Journal of Alloys and Compounds 577 (2013) 103–124

Contents lists available at SciVerse ScienceDirect

Journal of Alloys and Compounds

journal homepage: www.elsevier.com/locate/jalcom

Evolution of Fe based intermetallic phases in Al–Si hypoeutectic casting alloys: Influence of the Si and Fe concentrations, and solidification rate

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ARTICLE INFO

Article history:
Received 3 April 2013
Received in revised form 18 April 2013
Accepted 21 April 2013
Available online 2 May 2013

Keywords:
Al–Si alloys
Solidification
Microstructure
Intermetallic phases
Synchrotron diffraction
Non-equilibrium

ABSTRACT

Al–Si–Fe hypoeutectic cast alloy system is very complex and reported to produce numerous Fe based intermetallic phases in conjunction with Al and Si. This publication will address the anomalies of phase evolution in the Al–Si–Fe hypoeutectic casting alloy system; the anomaly lies in the peculiarities in the evolution and nature of the intermetallic phases when compared to the thermodynamic phase diagram predictions and past publications of the same. The influence of the following parameters, in various combinations, on the evolution and nature of the intermetallic phases were analyzed and reported: concentration of Si between 2 and 12.6 wt%, Fe between 0.05 and 0.5 wt% and solidification rates of 0.1, 1, 5 and 50 K s^{-1}. Two intermetallic phases are observed to evolve in these alloys under these solidification conditions: the τ_5-Al_8SiFe_2 and τ_6-$Al_9Fe_2Si_2$. The τ_5-Al_8SiFe_2 phase evolves at all levels of the parameters during solidification and subsequently transforms into the τ_6-$Al_9Fe_2Si_2$ through a peritectic reaction when promoted by certain combinations of solidification parameters such as higher Fe level, lower Si level and slower solidification rates. Further, it is also hypothesized from experimental evidences that the θ-$Al_{13}Fe_4$ binary phase precludes the evolution of the τ_5 during solidification and subsequently transforms into the τ_6 phase during solidification. These observations are anomalous to the publications as prior art and simulation predictions of thermodynamic phase diagrams of these alloys, wherein, only one intermetallic phases in the τ_6-$Al_9Fe_2Si_2$ is predicted to evolve and be retained as the terminal phase at the end of solidification. Several analysis methods such as light optical microscope, scanning electron microscope equipped with a dual beam focused ion beam milling machine and energy dispersive X-ray diffraction system, transmission electron microscope equipped with high resolution digital imaging system, energy dispersive X-ray diffraction system, and high energy synchrotron beam source for nano-diffraction coupled with X-ray fluorescence imaging system was used in this study.

1. Introduction

In the commercial Al–Si–Fe multicomponent casting alloy system, the mechanical properties and performance of the component is vastly influenced by the Fe based intermetallic phases evolved during solidification [1,2]. Apart from Fe, which is an impurity in the alloy, the Al–Si hypoeutectic commercial cast alloys contain several alloying elements such as Cu, Mg, Sr, Mn, Cr and Ti which participates in the formation of complex stable and metastable intermetallic phases along with Fe and influence the component properties and performance [3,4]. There have been several research studies trying to understand the complexities in the evolution and nature of Fe based intermetallic phases in the commercial Al–Si alloys [5–8], however, none of these studies have presented an in-depth understanding of the intermetallic phases in a ternary Al–Si–Fe system in the Al rich corner without any commercial elemental additions. The Fe in the Al–Si alloy is unavoidable as it occurs as impurities in the raw Al ingots [9] and hence, it is nearly impossible to study the Al–Si system without the Fe in it because, as low as 10 ppm of Fe in the alloy results in the formation of Fe based intermetallic phases under non-equilibrium solidification conditions [9]. We would like to mention that all the alloy compositions reported in this publication are in weight percent of the respective elemental composition unless otherwise mentioned.

Takeda and Mutuzaki [10] reported six Fe based intermetallic phases in the ternary Al–Fe–Si system; this number was increased to ten stable and one metastable intermetallic phase in the comprehensive literature review on this topic presented by Rivlin and Raynor [11] which was corroborated by Allen et al. [12], Gupta [13], Maitra and Gupta [14]; and recently, Krendelberger et al. [15] presented the existence of twelve stable Fe based intermetallic phases in this ternary system. These advances in our understanding of the

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http://dx.doi.org/10.1016/j.jallcom.2013.04.139

