MULTI-PURPOSE HIGH SHEAR MELT CONDITIONING TECHNOLOGY FOR EFFECTIVE MELT QUALITY AND FOR RECYCLING OF Al-ALLOY SCRAP

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ABSTRACT

Melt quality is crucial for both continuous and shape casting of light alloys and in order to improve it, removal of excessive inclusions, accumulated impurities and unwanted gases becomes necessary. To address this problem, a new multi-purpose high shear liquid metal treatment technology, based on intensive melt shearing by a rotor/stator unit, has been developed. The device ensures achieving uniform temperature and chemical composition and an efficient dispersion of gas and solid phases in the melt with minimal disturbance of melt surface, and can be used, among other things, for de-gassing and de-ironing of Al-alloy melts. Efficient degassing is achieved by dispersing each argon bubble into many small ones, which significantly increases the overall surface area of the bubbles and the time they remain in the melt capturing hydrogen before reaching the surface. This allows using much lower inert gas flow and mixing times than conventional rotary degassing. When applied to Al-alloy scrap, with accumulated iron, the high shear melt treatment speeds up the nucleation and growth of primary Fe-rich intermetallic particles, allowing a faster removal rate. Therefore it reduces processing times, increasing recycling productivity, and facilitates full metal circulation of secondary Al-alloys.

KEYWORDS

Aluminium alloys, High shear melt conditioning, Melt quality, Recycling, De-gassing, De-ironing, Sustainability, Full metal circulation

INTRODUCTION

Aluminium and magnesium alloys are widely considered in various industrial sectors for the purpose of weight saving (Polmear, 1995). In particular, they are used in the automotive sector, where components are mostly manufactured by high pressure die casting (HPDC) because of its simplicity and relatively low cost, but efficiency and mechanical properties are quite low compared with other processes. To date, the main focus to overcome this problem has been for improving the HPDC machinery (Dahle, 2001) but little attention has been paid to the opportunities of controlling the nature and quality of the molten metal supplied to the die. In this way, liquid metal treatment, which involves a variety of physical and/or chemical processing methods to improve melt quality prior casting, is crucial for both continuous and shape casting products.

Molten metals, and especially those with high reactivity like aluminium and magnesium, have a natural tendency to absorb hydrogen from the atmosphere and to easily oxidize (Polmear, 1995). In addition, the gradual accumulation of other impurities and inclusions, due to reactions with the refractories and crucible walls and also due to allowing additions to the melt, also have a detrimental effect on the quality of the casting products and therefore its presence in the melt should be always reduced or avoid completely before solidification. The existing liquid metal treatment methods for the control and removal of gas and solid impurities from molten aluminium include chemical inoculation, melt filtering, rotary de-gassing, rotary fluxing and melt stirring by mechanical, electromagnetic or ultrasound techniques (Czerwinski, 2017).

In general, conventional casting processes offer a limited component quality at a relative low cost, in contrast to solid-state forming, which provides better properties but at a substantially higher price (Czerwinski, 2017). The techniques offering high-quality components are associated with complex multistep operations exploring the wrought path with additional hot and cold forming, machining and other shaping processes after casting. As an intermediate measure there are efforts aimed at reducing the cost of solid-state processing and at the same time at improving the quality of the castings. It is believed that the ultimate solution may only be achieved by the development of a novel technology which combines the best features of both routes and can offer the highest properties, typical for wrought products, but at the low cost and simplicity of casting products (Czerwinski, 2008).

In this way, liquid metal treatment by intensive melt shearing in a twin-screw machine has been studied and used for both liquid and semi-solid processing and improved microstructure and mechanical properties of both wrought and cast Aluminium and Magnesium alloys were achieved (Fan, 2009). Based on this principle, a novel and simpler equipment, consisting of a rotor-stator unit to provide intensive melt shearing, has been recently developed and tested at BCAST laboratory (Fan, 2010).

In this manuscript we report on the development of this innovative multi-purpose technology, based on liquid metal treatment by intensive melt shearing, and its applicability to molten metal cleanliness, particularly on its use for de-gassing and de-ironing of secondary aluminium alloys.

