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Microstructures and mechanical properties of squeeze cast Al–5.0Cu–0.6Mn alloys with different Fe content

WeiWen Zhang *, Bo Lin, DaTong Zhang, YuanYuan Li

School of Mechanical and Automotive Engineering, South China University of Technology, Guangzhou 510640, China

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ABSTRACT

The microstructures and mechanical properties of gravity die cast and squeeze cast Al–5.0 wt% Cu–0.6 wt% Mn alloys with different Fe content have been studied using tensile test, optical microscope, scanning electron microscope, electron probe micro-analyzer and image analysis. The results show that four kinds of Fe-rich intermetallics may present in the final microstructures of the alloys: Chinese script α-Fe ($Al_{15}(FeMn)_3(CuSi)_2$) and $Al_6(FeMn)$, needle-like β-Fe(Al_7Cu_2Fe) and $Al_3(FeMn)$ when the Fe content increases from 0.1 wt% to 1.5 wt%. In the gravity die cast alloy with 0.5 wt% Fe, the Chinese script α-Fe presents as the main Fe-rich intermetallics, and a few needle-like β-Fe also exist. When the Fe content increases to 1.0 wt%, the main Fe-rich intermetallics change to needle-like $Al_3(FeMn)$ and Chinese-script $Al_6(FeMn)$. The needle-like β-Fe disappears when the Fe content is 0.5 wt% in the squeeze cast alloy with an applied pressure of 75 MPa. Furthermore, the secondary dendritic arm spacing of α(Al), the percentage of porosity and the volume fraction of the second intermetallics decrease distinctly in the squeeze cast alloy compared to the gravity die cast alloy. There is a peak value of ultimate strength and yield strength for the alloy with 0.5 wt% Fe. The elongations of the alloys decrease gradually with increasing Fe content and the elongation of the squeeze cast alloys is two times more than that of the gravity die cast alloys.

1. Introduction

As one kind of high strength and toughness aluminum alloys, Al–Cu cast alloys are widely used in transportation, aerospace and military industry owing to their excellent mechanical and physical properties. However, the tolerance of Fe content in Al–Cu alloy is very poor. For example, in the 206 cast alloy family, the maximum Fe content is usually limited to 0.15% (206.0) or less 0.10% for (206.2) for general purpose use. In the aerospace applications, the Fe content is even required below 0.07% (A206.2) [1] (all compositions quoted in this work are in weight percent unless indicated otherwise). It is difficult to control and remove iron impurity, since iron may originate from (1) iron tools and equipments used during melting, transferring and casting processes; and (2) metal charges including primary metal, master alloys and recycled aluminum alloys. Nowadays, the recycled aluminum alloys have become the main melting charge in aluminum industry for the purpose of energy saving and environment protection. The recycled aluminum alloys usually contain high content of impurity Fe, and it will accumulate during recycling [2,3]. Therefore, developing high performance cast Al–Cu alloy with high tolerance of Fe contents has become a great challenge.

In order to reduce the detrimental effect of iron in Al–Cu alloy, the solidification of Fe-rich intermetallics and its effect on mechanical properties are widely investigated. Backerud et al. [4] and Talamantes-Silva et al. [5] found only one needle-like Fe-rich intermetallic phase, named as β-Fe(Al_7Cu_2Fe) in the A206 alloy at low level of iron (<0.1%). Jacob and Fontaine [6] also pointed out that the needle-like shape compound of β-Fe(Al_7Cu_2Fe) formed in Al–5% Cu(0.23% Fe), and the Chinese script $Al_3(CuFe)$ compound formed when the Fe content reached 0.55%. It is well known that Mn can change the needle-like Fe-rich intermetallics into the Chinese script in cast Al–Si alloys, and the Chinese script α-Fe is thought to be less detrimental than the needle-like β-Fe [7–9]. In Al–Cu alloys, Tseng [10] found that β-Fe(Al_7Cu_2Fe) phase appeared in the A206 alloy at up to 0.29% Mn, but almost all the needle-like β-Fe(Al_7Cu_2Fe) phase was converted to the Chinese script Al–Cu–Mn–Fe phase when 0.66% Mn was added into the A206 alloy with 0.30% Fe. Moreover, Al–Cu–Fe–Mn and Al–Cu–Fe–Mn–Si phases were also reported in the A206 alloy with 0.2% Mn and 0.2% Fe by Sigworth [11]. Liu et al. [12] has investigated the solidification behavior of 206 cast alloy with 0.15% and 0.3% Fe systematically and found that the Fe-rich intermetallic phase in the fully solidified alloy is α-Fe($Al_{15}(FeMn)_3(CuSi)_2$) and β-Fe($Al_7Cu_2(FeMn)$/Al_7Cu_2Fe). Kamga et al. [13] also thought that the Fe-rich intermetallics in the fully solidified B206 alloy are β-Fe(Al_7Cu_2Fe) and α-Fe. Recently, it was found that the Chinese script Al_mFe phase would

