De-Ironing of Aluminium Alloy Scrap by High Shear Melt Conditioning Technology

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Abstract

Aluminium scrap, with accumulated impurities such as Fe, is typically either downgraded to low quality cast products or diluted with expensive primary aluminium in order to reduce Fe concentration to under the allowed specification limits. However, the increasing demand of high quality components at affordable cost makes iron removal a major concern for the aluminium recycling industry. To address this problem, BCAST has developed an innovative technology, based on High Shear Melt Conditioning that enables low grade Al post-consumer crap, with high levels of Fe, to be transformed into a low cost and low carbon feedstock for high quality castings. It has been found that High Shear Melt Conditioning technology applied to aluminium scrap enhances the nucleation and growth of dense primary Fe-containing intermetallics. Due to their enhanced formation kinetics, these particles settle out rapidly allowing a simpler and faster removal of Fe from the melt. The developed iron removal technology is not limited to batch processing but can be applied to continuous melt treatment of aluminium scrap with high efficiency. The refined metal can be used in all casting processes reducing the need of primary aluminium, with the associated energy savings and impact on embodied carbon footprint.

Keywords: Aluminium alloy, Recycling, Iron removal, High Shear Melt Conditioning technology.

1. Introduction

One of the main problems of repeated aluminium scrap recycling is that iron is gradually accumulated in the molten scrap, either by mixing with high-iron containing components or from the steel tools used in processing [1]. This contamination can be reduced by a proper classification of material prior to melting and the proper coating of tools, but cannot be avoided completely.

Because Fe has low solubility in solid aluminium, it tends to form a variety of intermetallic compounds (IMCs) during solidification [2, 3], which have a detrimental effect on mechanical and corrosion properties [4]. To minimize this undesirable issue, downgrading to low quality castings or dilution with primary aluminium are the typical strategies used in industry. But, this is not a long term solution and that is why different iron removal techniques [5] have been developed in the last decades, such as gravitational sedimentation, filtration, centrifuging, electromagnetic separation, electrolysis, fractional solidification, electroslag and fluxing refining.

Despite the potential efficiency of iron removal of all the above mentioned techniques, most of them are still at a laboratory research scale for proof of concept. Among them, the simplest and relatively low cost is gravitational sedimentation. The method has been mainly applied to Al-Si casing alloys, and Fe is removed by precipitation of heavy primary intermetallics, such as $\alpha(Al_{15}(FeMn)_3Si_2)$ or $\beta(Al_5FeSi)$, when the melt is maintained above the temperature of α(Al) formation [6, 7]. Addition of other elements, such as Mn or Cr, is known to promote the formation of larger compact Fe-rich phases, thus increasing separation efficiency [5]. However, the main disadvantage of gravitational sedimentation is that, under natural cooling conditions, IMCs nucleation and growth is slow and the separation process requires long residence times to be fully effective [7], which makes it unpractical for large scale processing.

Research has shown that Fe-rich phases tend to nucleate on the wetted side of oxide films entrained in aluminium alloys [8, 9]. But these oxides are normally agglomerated and not well dispersed within the melt, and this hinders the nucleation and growth of the Fe-rich IMCs and delays their precipitation.

The use of High Shear Melt Conditioning (HSMC) technology developed at BCAST can overcome this problem as it can disperse large oxide films and clusters into very fine and uniformly distributed individual particles, thereby enhancing the nucleation of intermetallic phases and refining the grain structure [10].

We have studied the applicability of this innovative technology to improve the removal of iron from aluminium alloy scrap by gravitational sedimentation, both in batch and continuous processing.

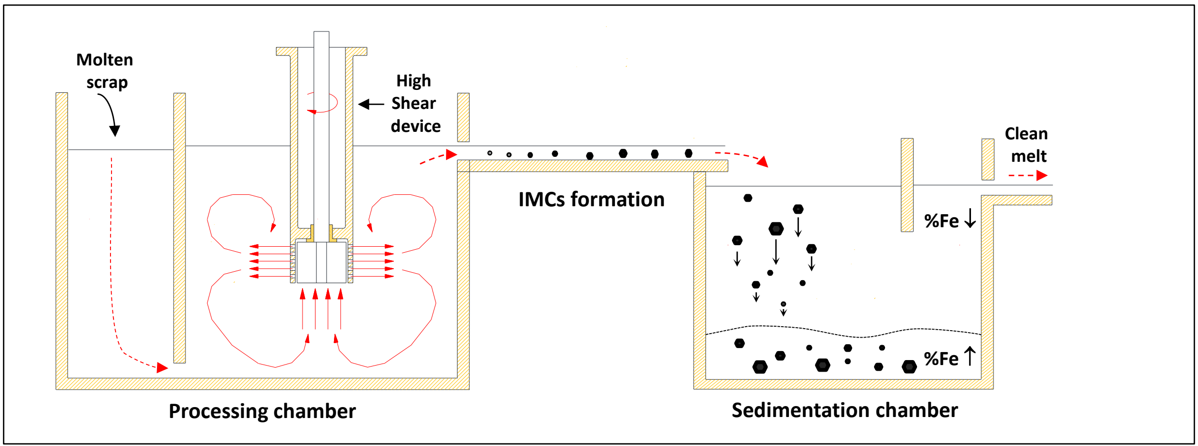

Figure 1: Schematic of High Shear Melt Conditioning (HSMC) technology for continuous processing of Al-alloy scrap for Fe removal.