HIGH SHEAR MELT CONDITIONING TECHNOLOGY

The high shear melt conditioning technology (HSMC) uses a rotor or impeller which is coupled with a stationary component, with slightly larger diameter, known as stator. The system is attached to an electrical motor with a speed control unit and then immersed into a chamber containing the melt (Fan, 2010). During its operation the motor transfers the power to the rotor by the shaft and drives the rotor to spin and shear the melt in the small gap in between the rotor and the inner wall of the stator and also when the melt passes through the lateral openings of the stator. The rotation speed can be varied from 1000 to 10000 rpm providing an extremely high shear rate of up to $10^5 s^{-1}$. Since the rotor is spinning at high speed, this creates a centrifugal force that displaces upwards the melt below the unit, in a pumping action, and squeezes the same volume of melt through the rotor-stator gap and the holes of the stator. So, the unit

provides macro-flow in the melt for distributive mixing, ensuring uniform temperature and chemical composition, and also intensive shearing near the tip for effective dispersing mixing.

The main advantages of this technique include significantly enhanced kinetics for chemical reactions or phase transformations, uniform dispersion, distribution and size reduction of solid particles and gas bubbles and also forced wetting of usually difficult to wet solid phases in the liquid metal. Hence, this high shear technology can be used for physical grain refinement by dispersing naturally occurring oxides, for degassing of melts, for preparation of metal matrix composites and also for the preparation of semi-solid slurries.

The technology can work in batch configuration by direct immersion of the rotor-stator unit in the crucible with the melt and then processing for certain time to ensure complete melt treatment. As shearing effect is higher in the vicinity of the tip of the device and decreases with distance, for each unit size and rotor speed there is a limitation in the volume of melt that is going to be fully effectively processed. To magnify the shearing effect, more units could be installed in parallel inside the same crucible. An alternative and simpler solution is the use of a continuous in-line system to process the melt (Fan, 2016). Figure 1 shows the schematic of this system, which consists of two chambers. The first one, denoted as the processing chamber, is a relatively small heated vessel with two sections, one for receiving the molten scrap and another for intensive melt shearing, using the rotor-stator unit. The processing chamber has an outlet that allows delivery of the fully sheared melt by overflow. Although the higher the rotor speed the higher the pumping effect and the overflow rate, under steady state conditions the discharged rate (outlet melt flow) is directly controlled by the inlet volume of melt. In that way if the inlet flow is stopped the device works in batch configuration. The processing chamber also includes an inlet for the injection of inert gases which can be used for de-gassing or inclusion removal by flotation.
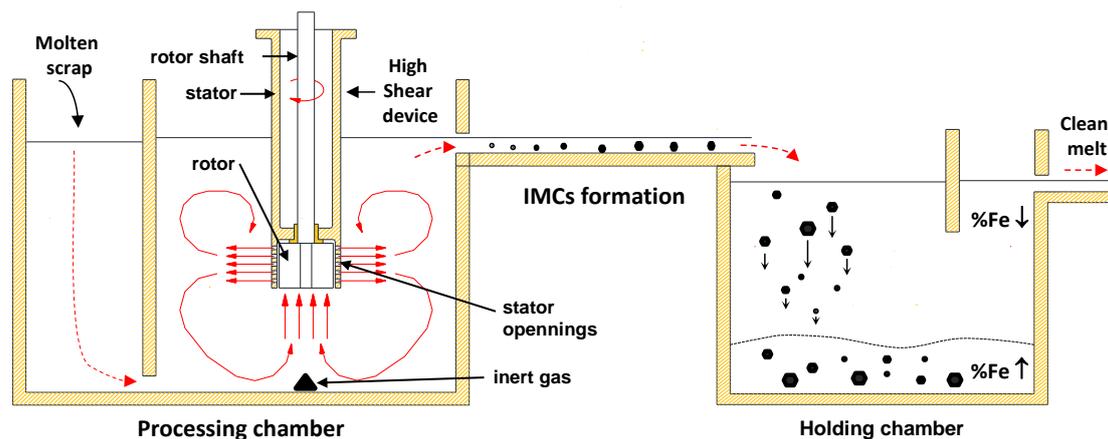

Figure 1. Schematics of the multi-purpose high shear melt conditioning technology with can operate both in batch and continuous mode

The discharged melt from the processing chamber flows down a controlled launder towards the second chamber, denoted as holding chamber. This is as well a heated vessel; designed to keep the processed melt at a controlled temperature, allowing dense solid particles (such as Fe-rich intermetallics) to sediment at the bottom of the chamber. The main advantage of this configuration is that "clean" material, with low levels of impurities, 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 solid particles remain inside, either floating, in which case the dross can be easily skimmed off or settling and accumulating at the bottom of the chamber, in which case they can be either drained in-situ or removed once the purifying processing has finished

