BATH MOVEMENT EFFECT ON AGGLOMERATION OF INCLUSIONS IN ALUMINIUM MELTS

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ABSTRACT

Presence of non-metallic inclusions becomes more important with increasing quality demand of aluminium products. Understanding of inclusion behaviour for different conditions is necessary to develop better inclusion detection and removal techniques. Inclusion agglomeration is one of the main issues which can be often seen in aluminium alloys. Agglomerates behave differently from single particles which causes difficulties with estimating how inclusions move in melts. Effective bath movement is present in different steps of aluminium production such as launders, casting furnaces and gas purging units. Therefore, it is important to understand the influence of different flow patterns on particles. Experiments were carried out in order to investigate behaviour of non-metallic particles in molten aluminium alloys under the stirring effect of magnetic field. The influence of bath movement on particles was observed as agglomerates under optical microscope.

Keywords: inclusion behaviour, agglomeration, magnetic field effect, turbulent flow

1. INTRODUCTION

Molten systems are always influenced by any type of bath movement in ladle, launder or casting furnace. In all kind of movement areas, we have to consider agglomeration effect of bath movement. Turbulent heat and mass exchange including turbulent bath movement are topics of great interest. Knowledge of melt flow is the key of inclusion generation, transport and interactions. One of the factors which generate strong turbulence is induction heating technology. The induction furnaces are widely used in industries for melting alloys. The main advantages of electromagnetic (EM) heating are, very fast melting and treating materials without direct contact which is important for high purity products. Beside these advantages, stirring effect of EM forces causes some unwanted phenomena. One of those phenomena is mixing of oxides by breakage of oxide layer on the melt and continuous oxidation of melt under oxidative atmosphere. Another possible unwanted phenomenon is agglomeration of non-metallic inclusions by increasing collision between particles by turbulent flow and clustering of inclusions results; faster settling in casting furnaces, better filtration of melt, and reduction in ductility. Therefore, it is important to be able to investigate and understand the agglomeration behaviour of particles.

Non-metallic inclusions in aluminium melt play critical role to reach required quality in final products. In order to develop better inclusion detection and removal techniques, it is necessary to have wide knowledge about behaviour of inclusions in molten aluminium and about how they are affected from different melting conditions. When the same material is melted in different furnace types, such as resistance, induction or gas injection, inclusions interact differently and the final product quality changes accordingly.

A fundamental research is carried out in this present work for validation of the experimental approach to investigate inclusion behaviour under turbulent flow, especially under the influence of electromagnetic forces.

2. INFLUENCES ON AGGLOMERATION OF SOLID PARTICLES IN MELTS

Particles collide with other particles and form dendritic structures due to their relative motions. This process is called agglomeration and results agglomerates and clusters. The relative motions can be Brownian motion, inhomogeneities in fluid and different forces such as electromagnetic, gravitational, shear or turbulence forces. Agglomeration can be simply described as natural tendency for minimization of energy by decreasing surface area.

If particles coalesce into each other due to collision, it is referred to as coagulation which is a special case of agglomeration. Coagulation and coalescence processes are also called for droplets which are commonly achieved by adding chemicals (coagulants) to destabilize the colloid dispersion.

Agglomeration of inclusions is a complex mechanism which is affected by different parameters such as inclusion type, size, stirring and temperature. This phenomenon was described by Levich mainly as four mechanisms which are never independent from each other. These mechanisms are Brownian agglomeration, gradient agglomeration, turbulent agglomeration and agglomeration in polydisperse systems. [1]

There are many different influences on agglomeration and cluster growth of inclusions in molten metal. It is known that stirring (turbulence) promotes inclusion clustering due to increasing collision frequency of particles. The collision between particles can also originate from gravitational motion. However, collision mechanisms are not only factors influencing clustering. Attractive forces between particles have very strong influence and those forces vary for different types of inclusions.