2. HSMC De-ironing technology

A schematic illustration of High Shear Melt Conditioning technology (HSMC) for continuous purification of aluminium scrap [11] is shown in Figure 1. It consists of two chambers. The first one, denoted as the processing chamber, is a heated vessel with two sections, one for receiving the molten scrap and another for intensive melt shearing, using a rotor–melt conditioning unit [12]. The processing chamber has an outlet that allows delivery of the fully sheared melt to a cooling launder, where the melt temperature is reduced as it flows down. It is during this stage that the nucleation and growth of the Fe–rich intermetallic compounds (IMCs) takes place, which are carried with the flow. From the launder, the melt is transferred into the second chamber, called the sedimentation chamber, a heated vessel designed to keep the melt at a controlled temperature to allow the solidified intermetallics to settle from the melt.

The main advantage of this configuration is that "clean" material, with low levels of Fe, can be directly collected from the outlet of the sedimentation chamber due to continuous feeding of melt into the processing chamber. The chamber includes a baffle to ensure that the incoming particles remain inside and precipitate and sediment rapidly to the bottom. The particles accumulated in the bottom of the chamber can be either drained in situ or removed once the processing has finished.

3. Applicability of HSMC

3.1 Presence of Fe in recycled Al-alloy scrap

To test the efficiency of the melt conditioning technology on the removal of iron from the melt, a commercial LM24 ((A380) alloy (composition shown in Table 1), combined with Al–80Fe and Al–60Mn master alloys were used to prepare experimental alloy compositions (LM24 scrap in Table 1) simulating a typical recycled casting alloy scrap composition [5], with accumulated concentration of Fe (1%) and Mn (1%).

Figure 2, shows the equilibrium phase diagram of LM24–1Mn–xFe, calculated using Pandat software [13]. It can be observed that for 1%Fe, only one primary intermetallic phase, α($Al_{15}(FeMn)_3Si_2$), is formed before the formation of α(Al), in the range between 645°C and 595°C. The density of the α($Al_{15}(FeMn)_3Si_2$) intermetallic particles is about 3.2 g/cm^3 [14], which is denser than the molten aluminium (~2.3 g/cm^3), and therefore they tend to sediment once they are formed.

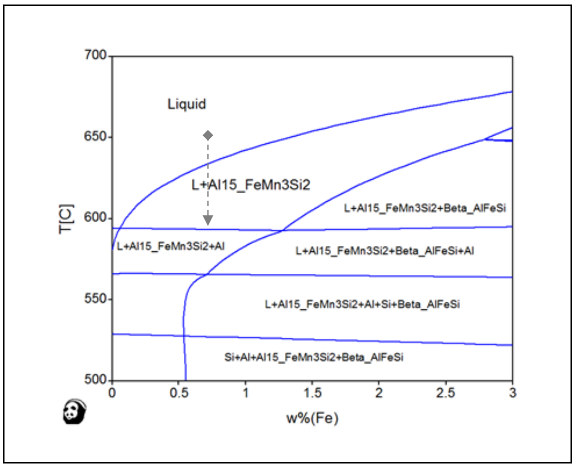

Figure 2: Equilibrium phase diagram of LM24–1Mn–xFe system.

3.2 HSMC De-Ironing in batch processing

The LM24 scrap alloy was melted in a SiC crucible in an electric furnace and then poured into the processing chamber at 650°C, where it was melt conditioned by intensive high shearing at 3000 rpm for 2min. The chamber was then tilted and the processed melt flowed along the launder, while cooling down (dashed arrow in Figure 2). The sedimentation chamber, a controlled heated steel mould (50mm in diameter and 250mm in length) was used to receive the melt and keep it at 600°C (i.e. 5°C above the temperature at which α(Al) forms) for different times before allowing the melt to fully solidify.

In a second set of experiments the molten scrap was processed in the same way but without using the High Shear Melt Conditioning technology, as a reference for typical gravitational sedimentation.

Castings were sectioned and ground for compositional analysis by optical emission spectroscopy (OES) using a Foundry–Master analyser

Table 1: Typical composition (wt.%) of commercial LM24 alloy and the composition of the material used in this study (LM24 scrap).