EXPERIMENTAL VISUALIZATION OF HIGH SHEAR DISPERSION IN WATER

In order to demonstrate the effect of high shear melt conditioning technology on the dispersion and distribution of solid and gas phases in the molten metal, an experimental verification of the concept has been performed using a water-air system. With this configuration the process can be directly observe without the need of indirect 3D computing methods or the use of tracking tomography systems which complicates the design of a high-temperature experimental setup (Klaasen, 2014). In addition it allows to directly determining the dispersion mechanisms and the optimum parameters for an effective dispersion, of bubbles in this case, all over the volume of the processing chamber. In the water experiments, two air flow rates were chosen, 1 L/min and 0.1 L/min, and the rotor speed varied from 2000 rpm until full bubble dispersion was observed. The bubble dispersion process inside the water tank with intensive high shearing was recorded with a video camera, and representative images from steady state conditions were extracted and are presented in Figure 2.
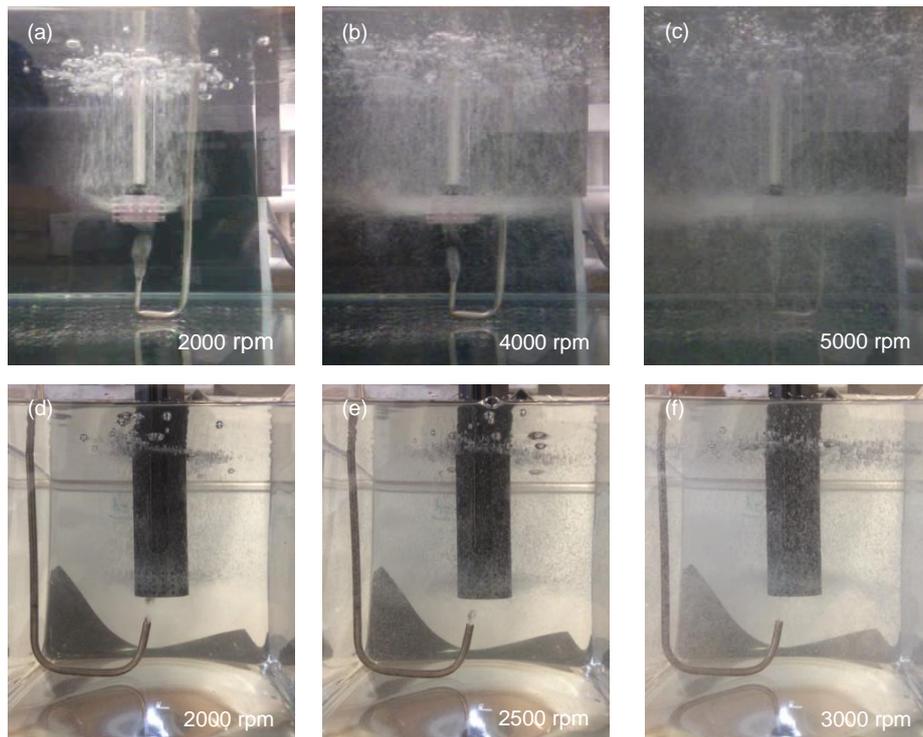

Figure 2. Visualization of high shear melt conditioning process in water when varying the rotor speed and the Ar gas flow rate: (a, b, c) 1 L/min, (d, e ,f) 0.1 L/min

When the air flow rate was set at 1 L/min and low speed (Figure 2a), large bubbles can be seen leaving the tip of the unit and at the surface just near the stator, while no bubbles are observed in the rest of the volume. The diameter of the gas bubbles released from the tube is a function of flow rate. The higher the flow rate, the larger the diameter of the bubble and the higher the speed at which it travels towards the surface without being dispersed. Appreciation of these large bubbles decreases as rotor speed increases (Figure 2b) and only when the unit is operated at 5000 rpm (Figure 2c) is when maximum bubble dispersion is observed and no large bubbles on surface. In comparison, when the gas flow rate was set at 0.1 L/min (10 times lower) the rotation speed required to achieve full bubble dispersion was only 3000 rpm (Figure 2f).

