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# Comparative study on microstructures and mechanical properties of the heat-treated Al–5.0Cu–0.6Mn–*x*Fe alloys prepared by gravity die casting and squeeze casting

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ABSTRACT

The Al–5.0 wt% Cu–0.6 wt% Mn alloys with different Fe contents were prepared by gravity die casting and squeeze casting. The difference in microstructures and mechanical properties of the T5 heat-treated alloys was examined by tensile test, optical microscopy, deep etching technique, scanning electron microscope and electron probe micro-analyzer. The results show that both β-Fe and α (CuFe) are observed in T5 heat-treated gravity die cast alloy and only α (CuFe) appears in the squeeze cast alloy when the Fe content is 0.5 wt%. When the Fe content is more than 1.0 wt%, the main Fe-rich intermetallics is α (CuFe) in both squeeze cast and gravity die cast alloys. The mechanical properties of both the gravity die cast and squeeze cast alloys decrease gradually with the increase of Fe content due to the decreased volume fraction of precipitation particles, the increased volume fraction of Fe-rich intermetallics and the increased size of α (Al) dendrites. The squeeze cast alloys with different Fe contents have superior mechanical properties compared to the gravity die cast alloys, which is mainly attributed to the reduction of porosity and refinement of Fe-rich intermetallics and α (Al) dendrite. In particularly, the elongation of the squeeze cast alloys is less sensitive to the Fe content than that of the gravity die cast alloys. An elongation level of 13.7% is obtained in squeeze cast alloy even when the Fe content is as high as 1.5%, while that of the gravity die cast alloy is only 5.3%.



## 1. Introduction

The increasing usage of recycled materials for the production of Al-based alloys is helpful for the energy saving, environment protection and development sustainability in the aluminum industry. However, the recycled aluminum alloys usually contain high content of impurity Fe and Fe even accumulates during recycling. It is a great challenge to remove the impurity Fe from aluminum because the complicated processing techniques have to be adopted and the cost is generally very high. Therefore, developing high performance cast aluminum alloys with high Fe content by an economical way has attracted considerable attention.

Fe is thought to be one of the most harmful impurities in most of the commercial aluminum alloys, especially in Al–Cu based alloys. Almost all the Fe will precipitate from liquid Al–Cu cast alloys in the form of Fe-rich intermetallic phases for its low solubility in aluminum matrix. The needle-like β-Fe, which is the most frequently observed Fe-rich intermetallic phase, is considered to be detrimental to the mechanical properties due to its brittle feature and stress concentration [1,2]. In order to reduce the harmful effect of needle-like β-Fe and extend the tolerance of Fe content in Al–Cu cast alloys, composition design and processing improvement have drawn many interests. Kamaga and Liu found that Mn and Si additions are useful to convert needle-like Fe-rich intermetallics to less detrimental Chinese script Fe-rich intermetallics in Al–Cu cast alloys with the Fe content varies from 0.15% to 0.3% (all compositions quoted in this work are in weight percent unless indicated otherwise) [3,4]. Recently, Liu investigated systematically the formation of Fe-rich intermetallics in A206 alloys at a higher Fe content of 0.5% [5,6]. They found that a new Chinese script $Al_mFe$ presents as the dominate Fe-rich intermetallics in Al–4.6Cu–0.5Fe–0.1Si alloy at a low level of Mn content (0.03%), and the needle-like $Al_3(FeMn)$ becomes the major Fe-rich intermetallics when the Mn content is increased to 0.5%. Therefore, it is difficult to obtain the favorable Fe-rich intermetallics just only by composition design because the Fe-rich intermetallics that can form in the aluminum alloys with different Fe contents are so complicated. Liu and Kamaga also reported that increasing the cooling rate is an efficient method to hinder the formation of needle-like Fe-rich

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intermetallics in Al–Cu cast alloys [3,7,8]. However, it is difficult to obtain the high cooling rate in traditional gravity casting. As proved in Maeng's work, the high cooling rate can impede the growth of Fe-rich intermetallics in B390 alloy during squeeze casting [9]. Therefore, squeeze casting may be employed to develop the high performance and low cost aluminum alloys with high Fe content.

The impact of Fe contents on mechanical properties in Al–Cu alloy is detrimental in most cases. Tseng studied the mechanical properties of T7 heat-treated A206 alloy with different Fe contents [10]. They concluded that the strength and ductility of the A206 alloy decreased linearly with increasing Fe content because the needle-like $Al_7Cu_2Fe$ phase acting as crack initiation sites increases. Tseng also reported that most of the needle-like β-Fe is completely converted to Chinese script α-Fe when 0.66% Mn is added into the A206 alloy with 0.30% Fe [11]. It was found that Mn addition can improve the ultimate tensile strength (UTS), especially the elongation. Kamaga studied the effect of Fe/Si ratio on the mechanical properties of B206 alloy with low concentrations of iron and silicon and the best properties were obtained with a Fe/Si ratio close to 1 [12]. They thought that the acceptable mechanical properties can still be achieved for the A206 cast alloys at the Fe content level of 0.3%. Until now, studying the effect of Fe-rich intermetallics on microstructures and mechanical properties is mainly focused on the gravity die cast Al–Cu alloys with low Fe content. Little work has done on the relationship between the Fe-rich intermetallics and mechanical properties of the high Fe content squeeze cast Al–Cu alloys.