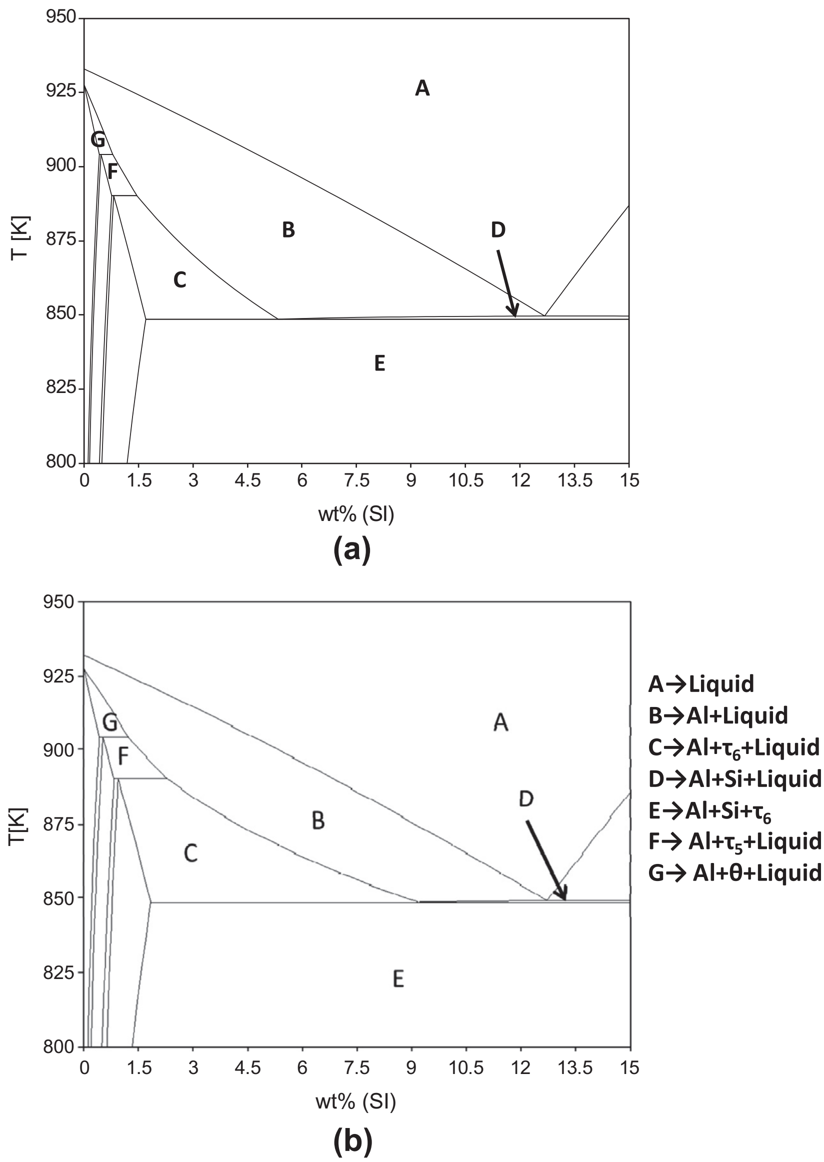

Fig. 1. Isopleths of equilibrium phase diagram simulations for the (a) Al–0.25Fe–*x*Si (*x* = 0–15) and (b) Al–0.5Fe–*x*Si (*x* = 0–15) alloy systems.

Fe based intermetallic phases in this alloy system reflects the significantly complex nature of evolution of these phases during solidification; the technological advances in material characterization lead to the identification of additional phases during the last sixty years. It is notable that the prior art in identification of the intermetallic phases in the Al–Si–Fe alloys were carried out at near-equilibrium conditions [10,13,15], whereas, there is insufficient background literature information on such phases in non-equilibrium solidification conditions observed in commercial operations such as casting. It is also notable, that the nomenclature attributed to the Fe based intermetallics phases, especially in the Al rich corner of the Al–Si–Fe system is not consistent in the background literature; a summary of the several different nomenclatures for these phases in the ternary Al–Si–Fe system has been presented in Rivlin and Raynor [11] and Krendelsberger et al. [15], alike. For simplicity, the nomenclature of the ternary intermetallic phases observed in this study adopted the traditional method of using the Greek alphabet τ along with numeric subscripts; specifically two phases in τ_5-Al_8SiFe_2 and τ_6-$Al_9Fe_2Si_2$ are predominantly discussed in this work along with the θ-$Al_{13}Fe_4$ binary phase. The τ_5 and τ_6 are also commonly referred to as the α (hexagonal) and β (monoclinic) phases, respectively in the literature.

The brittle τ_6-β-$Al_9Si_2Fe_2$ phase has a significant influence on the mechanical properties of the Al–Si alloys [16,17] due to its plate-like morphology with sharp interfaces, which act as locations of high stress concentrations. The investigation of Al–Fe and Al–Si–Fe intermetallic phases in commercially pure Al alloys by Liu and Dunlop's [18] was carried out in Direct Chill (DC) cast alloys with compositions of Al–0.13Si-0.25 and 0.5 Fe (all wt%) in the as cast and heat treated conditions [18]; six different binary Al–Fe intermetallic phases were found along with several ternary Al–Fe–Si phases. In both the as-cast and heat treated conditions, under slow solidification rates, the presence of the θ-$Al_{13}Fe_4$ phase was dominant in the microstructure and at higher solidification rates, the Al_mSi_x, α-Al, Si, Fe, q_1-AlSiFe and q_2-AlSiFe metastable phases were observed. An important outcome of this work [18], is the validation that all these Al–Fe and Al–Fe–Si intermetallic phases nucleated on the primary Al phase during solidification. Westengen [19] in his work identified intermetallic phases in DC cast ingots of 1000 series Al alloy with 99.5 Al, 0.25 Fe, 0.13