2.1. Collision of Particles due to Different Mechanisms

Particles collide with each other due to their relative motions and they form particle clusters. This clustering causes a reduction in the number of particles [2]. The frequency of collision for spherical particles, N_{ij}, can be calculated per unit time by equation (1):

$$N_{ij} = \beta(v_i,v_j)n_i n_j \tag{1}$$

v_i and v_j are particle volumes and $\beta(v_i,v_j)$ is a function of collision frequency between two particles i and j. This function is defined by flow type and size of particles. Moreover, n_i and n_j are concentration of individual particles in i and j ($1/m^3$).

Brownian Motion: Brownian agglomeration is one of the mechanisms related to collision. It is defined as disorganized movement of small particles in fluids. This random movement of particles is caused by collisions with molecules of surrounding medium [3]. A simulation work of Tian et al. reported that Brownian motion can be neglected for particles bigger than 10µm [22]. Random motion of a particle can be seen in Figure 1 and Brownian agglomeration can be described by equation (2).

$$\beta_b\,(v_i,v_j) = 2kT/3\mu.(v_i^{-1/3}+ v_j^{-1/3}).(v_i^{1/3}+ v_j^{1/3}) \tag{2}$$

Here, k is Boltzmann constant (J/K), T is absolute temperature (K) and µ is viscosity of fluid (Pa.S).

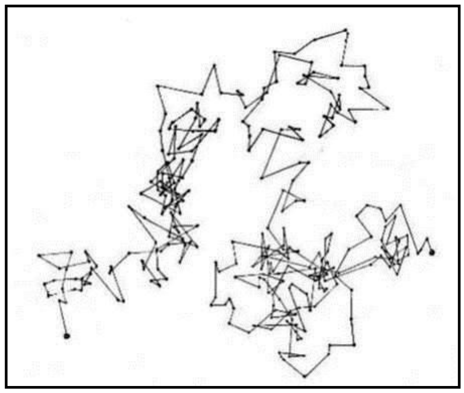

Figure 1. Brownian movemenent of a particle [5]

Turbulent Flow: Turbulent agglomeration can be understood by two processes which are turbulent inertial agglomeration and turbulent shear agglomeration. [6]

When the particles leave their flow streamlines due to inertia and promote collisions with the particles in the neighboring streamlines, this mechanism is called inertial agglomeration. In second type, turbulent shear, due to particle relative velocity gradients agglomeration, causes particles to collide with another particle in a different pathline because of their different traveling velocities. These two turbulent mechanisms can be described schematically as follows:

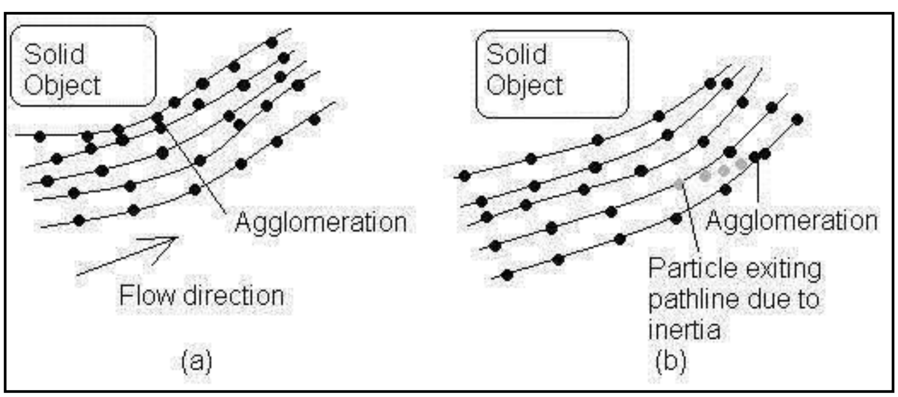

Figure 2. Turbulent agglomeration types (a) Shear Agglomeration, (b) Inertial Agglomeration [5]

These mechanisms must be well understood for further modellings and designs. Since turbulence flow has very complex and random behaviour, there are many difficulties to understand particle behaviour under these conditions [7]. Function of collision frequency can be basically calculated by equation (3).

$$\beta t\ (v_i,v_j) = \alpha_T\ 1.3(a_i+a_j)^3\ (\varepsilon/v)^{1/2} \tag{3}$$

Here, α_T is coagulation coefficient, a_i and a_j are the radii of the spherical particles (m) and ε is the dissipation rate of turbulent kinetic energy.