On the other hand, for the 1 L/min gas flow rate, no bubbles were observed below the high shear device up to 4000 rpm, whereas for 5000 rpm fine bubbles were uniformly distributed in the volume of

water below the high shear device. The same observation was made for the 0.1 L/min gas flow rate, with no bubbles below the unit tip at 2000 rpm (Figure 2d) or 2500 rpm (Figure 2e) but finely dispersed bubbles below the unit at 3000 rpm (Figure 2f). This was due to the high velocity jets of water from the stator holes which create a strong macroscopic flow that hit the wall of the container and then flow both upwards and downwards carrying the bubbles. The bubbles must be small enough to survive this kind of motion and as mentioned before, the lower the inlet gas flow it is more likely to happen. In that way the smallest bubbles may not escape the macroscopic flow until the mixer is actually stopped and the water is left to rest. In addition, the surface of the water when the gas flow is set to 0.1 L/min as shown in Figures 2d, 2e, and 2f is stable at all RPMs, while when gas flow is increased (Figures 2a, 2b, and 2c) the rising of larger bubbles creates surface turbulences and the need of higher rotary speed promotes the generation of vortex. This is more clearly observed in the video recordings. These characteristics are the most unique features of the high shear melt conditioning de-gassing technique.

APPLICATIONS

De-gassing of Aluminium Alloy Melts

The current industrial methods for de-gassing aluminium alloy melts include: injection of inert or reactive purge gases, plunging with a hexachloroethane (C_2Cl_6) tablet and flux addition (Davis, 1993), vacuum degassing (Iwamoto, 2007), ultrasonic degassing (Eskin, 2015), spray degassing (Wu, 2007), and rotary degassing (Warke, 2005). Among them, rotary degassing method, where Ar (or other inert gas) is supplied into the melt through a hollow graphite rotor which spins at relatively low speed (< 500 rpm), is currently the most popular method used to remove hydrogen from aluminium alloy melts. However this technique exhibits difficulties to reduce the bubbles size and effectively disperse them through the volume of the melt without causing turbulences and vortex creation near the surface, which accelerates the absorption of hydrogen (re-gassing) from the surrounding air or the entrapment of dross, both affecting the melt quality (Dispinar, 2010). As a consequence, rotary degassing requires of long processing times (up to 2 to 30 minutes) and significant argon flow rates (up to 5 to 20 L/min) to lower the hydrogen content to industrially accepted levels.

By replacing the current graphite rotor with the new rotor-stator system, each Ar bubble can be effectively dispersed into many tiny bubbles (Figure 2). This results in significantly improved de-gassing efficiency because it offers much larger liquid-gas interface for the diffusion of dissolved hydrogen. In addition, the smaller the bubbles stay longer in the melt capturing hydrogen before the reach the surface.

Efficient De-Gassing in HSMC Batch Configuration

In order to evaluate the accuracy of the experimental visualizations in water, the optimised parameters from the water experiments (0.1 L/min and 3000 rpm, Figure 2f) were applied to HSMC degassing experiments with molten aluminium in batch configuration.

The determination of the hydrogen content was done via the "reduced pressure test" (RPT) (Dispinar, 2004). This indirect method is commonly used in industry, because of its simplicity, and is based on the solidification of small amounts (~100 g) of same type of melt in steel cups both in air (atmospheric pressure) and under partial vacuum (80 mbar). The hydrogen content is then assessed by calculating the density index (D_i) from the measured densities using the following equation (1), where D_a is the density of sample solidified in air and D_v is density of sample solidified under partial vacuum. The smaller the D_i value, the lower the hydrogen content, with a direct correlation in between both magnitudes (Eskin, 2015). The industrially accepted value for obtaining a casting product free from gas porosity is an hydrogen concentration of $< 0.15 cm^3/100g$ (Davis, 1993), which corresponds to $D_i < 5\%$ (Eskin, 2015).

