In-Situ Observation the Growth of Fe-Rich Intermetallic Particles During Solidification by Synchrotron X-Ray Imaging

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Abstract: Plate-like iron-rich intermetallic phases (Fe-rich phases) greatly decrease the elongation and fatigue strength of recycled Al alloys. The alloy composition and the manufacturing process parameters influence the type, and shape of Fe-rich phases. In this study, the influence of the cooling rate on the nucleation and growth of primary Fe-rich phases during solidification of Al-Fe(-Cu) alloy has been quantified by synchrotron X-ray radiography. The number and number density of primary Fe-rich phases in Al-Fe alloys. The nucleation rate of Al_3Fe in Al-Fe alloys at three cooling rates are 15.5, 44.0, 25.0 No./s, respectively. The maximum length of typical Al_3Fe phases in Al-Fe alloys decrease from 845 μm to 222 μm as the cooling rate increased. The combined Cu addition and higher cooling rate resulting in the constitutional undercooling, and finally promote the formation of refined primary Al_3Fe particles.

Keywords: Al alloy; solidification; Fe-rich intermetallic; synchrotron X-ray imaging.

1 Introduction (Bold, 10 pt., Arial)

Aluminium (Al) alloys are broadly used as engineering materials in the field of transportation, packing, and aerospace industry due to the advantage of lightweight, high-specific-strength, and good corrosion-resistant properties [1]. With increasing use of Al alloys parts in the past years, many of them come to end of service life and resulting in an increase of solid waste [2]. These Al scraps can be easily recycled due to their excellent recyclability [3]. However, recycled Al alloys have a high Fe content, which easily form sharp-edge iron-rich intermetallic phases (shorten as Fe-rich phases), such as, Al_3Fe, β-Al_5FeSi, and β-Al_7Cu_2Fe. They significantly deteriorate the ductility and fatigue properties of the alloys [4-5]. Hence, a lot of trails had been conducted to modify the Fe-rich phases by altering the cooling rates and adding alloying elements. In present study, the effect of cooling rate (0.1, 0.5, and 1.0 °C/s) on the growth behaviour of Al_3Fe in Al-Fe(-Cu) alloys was studied via radiography sequences.

2 Experimental procedure

The in-situ synchrotron X-ray radiography experiment was performed at the BL13HB beamline, Shanghai Synchrotron Radiation Facility (SSRF), P.R. China. The specific information about the furnace and beamline parameters used in this study is reported in [6].

3 Result and discussion

The growth behaviour of Fe-rich phases was captured by radiography sequences, as shown in Fig. 1. The Al-Fe clusters segregate and form the dark Al_3Fe phases shown in the radiograph at 650 °C, Fig. 1a. The Al + Al_3Fe eutectics were observed at the solid/liquid solidification front at 630 °C. When the cooling rate changes from 0.5 °C/s to 1.0 °C/s, the size of Al_3Fe and their nucleation temperature significantly decrease. Therefore, the higher the cooling rate, the higher the number density of Fe-rich particles and the smaller their size. Fig. 2 shows the X-ray radiographies taken during solidification of Al-Cu-Fe alloys. The presence of Cu significantly changes the morphology, amount and shape of primary Fe-rich phases. Similarly, the cooling rates reduced their size and increase their number. The nucleation temperature of the primary Fe-rich phase in the Al-Cu-Fe alloy is 3-4 °C higher than in Al-Fe alloys. In addition, the branch possibility of $Al_3(CuFe)$ phases in the ternary alloys is higher due to the different solute concentrations.

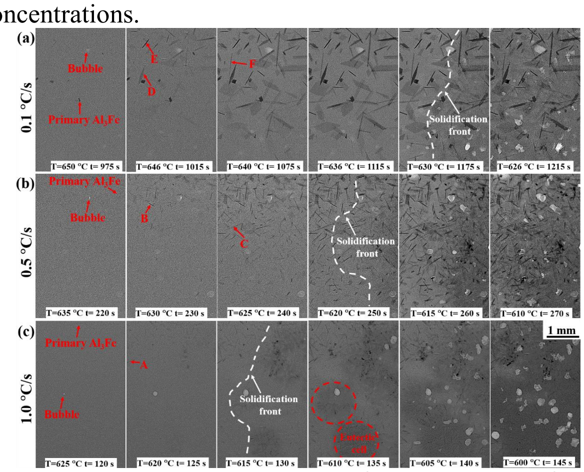

Fig. 1. X-ray radiography showing solidification sequence of Al-Fe alloys at different cooling rates.