Alloy	Si	Fe	Mn	Mg	Cu	Zn	Ti	Ni	Pb	Sn	Al
LM24	7.5-9.5	<1.3	<0.5	<3.0	3.0-4.0	<3.0	<0.2	<0.5	<0.3	<0.2	Bal.
LM24 scrap	8.3	1.0	1.0	0.15	3.5	1.9	-	-	-	-	Bal.

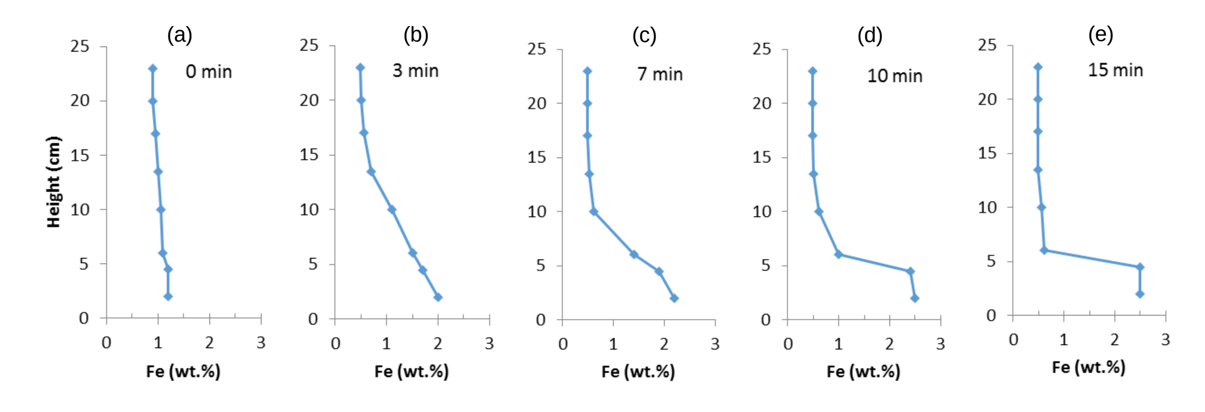

Figure 3: Fe concentration along the vertical section of the reference castings prepared by cooling LM24–1Mn–1Fe from 650°C to 600°C and holding at 600°C for different times before solidification: (a) t_{hold} = 0 min; (b) t_{hold} = 3 min; (c) t_{hold} = 7 min;(c) t_{hold} = 10 min; (d) t_{hold} = 15 min.

Figure 3 shows the content of Fe along the longitudinal section of the reference castings. For direct cooling to room temperature (no holding, Figure 3a), although a very slight increase from the top to the bottom was found, the Fe level along the sample was close to the original value (1%) because the intermetallic particles did not have the time to nucleate and grow enough to settle.

When the melt was maintained at 600°C (Figures 3b–c) a clear gradient in Fe concentration was observed. The zone near the top showed low Fe levels, while the central and lower sections showed a rapid increase in Fe level due to the accumulation of particles from the top. The transition moved towards the bottom and became more step-like with increasing holding time at 600°C (Figure 3d).

After 10–15 min (Figure 3d–e) the %Fe gradient along the sample had little change, showing that all the primary intermetallic particles had fully settled. The refined melt at the top of the casting had an Fe level of 0.5 wt.%, in agreement with calculated values and previous studies on similar compositions [7].

According to Stoke´s Law, the velocity (v_s) at which the intermetallic particles settle, assuming spherical shape, can be described by Equation 1, where g is the acceleration due to gravity, ρ_p and ρ_f are the density of particle and fluid respectively, D_p is the diameter of the intermetallic particle and μ is the viscosity of the liquid Al (~1.4 10^{-3} Pa s [14]).

$$v_s = \frac{g(\rho_p - \rho_l)D_p^2}{18\mu} \qquad (1)$$

Intermetallic sizes for this type of casting are typically in the range from 10 to 50 μm [14], which corresponds to falling speeds (v_s) between 0.03 and 1 mm/s and times from 5 to 120 min for particles formed at the top of the melt to settle to the bottom. In the present experiment, the time of 10–15min needed to fully complete sedimentation corresponds to the sedimentation of intermetallic particles with a representative size of approximately 30 μm.

This result confirmed that the natural nucleation and growth of the Fe-rich phases is not as fast enough for an efficient removal by gravitational sedimentation.

When HSMC technology was included in the process the results were different as is shown in Figure 4.