$$D_i = (D_a - D_v) / D_a \qquad (1)$$

Figure 3 shows the results obtained by high shear melt conditioning (HSMC) de-gassing of an A356 alloy, in terms of density index (D_i) as a function of degassing time and holding time. Initially the

non-degassed melt had a high density index (14.82%) as a consequence of the absorbed hydrogen and the RPT sample solidified in vacuum exhibited high porosity. However, only after 1 min of HSMC de-gassing treatment, the D_i dropped below 10%, with the RPT sample porosity highly refined as a consequence of the efficient dispersion, and decreased to less than 1% D_i after 4 and 7 min and to less than 0.1% D_i after 10 min. In these last samples no gas porosity was detected in the RPT samples. The lowest value of Di achieved was 0.06%, which represents a hydrogen content of 0.04 $cm^3/100g$ (Eskin, 2015). After 10 min, the HSMC degassing was stopped and the melt was left to rest for 45 min at a constant temperature. After 45 min of holding the D_i increased from 0.06% to 1.32%, which is still well below the industrially required 5%, hence the HSMC treated melt is more likely to stay degassed for longer than 45 min. This is an important result, especially for large scale casting operations where melts are held in holding furnaces for several hours before being used in a casting process.
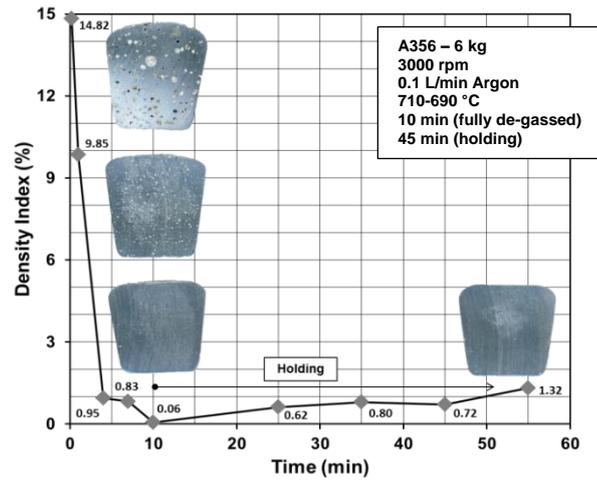

Figure 3. Density Index versus time for HSMC de-gassing of A356 alloy in batch processing configuration

HSMC De-Gassing System in Continuous In-Line Configuration

The HSMC de-gassing technology can be also applied in continuous mode by simply pouring melt into the first section of the processing chamber and collecting from the outlet. Figure 4 shows the D_i results achieved after HSMC de-gassing of an A380 alloy by using a melt flow rate of 2 kg/min, with the same Ar flow of 0.1 L/min and varied rotor speed to evaluate its influence. The HSMC de-gassing is not fully effective for low rotor speeds, in concordance with what is shown in Figure 2. However for certain rotor speed, in this case around 2000 rpm, it becomes more effective and can easily drop D_i from 12.93% to 4.66% (~ 0.13 $cm^3/100$ g), which is lower than the industrially accepted value of 0.15 $cm^3/100$ g H_2.
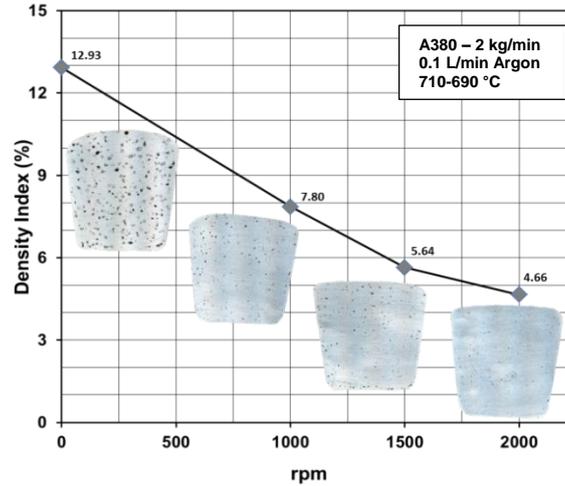
Figure 4. Density Index versus rotor rpm for HSMC de-gassing of A380 alloy at melt flow rate of 2 kg/min

De-Ironing of Aluminium Alloy Scrap

Presence of Iron in Aluminium Alloys

One of the main problems of aluminium scrap recycling is that iron is gradually accumulated, either by mixing with high-iron components or from the steel tools used during casting processes (Green, 2007), and it tends to form a variety of intermetallic compounds (IMCs) during solidification, which have a detrimental effect on the final mechanical properties.