Turbulent flow appears very often in induction heating furnaces. Therefore, understanding of particle movements in turbulent conditions plays an important role to be able to optimize the heating processes.

Gravitational Motion: Small particles settle slowly down in a fluid and the settling velocity increases with increasing size of particle due to higher gravitational forces (F_G) [2]. The function of collision frequency of particles due to different gravitational forces can be basically defined by equation (4):

$$\beta_d\ (v_i,v_j) = \pi\ (a_i-a_j)^2 \left| v_i-v_j \right| \tag{4}$$

Here, v_i and v_j are the settling velocities of the particles (m/s).

During this settling process, the larger particles catch up and collide with smaller particles and it might cause agglomeration. This phenomenon is almost always present in all molten metal systems since there are always inclusions in different shapes and sizes. The mechanism can be seen in Figure 3.

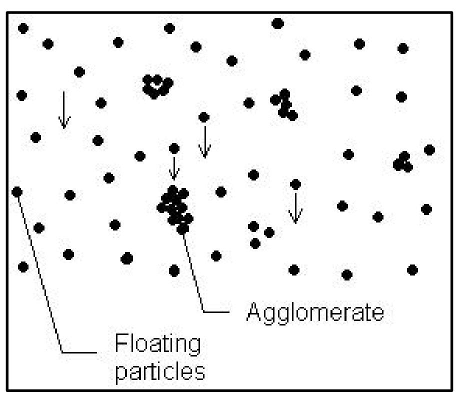

Figure 3. Agglomeration due to gravitational effect [5]

Velocity gradients between particles can be affected by particle shapes due to different drag coefficients (C_D). Drag forces (F_D) vary for each shape and it has strong influence on settling or floating velocities. Another effect is caused by density of the melt which directly affects the buoyancy force (Fv). Main forces acting on a particle in melts are shown in Figure 4 without taking other mechanism such as convection and interaction between particles into consideration.

Each particle has its own nature such as, density, shape and size. Particles are influenced by melt flow differently according to their characteristics. Therefore, the experimental researches must be performed with defined particle type and size in order to understand the mechanism more specifically for different parameters.

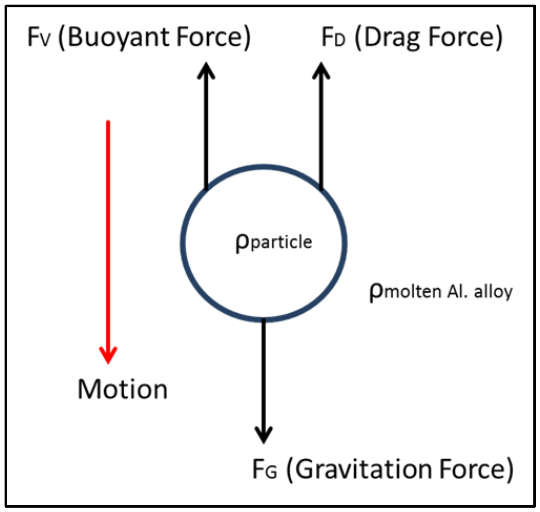

Figure 4. Forces acting on a particle in a melt while settling [8]

It is possible to calculate settling velocities of particles according to Navier-Stokes equations however the equations are useful for spherical particles under laminar flows. It is hard to work with laminar flow and perfect spherical particles in practice.

2.2. Agglomeration due to Attractive Forces

Although it is known that melt flow has a strong effect on particle agglomeration, it is not the only crucial factor. Agglomeration tendency of some different particles such as alumina, calcium aluminate and spinel was investigated in the work of Kang et al. It was reported that agglomeration tendency of each particle nature is different from each other and this difference is caused by attractive forces. [9]

Every particle attracts other particle by a force which is proportional to masses and inversely proportional to square root of distance between those two particles. The force is called gravitation force (F_G) and can be described by Newton's law (5) of universal gravitation:

$$F_G \propto M_1.M_2/R^2 \tag{5}$$

In some particular cases, the attractive forces can even dominate the bath movement. This mechanism has been investigated by Yin et al. and they reported that the attractive forces are a very dominating factor especially for alumina particles. Figure 5 presents an interesting explanation of attraction between particle A and B. Every step in the image presents 1/30 second interval and decreasing distance between two alumina particles can be clearly seen in each step. Distance between two particles decreases with an increasing rate and almost vertical to flow direction which shows how strong the attractive force is.