In our previous work, we have studied the effect of Fe content on microstructures and mechanical properties of Al–5.0Cu–0.6Mn alloys in as-cast condition [13]. Since the squeeze cast Al–Cu alloys are usually used in heat treatment condition, it is important to investigate the relationship between the Fe-rich intermetallics and mechanical properties of the heat-treated Al–Cu alloys. The Al–Cu-based cast alloys are often used in T4 or T7 condition in order to improve the stress corrosion resistance. However, the Al–Cu-based alloys with high Fe content are generally of low elongation in T7 condition [10–12]. In order to obtain good toughness, the T5 heat-treatment was used in present study for high strength and elongation of the alloy. Therefore, the effect of Fe content on microstructures and mechanical properties of Al–5.0Cu–0.6Mn alloys in T5 heat treatment condition were investigated. The concern is focused on the difference in microstructures and mechanical properties of the alloys prepared by gravity die casting and squeeze casting.

## 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 chemical compositions shown in Table 1 were analyzed by an optical emission spectrometer. The raw materials were melted at 1053 K in a clay-graphite crucible using an electric resistance furnace. All melts were degassed by $C_2Cl_6$ and string about 3 min in order to minimize hydrogen. Then the melt was poured into a cylindrical die under different applied pressures 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 casting. Finally, the samples were obtained with the size of 65 mm in height and 68 mm in diameter. All samples for tensile test were cut into the dimension of $\Phi 10\ \mathrm{mm} \times 65\ \mathrm{mm}$ by line-cutting machine from the same radius of the castings. The samples were solution treated at 811 K for 12 h, quenched into water at ambient temperature and then aged to a T5 condition at 428 K for 8 h. The tensile test was performed according to En ISO 6892-1 [14] 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.

Samples for metallographic observation were cut in the gauge length part from selected tensile specimens. Metallographic samples were etched with a solution of 1 ml HF + 16 ml $HNO_3$ + 3 g $CrO_3$ + 83 ml $H_2O$ for 30 s. A Leica optical microscopy equipped with the image analysis software Leica Materials workstation V3.6.1 was used to quantitatively measure the size of α (Al) dendrite. 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). To further reveal the morphology of the intermetallics in three dimensions, some samples were deeply etched to preferentially remove α (Al) matrix. Deep etching was carried out on alloy samples that were mounted and polished to 1 μm diamond and then held face down in a gently stirred solution of iodine in methanol (10 g in 100 ml) at room temperature for approximately 4–5 h [15]. The samples were then rinsed gently in methanol and air dried prior to examinate by Navo Nano SEM430 scanning electron microscope. In order to obtain more accurate result of the solid solubility in α (Al) matrix, the Cu and Mn contents in α (Al) matrix after solution heat treatment was measured by EPMA-1600 electron probe micro-analyzer.

**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 |

## 3. Results

### 3.1. Microstructures

Fig. 1 shows the two dimensional morphology of Fe-rich intermetallics at high magnification in T5 heat-treated gravity die cast alloys with different Fe contents. There are two main Fe-rich intermetallics, namely β-Fe and α (CuFe), presented in the alloys. The β-Fe takes needle-like. The α (CuFe) takes Chinese script shape in low Fe content alloys (<0.5%) but displays rod-like or Chinese script shape in high Fe content alloys (Fig. 1c and d). The SEM–EDS results show that the chemical composition of α (CuFe) phase is close to that of $Al_7Cu_2(FeMn)$, as shown in Table 2. The Chinese script α (CuFe) ($Al_7Cu_2Fe$ or $Al_7Cu_2(FeMn)$ is transformed from the Chinese script $Al_mFe$, α-Fe or $Al_6(FeMn)$ that present in the as-cast alloy, which have been proved by Kamaga [12], Liu [16], Pannaray [17] and our previous study [18]. It should be noted that a little untransformed $Al_6(FeMn)$ or $Al_3(FeMn)$ can still be found in Fig. 1c and d.

Fig. 2 presents the microstructures of the T5 heat-treated gravity die cast alloys with different Fe contents. Obviously, the volume fraction of intermetallic particles increases with the increase of Fe content. When the Fe content is 0.1%, only a few Chinese script α (CuFe) are observed (Fig. 2a). In Fe05 alloy, a few needle-like β-Fe can be observed although most of Fe-rich intermetallics still