Figure 5 shows the equilibrium phase diagram of A380-1Mn-xFe, calculated using Pandat software (Chen, 2002). It can be observed that for 1%Fe, a primary intermetallic phase, $\alpha(Al_{15}(FeMn)_3Si_2)$, is formed before the formation of $\alpha(Al)$, in the range between 645°C and 595°C. The density of this type of intermetallic particles is about 3.2 g/cm^3 (Yang, 2015), which is denser than the molten aluminium (~2.3 g/cm^3), and therefore they naturally settle. As this happens, the concentration of Fe in the liquid phase decreases, allowing the recovery of clean melt.
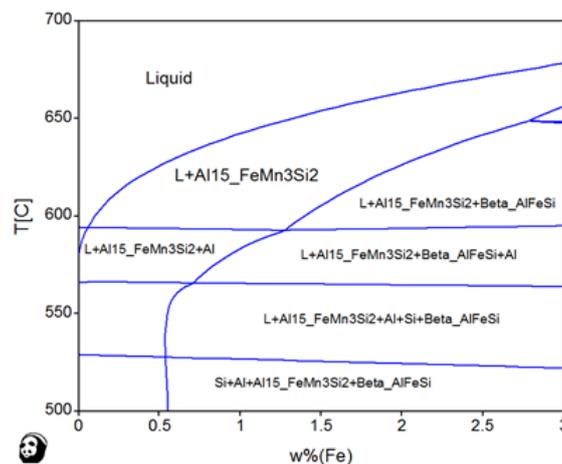

Figure 5. Equilibrium phase diagram for A380-xFe system

<u>Enhanced Nucleation and Growth of Iron-Rich Intermetallics</u>

The Fe-rich intermetallic compounds tend to nucleate on the wetted side of the naturally occurring oxide films entrained in the alloy melt (Cao, 2000). These oxides are normally agglomerated and not well dispersed within the melt, which hinders the nucleation and growth of the Fe-rich intermetallic compounds and delays its sedimentation. The use of HSMC technology can easily disperse this large oxide films into very fine and uniformly distributed individual particles, which later act as active nuclei for the formation of the Fe-rich solid phase.

In this study, the high shear melt conditioning technology for the iron removal has been tested with a commercial A380 alloy (composition shown in Table 1), combined with Al–80Fe and Al–60Mn master alloys to simulate a typical recycled A380 alloy scrap composition (Zhang, 2012), with accumulated concentration of Fe (1%) and Mn (1%). Compositions of both commercial and prepared scrap used in this study are shown in Table 1.

Table 1. Typical composition (wt.%) for commercial A380 alloy and for the material used in this study (simulated A380 scrap).

Alloy	Si	Fe	Mn	Mg	Cu	Zn	Ti	Ni	Pb	Sn	Al
A380 spec.	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.
A380 scrap	8.3	1.0	1.0	0.15	3.5	1.9	-	-	-	-	Bal.

The scrap alloy was poured into the processing chamber (Figure 1) at 650°C, and then high shear melt conditioned at 3000 rpm for 2min in batch configuration. The chamber was then tilted and the processed melt flowed along the launder, while cooling down (dashed arrows in Figure 1). A controlled heated graphite mould (50 mm in diameter and 250 mm 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).

Figure 6a shows the concentration of Fe along the longitudinal section of the castings when the molten scrap has been HSMC and then transferred to the holding chamber at 600°C. It can be appreciated that the sedimentation process is very fast. Even for a direct cooling to room temperature (0 min at 600°C), the sedimentation has taken place in most of the casting, leaving the top half with Fe levels close to the thermodynamic limit for this alloy (0.5%). Full sedimentation takes place in less than 3 minutes, evidencing the enhancement of Fe-rich intermetallics nucleation and growth from the moment the melt temperature decreases below the liquidus (645°C).
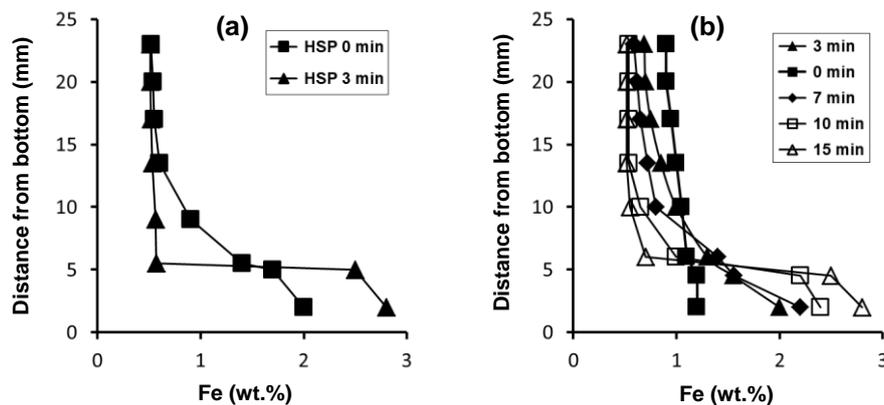