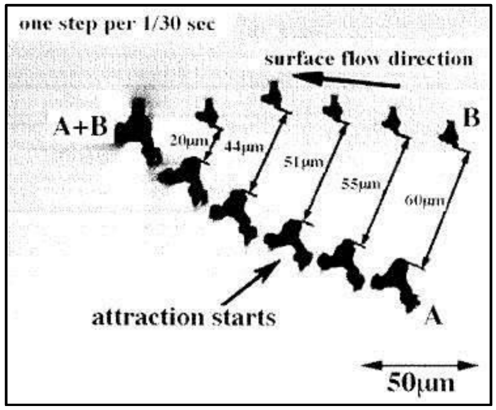

Figure 5. Sequence of agglomeration caused by strong attraction between alumina particles [10]

The distance between particles has also influence on attraction forces. Figure 6 presents the aggregates A and C, moving towards cluster B by surface flow. Aggregate reached the minimum distance of 30 µm to the cluster and it became a part of B due to attraction forces. On the other hand, the closest distance of aggregate C to the cluster B was 50 µm, and it was driven away by surface flow. In case b, melt flow was not able to dominate attractive forces due to longer distance between cluster and aggregate [10].

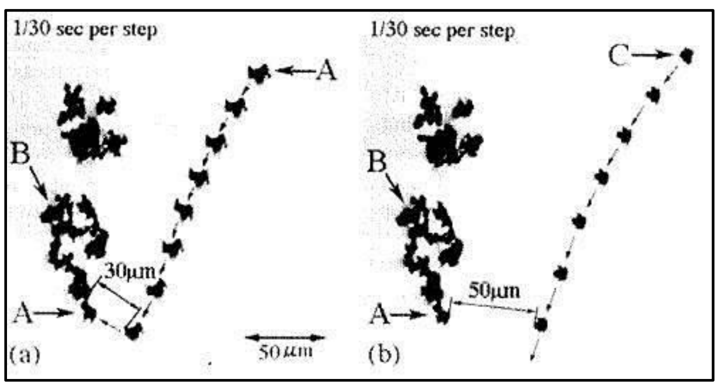

Figure 6. a) attracted b) not attracted alumina particle by cluster [10]

Kimura et al. calculated attractive forces in their work by Newton´s equation and they reported that the attractive force between alumina particles is between 5.10^{-17} and 5.10^{-15} N. This value is almost the biggest attractive force between inclusions found up to now 11. There are not many works about attractive forces between defined particles but it is known that those forces must be taken into account by comparing different inclusion families.

2.3. Wetting Behaviour of Particles in Melt

Influence of wetting behaviour of particles on agglomeration has been discussed in few articles. In the work of Sarina Bao, wetting of Al_2O_3 and SiC was measured on aluminium and concluded that Al_2O_3 has poorer wetting than SiC on aluminium. This result was interpreted that, poor wetting of Al_2O_3 might be the reason of better clustering tendency of particles [12].

Kumar et al. and Gazanion et al. investigated settling behaviour of inclusions after adding grain refining master alloys in liquid aluminium. TiC and TiB_2 agglomerates were seen in experiments and agglomeration tendency of TiC was poor than TiB_2 particles. Kumar reported that this tendency difference might originate from good wettability of TiC particles in Al-melt [13]. High tendency of clustering was also proved in a work of Guo [14].

Possibly, wetting of inclusion in Al-melt plays important role for agglomeration. On the other hand it is know that, wettability of Al-melts vary by alloying [15]. Agglomeration tendency of inclusions changes probably by alloy composition which should be also investigated.