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* Corresponding author. Tel.: +86 20 87112272; fax: +86 20 87112111.
E-mail address: mewzhang@scut.edu.cn (W. Zhang).

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become the dominant Fe-rich intermetallic compound in Al–4.6% Cu cast alloys at a high Fe content of 0.5% with low levels of Mn (0.003%) and Si (0.1%) [14]. Liu et al. [15] also found a new Fe-rich intermetallic phase $Al_3(FeMn)$ with needle-like morphology in A206 alloy at a cooling rate of 0.2 K/s. It is different from the Chinese script $Al_3(FeMn)$ mentioned in the classic reference of Mondolfo [16]. The result indicated that the Mn addition may not modify the morphology of the needle-like intermetallics in 206 alloys, which is completely different from the well-known observations in cast Al–Si alloy. Therefore, the morphologies and kinds of Fe-rich intermetallic phases are complex, depending on the composition of the alloy, cooling rate and processing method of materials.

For the effect of Fe contents on mechanical properties of Al–Cu alloy, Tseng et al. [17] studied A206 alloy in T7 condition. They concluded that the strength and ductility decreased linearly with increasing Fe content, since the needle-like Al_7Cu_2Fe phase acting as crack initiation sites increases. Kamga et al. [18] studied the effect of Fe/Si ratio on the mechanical properties of B206 alloy, and it was found that the best properties were obtained with a Fe/Si ratio close to 1 and low concentrations of iron and silicon. Both of them thought that the acceptable mechanical properties can still be achieved for the A206 cast alloys at a Fe content level of 0.3% [10,18]. Bonsack [19] found that the mechanical properties were slightly improved when the Fe content was increased from 0.73% to 1.06% in Al–4.5Cu cast alloy, indicating the significant potential of extending the allowable Fe content. Since the applied pressure increases the heat-transfer coefficient between the die and the castings, the fine-scale microstructures can be achieved by the comparatively short solidification time and high cooling rate [20–21]. So, squeeze casting may be one of the efficient methods to develop the high performance and low cost aluminum alloys with higher Fe contents. Dong et al. [22] and Maeng et al. [23] studied the effect of Fe-rich intermetallics on the mechanical properties of Al–7Si–0.3Mg and B390 alloys prepared by squeeze casting respectively, they found that the squeeze cast alloys had superior mechanical properties compared to the gravity die cast alloys. However, the effect of Fe-rich intermetallics on the microstructures and mechanical properties is mainly focused on Al–Si alloys, studies on the squeeze cast Al–Cu alloys with Fe content more than 0.5% are rarely reported.

In this paper, the effect of Fe content and applied pressure on microstructures and mechanical properties of squeeze cast Al–Cu alloys was investigated. This study would be helpful for developing the high performance cast aluminum alloys with high Fe content.

2. Experimental procedures

Commercially pure Al (99.5%), Al–50% Cu, Al–10% Mn and Al–5% Fe master alloys were used to prepare the experimental alloys and the final chemical composition was analyzed using an optical emission spectrometer as shown in Table 1. The raw materials were melted at 1053 K in a clay–graphite crucible using an electric resistance furnace. The melts about 10 kg were degassed by 0.5% C_2Cl_6 to minimize hydrogen content. The melt was poured into a cylindrical die under different applied pressure ranging from 0 MPa to 75 MPa. The die temperature was set at approximately 523 K, and the pouring temperature was set at 983 K before squeeze casting. Finally, the samples with the size of 65 mm in height and 68 mm in diameter were obtained.