Figure 6. Fe concentration along the vertical section of samples after cooling A380-scrap from 650°C to 600°C and holding for different times before solidification. (a) after HSMC at 650°C and (b) no HSMC

On the other hand, when HSMC is not applied in the processing chamber, the natural nucleation and growth of the Fe-rich IMCs is slow as shown in Figure 6b. Direct cooling or holding the melt at 600°C for short times is not enough for the intermetallics to form on the agglomerated oxides and start settling and therefore the separation process needs a lot of time, in this case 10 to 15 min, to be fully completed. This is at least 3 to 5 times faster when using HSMC technology, making gravitational separation a more efficient and productive method for iron removal.

<u>Continuous Iron Removal by HSMC Technology</u>

As mentioned before (Figure 1), the HSMC technology can also operate in continuous or semi–continuous mode, which is much more practical for industrial implementation. Figure 7 shows the concentration of Fe in the liquid metal collected from the equipment as a function of time (at 4 kg/min), for two types of trials, with and without using the HSMC technology. When HSMC is not used, the holding chamber delivered melt with high Fe levels, very close to the original concentration values (1% Fe). 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 holding chamber and not during the cooling stage. As particles nucleated and grew in the chamber, they tended to settle and the Fe level at the outlet decreased with time. However this is a slow process and it takes more than 8 min to decrease Fe level below 0.8%. On the other hand, when HSMC was applied, the melt collected from the holding chamber had a low Fe% from the beginning. This result proves that the IMCs are formed along the launder and they rapidly settle once they reach the holding chamber. The Fe level in the HSMC melt was quite stable and close to the thermodynamic limit of the alloy (0.5%) with an increasing tendency but always below 0.7%. This increment is 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 issue can be solved by in-situ removal of the sediment and/or the use of filter at the outlet.
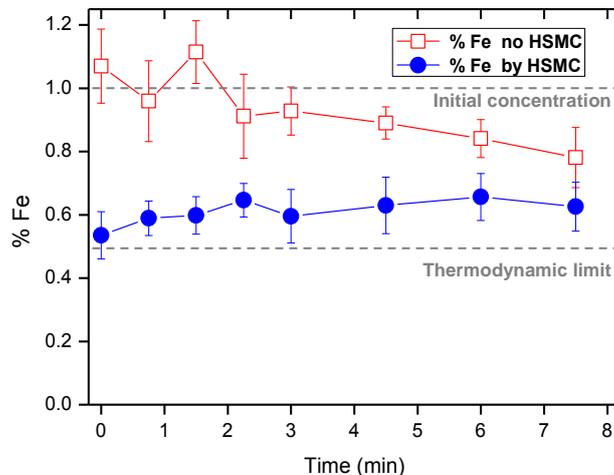

Figure 7. Fe level in the melt collected from the holding chamber as it starts to flow out at 4 kg/min

CONCLUSIONS

The recently developed technology based on liquid metal treatment by intensive melt shearing is an effective and efficient way to remove the typically accumulated gases and impurities and can be applied both in batch configuration and in continuous in-line systems for large scale operations. It is also applicable to different casting processes making it a "multi-purpose" liquid metal treatment technology for obtaining high quality melts. In terms of removal of dissolved gasses (de-gassing), the key result is that very low inert gas flow rate is needed to achieve the lowest hydrogen content values, because the HSMC technology

is able to use every supplied bubble to its maximum efficiency at the same time that keeps the surface stable minimizing re-gassing or oxide entrapments. The continuous mode of HSMC degassing requires further optimisation of parameters such as passage chamber size and volume, melt flow rate, stabilising of melt temperature, to achieve the lowest possible Di value. Further experiments are required with wrought Al-alloys especially in continuous in-line mode treatment, since this is more applicable to casting processes such as twin roll casting and direct chill casting. In terms of aluminium scrap recyclability, the HSMC is able to speed up the formation of Fe-rich intermetallic compounds making the separation process much faster, even in a continuous in-line configuration. Therefore the technology can be used together with typical sludge separation techniques with a considerable reduction in the processing times and associated costs. These results provide high confidence for proceeding with further practical implementation of the technology at industrial scale and for the removal of other types of impurities or inclusions from the melt.

