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Microstructures and mechanical properties of conventionally solidified $Al_{63}Cu_{25}Fe_{12}$ alloy

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ABSTRACT

In this study, the microstructures and mechanical properties of conventionally solidified $Al_{63}Cu_{25}Fe_{12}$ alloy after different heat-treatments were investigated. The microstructures of the as-cast and subsequently heat-treated samples were investigated by X-ray diffraction (XRD), scanning electron microscopy (SEM) and differential thermal analysis (DTA). The XRD results showed the presence of quasicrystalline icosahedral phase (i-phase) together with crystalline phases corresponding to β-AlFe(Cu) solid solution phase (β-phase) and τ-AlCu(Fe) solid solution phase (τ-phase). The SEM investigations clearly showed the formation of i-phase with pentagonal dodecahedra structure. However, the i-phase together with β-phase was also observed in the heat-treated samples and the peak intensity of the β-phase decreased with increasing heat-treatment temperature. From the DTA curves, the melting point of i-phase was determined as 890 °C for this alloy composition. Mechanical properties of the as-cast and subsequently heat-treated samples were measured by a Vickers indenter. Results showed that the microhardness (*HV*) and the elastic modulus (*E*) of the as-cast sample were around 598 kg fmm^{-2} (5.86 GPa) and 104 GPa, respectively. In addition, the characteristic of material plasticity (δ_H) value was calculated to be 0.54.

1. Introduction

Since the production of the first quasicrystalline phase in the Al–Mn system by a rapid solidification technique [1], a number of studies have been carried out on the formation, structure and properties of the quasicrystalline alloys. Unique structure and unusual properties of these materials make them attractive materials in potential industrial applications, such as hydrogen storage, solar power, thermal insulation, surface engineering, etc. [2,3]. Up to now, the i-phase has been obtained in over 100 different alloy systems, and the majority of them have consisted of Al-based alloys. Among them, Al–Cu–Fe alloys have great importance because of their nontoxicity, easy availability, thermal stability and the favourable costs of their alloying elements [3,4].

It has been reported that Al–Cu–Fe quasicrystal materials can be prepared by conventional solidification, rapid solidification, mechanical alloying, laser- or electron-beam superficial fusion and electron irradiation [5–7]. However, in the $Al_{65}Cu_{20}Fe_{15}$ alloy thermodynamically stable i-phase was obtained by conventional solidification technique [8]. Therefore, the discovery of thermodynamically stable i-phase in Al–Cu–Fe alloy has opened a new way for its experimental investigations. Moreover, it has been reported that the i-phase in $Al_{63}Cu_{25}Fe_{12}$ alloy mostly co-exists with τ-phase which is a metastable phase with a lower melting temperature [9]. On further heat-treatments, the metastable τ-phase disappears and the amount of the i-phase increases.

Although there have been so many investigations on the formation, microstructure, surface morphology, thermal stability and mechanical properties of Al–Cu–Fe quasicrystals, the conventionally solidified $Al_{63}Cu_{25}Fe_{12}$ alloy has not yet been discussed in detail as a function of the heat-treatments. The aim of the present work is to investigate the formation of the i-phase and the mechanical properties during heat-treatments. Microstructures, thermal behaviours and mechanical properties of both as-cast and heat-treated samples were examined by combination of X-ray diffraction (XRD), scanning electron microscopy (SEM), differential thermal analysis (DTA) and Vickers microhardness techniques.