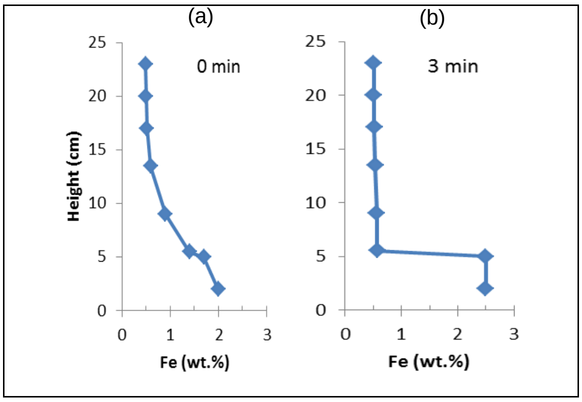

Figure 4: Fe concentration along the vertical section of the castings prepared by High Shear Melt Conditioning at 650°C during 2 min, then cooling and holding at 600°C for (a) 0 min and (b) 3 min before solidification.

In this case the iron separation was much faster. Even for a direct cooling of the melt from 650°C to room temperature (no holding, Figure 4a), the sedimentation of the intermetallic particles had already taken place in most of the casting, leaving the top half with Fe levels of 0.5%. This demonstrates that the Fe-rich intermetallic particles are nucleating and settling from the moment the melt temperature decreased below the liquidus (645°C).

When the high shear processed melt was kept at 600°C for longer time (Figure 3b) complete sedimentation of the intermetallics had taken place in less than 3 minutes, and probably within 1 or 2 minutes considering the state of casting after direct cooling. This corresponds, according to

Equation 1, to the sedimentation of particles with an average size of at least 70–100 μm, i.e. 2 to 3 times larger than without high shear melt conditioning.

This confirms that the effective dispersion of fine oxides in the molten metal by HSMC enhances the nucleation and growth of the primary Fe–rich intermetallic particles [10], in this case α($Al_{15}(FeMn)_3Si_2$).

3.3 HSMC-De-Ironing in continuous processing

As described (Figure 1), the technology can also operate in continuous or semi–continuous mode, regardless of the quantity of melt that needs to be processed, which is much more practical for industrial implementation.

Figure 5 shows the concentration of Fe in the liquid metal (average of three batches) from the equipment as a function of time (flow rate of 250 kg/h), for two types of trials, one using the HSMC technology and the other without, as a reference.

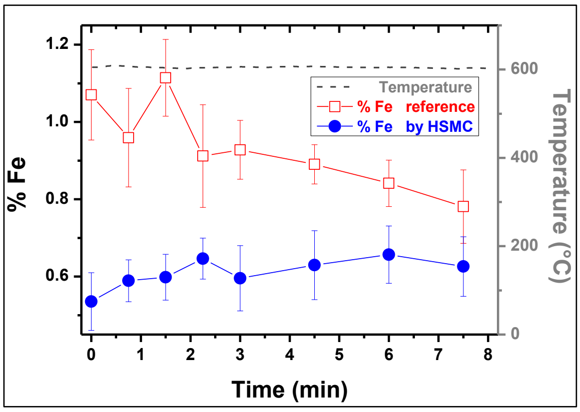

Figure 5: Concentration of Fe (wt.%) in the alloy collected from the sedimentation chamber as the molten metal starts to flow out (t=0) at 250 Kg/h.

The reference trial (no HSMC) delivered melt at the outlet of the sedimentation chamber with high Fe concentration, very close to the original concentration values. This highlights the problem already observed during batch processing, i.e. that the nucleation of the intermetallic particles is a slow process under natural cooling conditions and it is most probably took place after the melt flow had reached the sedimentation chamber. As particles nucleated and grew in the chamber, they tended to settle despite the flow and the iron level at the outlet decreased with time. However this process was again very slow and it took more than 8 min for the collected material to have a Fe level below 0.8%.

When HSMC was applied, the melt collected from the sedimentation chamber had a very low Fe concentration from the start. This result demonstrates the primary IMCs are formed along the launder connecting the processing and the sedimentation chamber. Once they reach this chamber they rapidly sediment directly to the chamber bottom.

The Fe level in the collected HSMC melt was quite stable and slightly higher the level obtained in batch processing, due to the gradual accumulation of IMCs (no removal was carried out during the trials) and the natural carryover of the intermetallic particles due to the vertical flow near the outlet of the sedimentation chamber. This could be solved by in-situ removal of the sediment particles and/or the use of filter at the outlet.

4. Summary

Gravitational separation is a simple method to remove iron from aluminium scrap due to the natural settling tendency of primary Fe–rich intermetallic particles. However, under natural cooling conditions the nucleation and growth of these intermetallics is slow, and therefore the separation process needs significant time to be fully completed.

High Shear Melt Conditioning technology applied to molten Al-alloy scrap at a temperature above the liquidus resulted in an efficient method to enhance the nucleation and growth of Fe–rich IMCs, therefore reducing sedimentation time and allowing more efficient iron removal.

This technology can be used in both in batch and continuous mode to process large melt with an efficiency comparable to other separation methods but with the major advantage of needing much shorter processing times.

These results provide high confidence for proceeding with further practical implementation of the technology at the industrial scale.

Acknowledgements

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