ACKNOWLEDGMENTS

REFERENCES

Cao, X., & Campbell, J. (2000) Precipitation of primary intermetallic compounds in liquid Al11.5Si0.4Mg alloy. *International Journal of Cast Metals Research, 13*(3), 175–184.

Chen, S. L., Daniel, S., Zhang, F., Chang, Y. A., Yan, X. Y., Xie, F. Y., Schmid-Fetzer, R., & Oates, W. A. (2002). The PANDAT software package and its applications. *Calphad, 26*(2), 175–188.

Czerwinski, F. (2008). Magnesium Injection Molding. Springer, New York, pp.81–110.

Czerwinski, F. (2017). Modern aspects of liquid metal engineering. *Metallurgical and Materials Transactions B, 48B*, 367–393.

Dahle, A. K., Sannes, S, St John, D. H., & Westengen, H. (2001). Formation of defect bands in high pressure die cast magnesium alloys. *Journal of Light Metals, 1*(2), 99–103.

Davis, J.R. (1993). *ASM specialty handbook: Aluminum and Aluminium Alloys*. Materials Park OH: ASM International.

Dispinar, D., & Campbell, J. (2004). Critical assessment of reduced pressure test. Part 1: Porosity phenomena. *International Journal of Cast Metals Research, 17(5)*, 280–286.

Dispinar, D., Akhtar, S., Nordmark, A., Di Sabatino, M., & Arnberg, L. (2010). Degassing, hydrogen and porosity phenomena in A356. *Materials Science Engineering A, 527*, 3719–3725.

Eskin, D., Alba-Baena, N. Pabel, T., & da Silva, M. (2015) Ultrasonic degassing of aluminium alloys: basic studies and practical implementation. *Materials Science Technololgy, 31*, 79–84.

Fan, Z., Wang, Y., Xia, M., & Arumuganathar, S. (2009). Enhanced heterogeneous nucleation in AZ91D alloy by intensive melt shearing. *Acta Materialia, 57(16)*, 4891–4901.

Fan, Z., Zuo, Y., & Jiang, B. (2012). *Apparatus and method for liquid metals treatment*, WO 2012035357 A1.

Fan, Z., Ji, S. & Stone, I. (2016). *Purifying an alloy melt*, WO 2016146980 A1.

Green, J. (2007). *Aluminium Recycling and Processing for Energy Conservation and Sustainability*. Materials Park OH: ASM International.

Iwamoto, K., Yamasaki, M., & Kawamura, Y. (2007). Vacuum degassing behavior of rapidly solidified Al–Mn–Zr alloy powders. *Materials Science Engineering A, 449–451*, 1013–1017.

Klaasen, B., Verhaeghe, F., Blanpain, B., & Fransaer, J. (2014). A study of gas bubbles in liquid mercury in a vertical Hele-Shaw cell. *Experiments in Fluids, 55,* 1652.

Polmear, I. J. (1995). *Light Alloys: Metallurgy of the Light Metals* (3rd ed.). Virginia University: Wiley.

Warke V.S., Tryggvason, G., & Makhlouf, M. M. (2005). Mathematical modeling and computer simulation of molten metal cleansing by the rotating impeller degasser: Part I. Fluid flow. *Materials Processing Technology, 168*, 112–118.

Wu, R., Qu, Z., Sun, B., & Shu, D. (2007). Effects of spray degassing parameters on hydrogen content and properties of commercial purity aluminum. *Materials Science Engineering A, 456*, 386–390.

Yang, W., Gao, F., & Ji, S. (2015). Formation and sedimentation of Fe-rich intermetallics in Al-Si-Cu-Fe alloy. *Transactions of Nonferrous Metals Society of China, 25*(5), 1704–1714.

Zhang, L. Gao, J., Damoah, L., & Robertson, D. G. (2012). Removal of iron from aluminium: A review. *Mineral Processing and Extractive Metallurgy Review, 33(2)*, 99–157.