2. Experimental

A master alloy with a nominal composition of $Al_{63}Cu_{25}Fe_{12}$ (in atomic percent) was prepared by induction melting a mixture of high purity (99.99%) Al, Cu, Fe under a dynamic purified argon atmosphere. The master alloy was cut into suitably shaped pieces for the subsequent heat-treatments. The alloy ingots were heat-treated at 200, 400 and 600 °C for up to 4 h followed by slow cooling to room temperature under air atmosphere. Structural characterization of all these samples was done by X-ray diffraction (XRD) using a Philips X'Pert powder diffractometer with Cu Kα radiation and by scanning electron microscopy (SEM) using a JEOL 5400 with an accelerating voltage of 15 kV. Thermal events were investigated for both master

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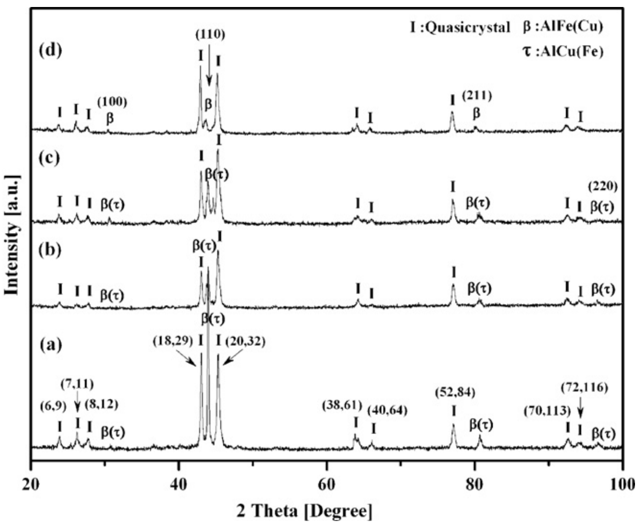

Fig. 1. XRD patterns for conventionally solidified $Al_{63}Cu_{25}Fe_{12}$ alloy before and after heat-treatments: (a) as-cast, (b) 200 °C, (c) 400 °C, and (d) 600 °C.

alloy and heat-treated alloys by differential thermal analysis (DTA) using a Perkin-Elmer Diamond TG/DTA at a heating rate of 20 °C min^{-1} under dynamic nitrogen atmosphere. Mechanical properties of the as-cast and the heat-treated alloys were measured by a Vickers indenter. The Vickers indenter was used in a dynamic ultra microhardness tester (Shimadzu, DUH-W201S). Vickers microhardness measurements were done by using a 0.98 N load and the loading rate was 23.5 mN s^{-1}. For a particular load at least five indentation tests were made and the experimental errors were also analysed.

3. Results and discussion

Fig. 1 shows the X-ray diffraction patterns for conventionally solidified $Al_{63}Cu_{25}Fe_{12}$ alloy before and after heat-treatments at 200, 400 and 600 °C for up to 4 h. The XRD result for the as-cast $Al_{63}Cu_{25}Fe_{12}$ alloy shows the presence of icosahedral quasicrystalline phase (i-phase) together with crystalline phases. The peaks corresponding to the i-phase and crystalline phases were completely indexed using Cahn indices (N,M) [10] and Miller indices, respectively. The crystalline phases were identified as cubic β-AlFe(Cu) solid solution phase (β-phase) and cubic τ-AlCu(Fe) solid solution phase (τ-phase). As shown in Fig. 1, the diffraction peaks of the τ-phase exactly superimpose on the peaks of the β-phase. Therefore, τ-phase was also denoted with parenthesis besides each β-phase. However, the XRD patterns are not suitable to discriminate the τ-phase from the β-phase since owing to same crystal structure of CsCl type cubic and very similar lattice parameter (a = 0.2910 nm) in the solidification product [11–13]. In the as-cast sample the peak intensity of the β(τ)-phase (1 1 0) at observed around $2\theta = 44^{\circ}$ is the strongest. Also, the lattice parameter of the β(τ)-(1 1 0) peak was found to be 0.2912 nm. During the heat-treatments at 200, 400 and 600 °C, the intensity of the β(τ)-(1 1 0) peak, at observed around $2\theta = 44^{\circ}$, significantly decreased with increasing heat-treatment temperature. Similarly, the intensity of the β(τ)-(2 2 0) peak, at observed around $2\theta = 96^{\circ}$, decreased with the heat-treatment temperature and disappeared after 600 °C for 4 h. However, no significant difference was observed in the peak intensities of the i-phase during heat-treatments. Therefore, this is an indication that the i-phase is the stable phase for this composition under the processing conditions studied. From three most intense diffraction peaks of i-phase ((18,29), (20,32) and (52,84)), the six-dimensional quasilattice parameter (a_{6D}) was calculated and optimised to be 0.630 nm.

