Available online at www.sciencedirect.com
ScienceDirect
Acta Materialia 68 (2014) 42–51
Acta MATERIALIA
www.elsevier.com/locate/actamat

Influence of Fe-rich intermetallics on solidification defects in Al–Si–Cu alloys

C. Puncreobutr [a,b], P.D. Lee [b,*], K.M. Kareh [a], T. Connolley [c], J.L. Fife [d], A.B. Phillion [e]

[a] Department of Materials, Imperial College London, Prince Consort Road, London, UK
[b] School of Materials, The University of Manchester, Oxford Road, Manchester, UK
[c] Diamond Light Source Ltd., Harwell Science & Innovation Campus, Didcot, UK
[d] Swiss Light Source, Paul Scherrer Institut, 5232 Villigen PSI, Switzerland
[e] School of Engineering, The University of British Columbia, Kelowna, Canada

Received 27 October 2013; received in revised form 9 December 2013; accepted 3 January 2014
Available online 12 February 2014

Abstract

To better understand the influence of Fe-rich intermetallics on solidification defect formation, fast in situ synchrotron X-ray tomographic microscopy experiments were performed on a commercial A319 alloy (Al–7.5Si–3.5Cu, wt.%) with 0.2 and 0.6 wt.% Fe. Real-time observations during solidification and semi-solid deformation experiments reveal that β-intermetallics contribute via several different mechanisms to porosity formation and hot tearing susceptibility. While β-intermetallics were not observed to nucleate porosity directly, they do block interdendritic channels, thereby reducing the shrinkage feeding, and increasing pore tortuosity. Pores also grow preferentially along the surface of the β-intermetallics, suggesting that the β-phase has a lower gas–solid interfacial energy than α-Al, thus assisting in increasing pore volume. During uniaxial tension experiments, the ductile failure of the semi-solid, intermetallic-poor, base alloy transitions to a brittle-like failure when a large amount of β-intermetallics are present. In all post-failure microstructures, internal damage was preferentially orientated perpendicular to the loading direction, agreeing with prior experimental and numerical studies.

Keywords: Intermetallics; Al–Si–Cu alloys; Porosity; Hot tearing; X-ray tomographic microscopy

1. Introduction

The excellent mechanical properties of Al–Si–Cu casting alloys have enabled this alloy family to find usage in many automotive applications, such as engine blocks and cylinder heads [1]. However, using recycled-grade Al–Si–Cu alloys as the base material for structural components remains a major challenge, especially when fatigue life is critical [2], because iron is easily picked up during the recycling process. The increased Fe content can be sufficient to promote the formation of coarse Fe-rich intermetallic compounds, including plate-like β-Al_5FeSi intermetallics, which have been shown to act as crack initiators and are thus detrimental to in-service mechanical properties [2–6]. In addition to their negative effects on the mechanical properties of the final product, β-Al_5FeSi intermetallics are also reported to be deleterious to castability, increasing the as-cast porosity content [7–10]. Many mechanisms by which β-Al_5FeSi intermetallics affect pore formation have been suggested, including blocking of interdendritic flow [10,11], acting as nucleation sites [12] and aiding pore growth [13]. They may also influence pore growth indirectly, e.g. inducing larger Al–Si eutectic grains that reduce feeding and thus increase porosity [14]. However, there has been no consensus on the choice of a

---

* Corresponding author.
E-mail address: peter.lee@manchester.ac.uk (P.D. Lee).

http://dx.doi.org/10.1016/j.actamat.2014.01.007
1359-6454/$36.00

dominant mechanism due to most studies providing only post-mortem analyses.

One important Al–Si–Cu casting alloy is A319, which exhibits a propensity to form plate-like β-Al_5FeSi intermetallics. In addition to as-cast porosity, A319 alloy castings are susceptible to hot tearing [15,16], another solidification defect that limits production yield during the casting of recycled aluminium. The formation of hot tears is a complex phenomenon caused by insufficient liquid feeding compensating for solidification shrinkage in the presence of thermal stresses and strains [17]. While an extensive number of experimental and numerical investigations have been conducted on binary alloys to relate various alloying and processing parameters to hot-tearing susceptibility [17–20], little is known about hot tearing in commercial Al–Si–Cu casting alloys, and even less about the influence of β-intermetallics. At the scale of the process, it has been shown that the addition of Sr and/or TiB_2 can have a beneficial effect in reducing the hot-tearing susceptibility of A319 alloys [15,16]. In parallel, Sr modifications [9] and TiB_2 grain-refiner additions [21] have been found to greatly alter microstructure, i.e. the size and morphology of plate-like β-intermetallics. However, the role of β-intermetallics on hot-tear formation has not been directly examined, and the correlation between elements that modify microstructure and reduction in hot tearing is still unclear.