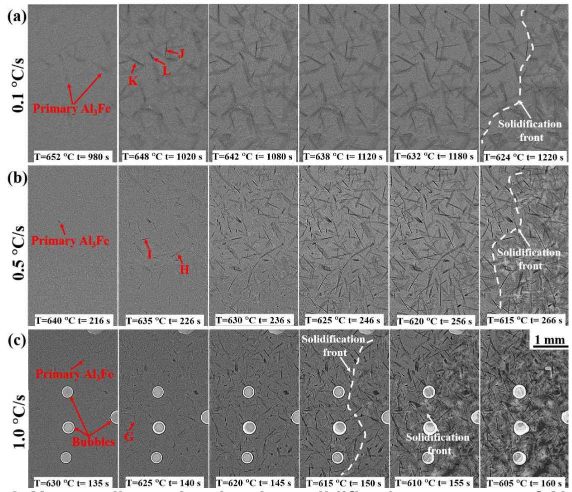

Fig. 2. X-ray radiography showing solidification sequence of Al-Cu-Fe alloys at different cooling rates.

The nucleation evolution of the Al_3Fe in the studied alloys under different cooling rates are illustrated in Fig. 3. The final number of the Al_3Fe in the FOV for the binary alloy firstly increases from 123 to 360 (increment: 192 %) and then decreases to 135 with increasing cooling rate from 0.1 to 1.0 °C/s. The addition of 6% Cu to the binary alloy increases the number of Al_3Fe nucleus in the cooling rate range 0.1 – 1 ºC/s. The nucleation rate of the Al_3Fe in the cooling rate range 0.1 – 1 ºC /s is plotted in Fig. 3b. In the present study, the area of FOV is 2.78 × 4.46 mm^2, the thickness of the sample is 0.3 mm, hence the FOV volume is 3.72 mm^3. The undercooling in the Al-Fe alloy is approximately 8, 24, and 34 °C with the cooling rates of 0.1, 0.5 and 1.0 °C/s, respectively. The undercooling in Al-Cu-Fe alloys is approximately 37, 47, and 55 °C with increasing cooling rate.

The effect of Cu content and cooling rate on the growth of Fe-rich phases are plotted in Fig. 4. The addition of Cu in the Al–Fe alloys, Cu can solubility in Al matrix and Al_3Fe particles. Cu addition changes the formation of primary Fe-rich phases from Al_3Fe to $Al_3(CuFe)$, the Fe atoms in Al_3Fe are partially substituted by the Cu atoms. Also, the Cu addition block the Fe atoms diffusion in the Al melt at solid/liquid interface. The addition of Cu in the Al–Fe alloys resulting in the constitutional undercooling and increasing the nucleation rate of Al_3Fe particles. As the cooling rate is increased, the temperature gradient is tendency to increased. This resulting in the reduction in size of constitutionally undercooling zone (Fig. 10b). Under the higher constitutional undercooling, which promotes the nucleation of Al3Fe particles and refine their size. At low cooling rate (0.1 ◦C/s), there is a plenty of time for these atoms to diffusion to the equilibrium condition, and vice versa. Thus, the combined Cu addition and higher cooling rate resulting in the constitutional undercooling, and finally promote the formation of refined primary Al3Fe particles

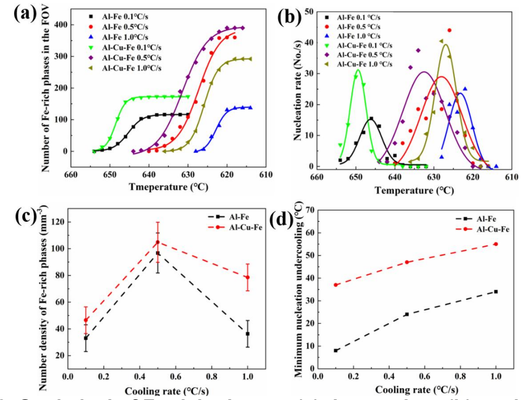

Fig. 3. Statistical of Fe-rich phases: (a) the number; (b) nucleation rate; (c) number density; (d) minimum nucleation undercooling.

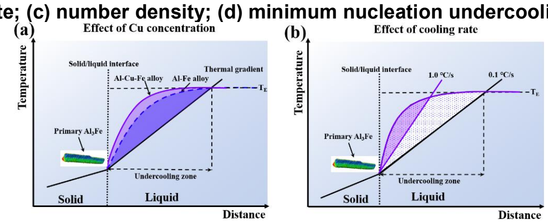

Fig. 4. the effect of Cu on the temperature profiles; (b) the effect of cooling rate on the temperature profiles.

Conclusion

1). With increased cooling rate, the number density of Al_3Fe in both alloys increases and their sizes decreases. The nucleation rate and number density of Fe-rich phases firstly increases and then decreased.

2). The increasing cooling rate and Cu addition increase the minimum nucleation undercooling of Al_3Fe in Al-Fe alloys.

Acknowledgments

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