On the other hand, it has been reported that the τ-phase is a metastable phase with a lower melting temperature and the β-phase is a stable phase, containing more amount of Fe content, with a higher melting temperature [11]. Thus, after heat-treatment at 600 °C, the metastable τ-phase disappeared and probably transformed into the i-phase and the β-phase. Therefore, XRD pattern of the $Al_{63}Cu_{25}Fe_{12}$ alloy after heat-treated at 600 °C for 4 h consists of i-phase and β-phase. Also using a peak-fitting program with the Pearson VII function, volume fraction of the i-phase was calculated by the ratio of sum of integrated areas of all diffraction peaks for the i-phase [14]. The resultant volume fraction of the i-phase was calculated to be around 62% in the as-cast sample and 72%, 73% and 88% in the heat-treated samples at 200, 400 and 600 °C for 4 h, respectively. These results indicate that as the heat-treatment temperature increased, the amount of the i-phase increased, corresponding with the relative decrease of the τ- and β-phases. This is in good agreement with other results [11–14].

In order to understand the microstructural evolution depending on the heat-treatment in conventionally solidified $Al_{63}Cu_{25}Fe_{12}$ alloy, the samples were examined by SEM. Fig. 2 shows the SEM micrographs for the as-cast and the heat-treated samples. These micrographs show similar morphologies. All micrographs revealed the formation of pentagonal dodecahedra in the quasicrystalline phase. These results confirm the XRD analysis. This observation is also in agreement with the earlier reported study for the conventionally solidified $Al_{65}Cu_{20}Fe_{15}$ by Tsai et al. [8].

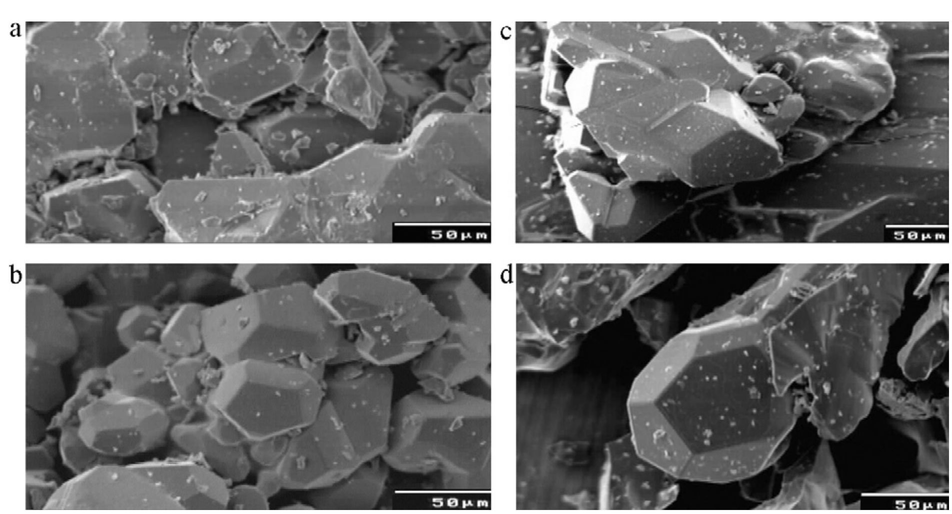

Fig. 2. SEM micrographs for conventionally solidified $Al_{63}Cu_{25}Fe_{12}$ alloy before and after heat-treatments: (a) as-cast, (b) 200 °C, (c) 400 °C, and (d) 600 °C.