Table 1
Chemical compositions of the experimental alloys, wt%.

Alloys	Cu	Mn	Fe	Si	Al
Al–5.0Cu–0.6Mn–0.1Fe (Fe01)	5.00	0.60	0.12	0.08	Balance
Al–5.0Cu–0.6Mn–0.5Fe (Fe05)	4.92	0.59	0.46	0.08	Balance
Al–5.0Cu–0.6Mn–1.0Fe (Fe10)	5.15	0.61	1.05	0.07	Balance
Al–5.0Cu–0.6Mn–1.5Fe (Fe15)	5.44	0.60	1.61	0.08	Balance

All samples for tensile test were cut into the dimension of Φ10 mm × 65 mm by line-cutting machine from the same radius of the castings. The tensile test was performed according to En ISO 6892-1 [24] on a SANS CMT5105 standard testing machine and the data reported below is an average value from at least three tested samples. Samples for micro-hardness test and metallographic observation were cut in the gauge length part from selected tensile specimens. The location for micro-hardness test is restricted in the center of α(Al) dendrite near the center of the etched specimens. The micro-hardness was measured on a tester equipped with a Vickers diamond indenter using an indentation load of 50 g and the average value is over 8 readings. Metallographic samples were etched with 0.5% HF solution for 30 s to reveal the microstructures. A Leica light optical microscopy equipped with the image analysis software Leica Materials workstation V3.6.1 was used to quantitatively analyze the intermetallic compounds, secondary dendrite arm spacing (SDAS) and the area percentage of porosities. In order to get statistically significant data, approximate 50 different regions each at magnification of 500 times around the center of the etched specimen were measured. Porosity measurements were carried out on over 25 different regions at magnification of 100 times around the center of the unetched specimen. The measured area fractions of the intermetallics were transferred as the volume fractions based on the assumption that the morphology of the intermetallics is equaled. Furthermore, the density and porosity were also measured according to the ASTM D3800M-11 and ASTM C948-81(2009). The average compositions of the various phases and fracture surfaces of tensile specimens were analyzed using Nova Nano SEM 430, equipped with an energy-dispersive X-ray analyzer (EDX). In order to obtain more accurate result of the solid solubility in α(Al) matrix, the chemical compositions in the α(Al) matrix were measured by EPMA-1600 electron probe micro-analyzer and at least five readings were taken for every samples.

3. Results

3.1. Microstructures

Fig. 1 shows the microstructures of the alloys with Fe content varying from 0.1% to 1.5% without applied pressure. Microstructures of the four different samples consist of α(Al) and the second intermetallics. The average compositions of the second intermetallics measured by EDS are given in Table 2. The EDS results show that the copper-containing intermetallics contains 35.94 at.% Cu and 64.06 at.% Al, which is in agreement with $\theta(Al_2Cu)$. There are four kinds of Fe-rich intermetallics in the cast Al–5.0Cu–0.6Mn alloys: Chinese script α-Fe and $Al_6(FeMn)$, needle-like β-Fe(Al_7Cu_2Fe) and $Al_3(FeMn)$. When the Fe content is 0.1%, only the Chinese script Fe-rich intermetallics α-Fe is observed (Fig. 1a). When the Fe content increases to 0.5%, a few needle-like β-Fe phases can be observed although most of Fe-rich intermetallics are still Chinese script α-Fe (Fig. 1b). Further increasing the Fe content to 1.0% and 1.5%, the dominate Fe-rich intermetallics are needle-like or rod shape $Al_3(FeMn)$ which are irregularly distributed in α(Al) matrix. Meanwhile, the Chinese script $Al_6(FeMn)$ is also observed. It is found that the amount of intermetallic particles increase with the increase of Fe content.

Fig. 2 presents the microstructures of the as-cast alloy with different Fe content when the applied pressure is 75 MPa. The morphology of the intermetallic phases in the squeeze cast alloys