Direct observation of defect formation during solidification has recently been made possible both in two dimensions, via X-ray radiography, and in three dimensions, via X-ray tomographic microscopy, yielding better insights into real-time pore formation [22–25] and hot-tearing processes [26–30] in binary Al–Cu alloys. Over the past two decades real-time observation has also enabled quantitative studies of microstructure evolution and secondary phase formation during solidification [31–33] and coarsening [34,35], as reviewed by Maire and Withers [36]. In the present study, fast in situ synchrotron X-ray tomographic microscopy experiments were performed on commercial A319 alloys (Al–7.5Si–3.5Cu, wt.%) with differing Fe-levels (0.2–0.6 wt.% Fe). Real-time 3-D observations of porosity and hot-tear formation were made during both in situ solidification and semi-solid uniaxial tension experiments to provide a greater understanding of the influence of β-intermetallics on defect formation in the semi-solid state.

2. Experimental methodology

2.1. Materials

To perform the solidification and semi-solid deformation experiments, A319 alloys (Al–7.5Si–3.5Cu, wt.%) with two different levels of Fe (0.2–0.6Fe, wt.%) were prepared from a commercial A319 ingot (as-received from Ford Motor Company) and a commercially pure Al–10Fe (wt.%) master alloy. These metals were melted using an electric-resistance furnace in a clay-bonded graphite crucible at 730 °C and were then cast into a pre-heated well-fed permanent mould [37] to form a wedge-shaped specimen. The resulting microstructure was equiaxed with an as-cast secondary dendrite arm spacing of ~30 μm. The chemical compositions obtained using X-ray fluorescence were found to be Al–7.49Si–3.4Cu–0.15Fe (wt.%) and Al–7.52Si–3.53Cu–0.59Fe (wt.%) for alloys with 0.2 wt.% Fe and 0.6 wt.% Fe, respectively.

The fraction of intermetallics, f_I, for these two alloy compositions is plotted in Fig. 1 using a Scheil approximation within the Thermo-Calc software (Thermo-Calc, Sweden) and the database from Ref. [38]. The thermodynamic calculation predicts a 3-fold increase in β-intermetallic phase fraction, from ~0.65% to nearly 2.1% as the Fe content is increased from 0.2 to 0.6 wt.%. Longitudinal sections of the as-cast microstructure from the high-resolution tomography images (0.9 μm), described in Section 2.3, for both wedge castings are also shown in Fig. 1. Fig. 1 shows that the plate-like β-intermetallics can only be resolved in the specimen with 0.6 wt.% Fe. The β-intermetallic phase cannot be resolved with the given spatial resolution in the specimen with 0.2 wt.% Fe and cooled at the rates given by the wedge casting setup. Thus, the 0.2 wt.% Fe alloy corresponds to a primary-grade material while the 0.6 wt.% Fe alloy corresponds to a recycled-grade product.

Subsequent to the wedge-casting, a tensile specimen was extracted from the 0.2 wt.% Fe wedge for the in situ

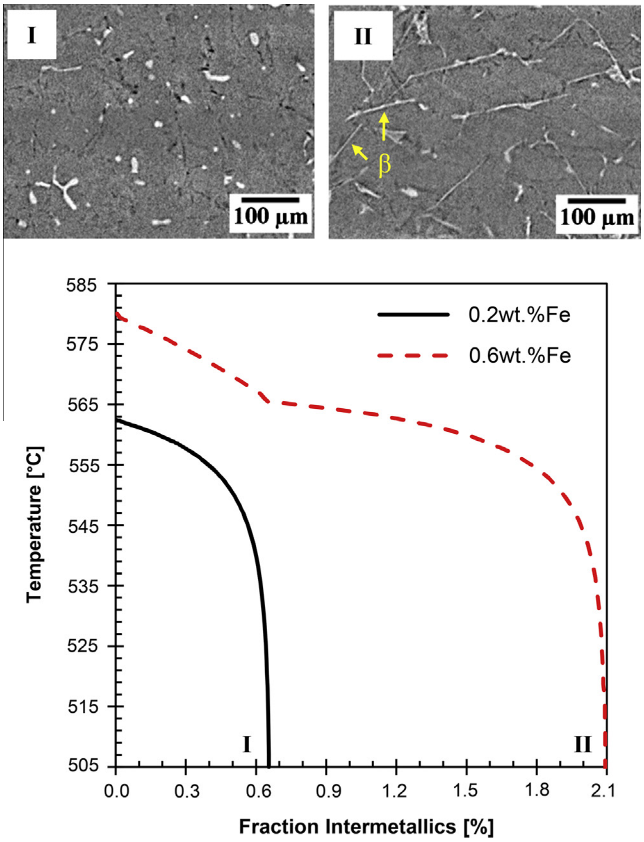

Fig. 1. Calculated fraction of the β-intermetallics in Al-A319 alloys at two Fe levels of (I) 0.2 wt.% Fe and (II) 0.6 wt.% Fe, assuming the Scheil solidification model. (I) and (II) show high-resolution longitudinal sections of typical as-cast solidified microstructures.