3. BATH MOVEMENT WITH SPECIAL FOCUS ON INDUCTION HEATING

Bath movement is generally present in most steps of aluminium production chain which is presented in Figure 7. Strong metal flow appears in launders, casting furnaces and gas purging units. Size of aggregates might change after these steps just because of the movement of molten metal. This size change due to clustering might have advantages and disadvantages but the key point is to understand the fundamental effects of different flow mechanisms on particles.

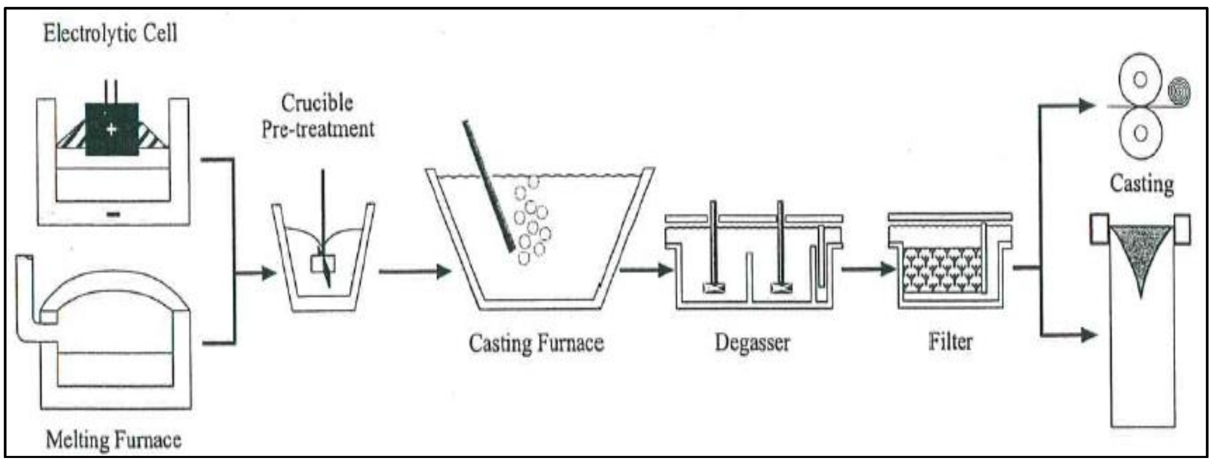

Figure 7. Molten aluminium processing steps [16]

Principle of Induction heating is based on the relationship between magnetism and electricity. Induction heating principle can be described by electromagnetic induction theorem and Joule-Lenz’s law. An alternating voltage is applied to an induction coil. This voltage results an alternating current in the coil circuit which produces in its surroundings a time variable magnetic field and it has the same frequency as the coil current. The strength of magnetic field depends on the coil geometry, the current in the induction coil, and the distance from the coil. Alternating eddy currents produce heat by the Joule effect [17]. Heat generation is shown in equation (6) and it is proportional to resistance and square of current.

$$Q= i^2.R \tag{6}$$

A conventional induction heating system that consists of a cylindrical load surrounded by a multiturn induction coil and flow cycle of melt is shown in Figure 8. The heat produced by electromagnetic (EM) field, heats and melts a conducting material. The electromagnetic induction theorem can be described as following; when magnetic flux passes through the plane that is limited by each closed loop changes as time, the closed loop can produce motional electromotive force which is the magnetic force component of Lorentz force. [18] The force is presented in equation (7) with electric force “qE” and magnetic force “qv × B” components.

$$F= q(E+VxB) \tag{7}$$

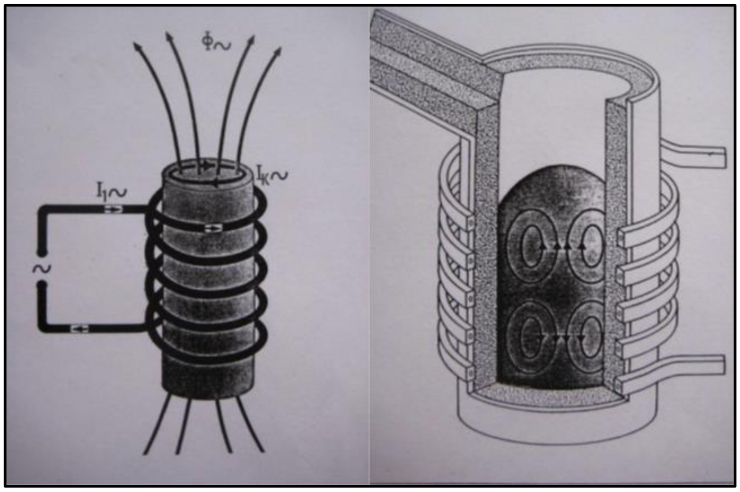

Figure 8. The principle of the heating system in an induction furnace (left) and the flow cycle in the crucible (right) [19]

