strength

Table 1
Chemical compositions of the hypereutectic Al–Si alloys (mass%).

Alloy	Si	Cu	Fe	Ni	Mg	Mn	Al
A0	17	2	0.23	1	0.4	0.4	Balance
A1	17	2	2	1	0.4	0.4	Balance
A2	17	2	2	1	0.4	0.8	Balance

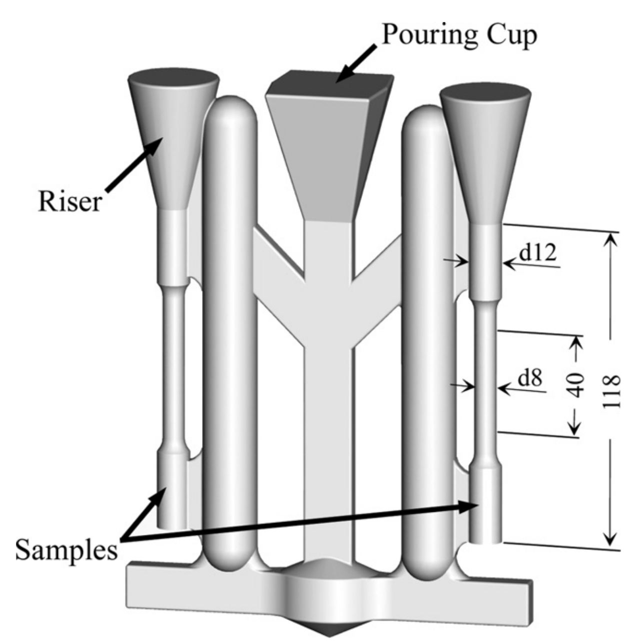

Fig. 1. The schematic of casting and tensile samples (unit: mm).