The molten metal behaves as moving conductor with velocity $\vec{V}$ and it flows perpendicular across magnetic field $\vec{B}$ of the magnet. This initiates the movement of liquid metal and results some characteristic phenomena which are bath cone and bath movement (see Figure 9). Magnetic field is proportional to the velocity of the flowing metal which corresponds to Reynolds numbers greater than 10^4 and the melt velocity is influenced by; density and viscosity of the melt, type of crucible, frequency of induction system, and diameter of coil [20]. Melt velocity is defined by following equation (8):

$$v_{melt} = I_{coil}.(f.\ \lambda/\rho)1/2.\mu \tag{8}$$

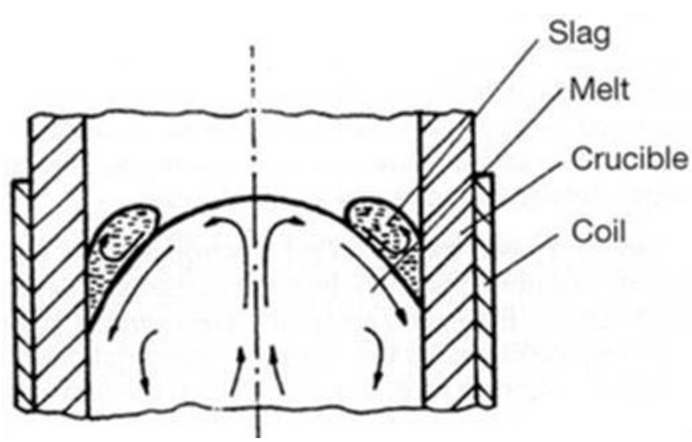

Figure 9. Bath cone and current melt and slags [21]

Turbulent flow is desired in particular cases due to its positive effects such as improvement of final product quality by effective melt mixing and homogenization of the melt. On the other hand, construction of melting equipment is more complicated and more expensive than a resistance furnace. Moreover, it is well known that inclusions are strongly influenced by melt flow. [20]

4. EXPERIMENTS

4.1. Experimental Setup

A schematic view of the experimental setup is presented in Figure 10 which consists, an induction coil, a clay graphite crucible with inner diameter of 70mm^2 (0,2 l) and a K-type thermocouple. The induction furnace with a maximum power of 50kW and the frequency of 10 kHz was used for melting the inclusion containing aluminium alloys in order to generate turbulent stirring in melt.

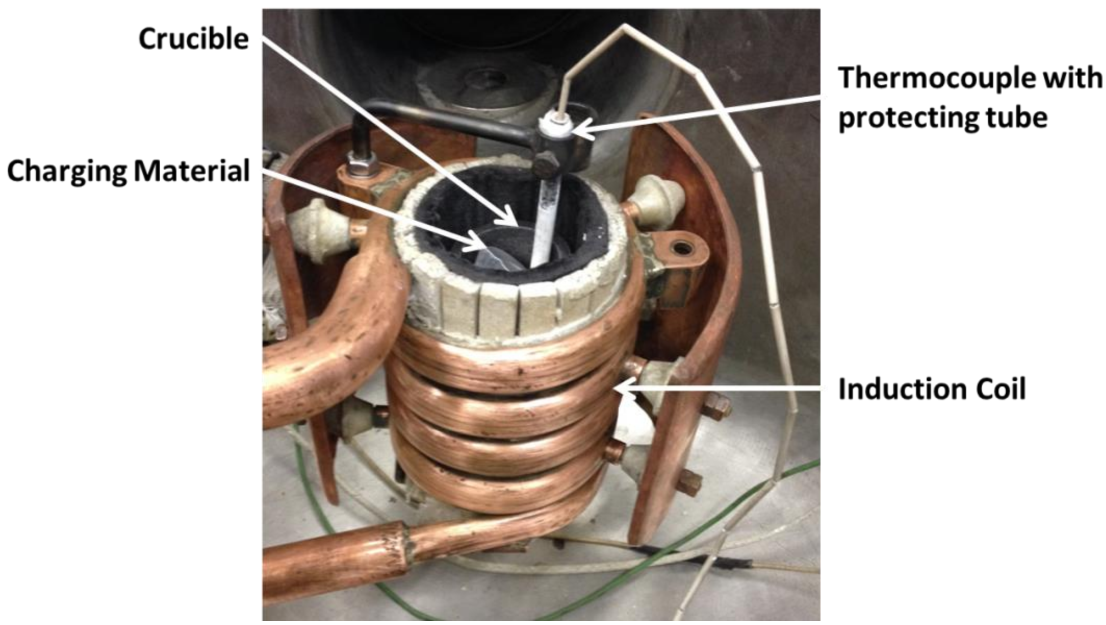

Figure 10. Experimental setup in an induction heating furnace

Temperature of molten metal was measured by an external thermocouple in order to reach desired temperature and to be able to manipulate the power of furnace in the range of 5.5 – 5.7 kW. Necessary heating power varies due to material amount and type.

4.2. Experimental Procedure

Aluminium alloy with defined inclusion types were charged into induction furnace. The inclusion content of melt was targeted to 0.5wt% for different inclusion chemistries. Molten metal was hold under magnetic field to stir the melt by electromagnetic forces. Experiments were carried out for different durations to be able to observe the influence of turbulence duration on agglomeration. Bath movement caused by electromagnetic forces was clearly observed as bath cone during the experiments. Bath cone with a breakage of oxide layer is shown in Figure 11.

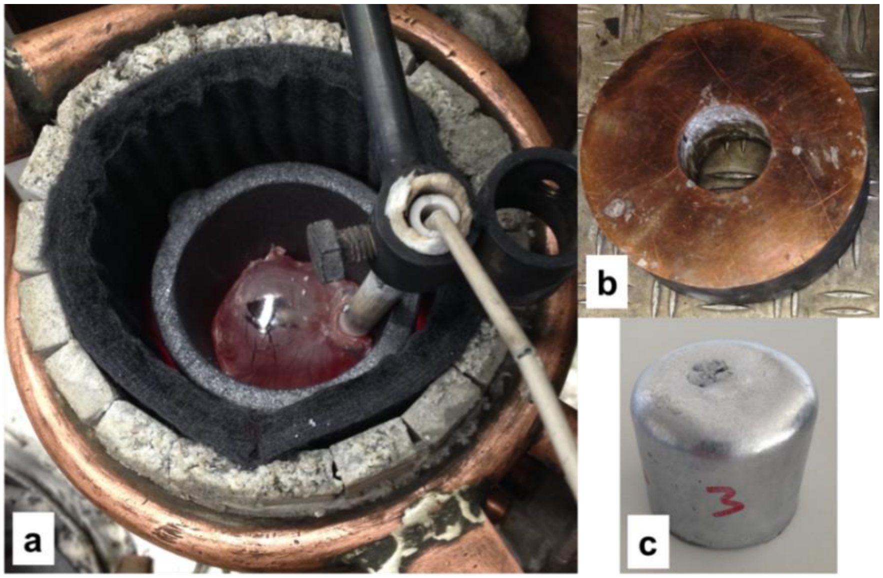

Figure 11. a) Experimental setup from top view and bath cone, b) copper mould, c) sample

After a certain holding time, molten aluminium was casted into a thick copper mould to accelerate the solidification. Cross-section of each solid sample was firstly polished and a defined area was scanned under light microscope. Images (50X magnification) were collected for each cluster and afterwards images were characterized by Image Analysis Software in order to define surface area, axis lengths, inclusion amount and form factors of clusters.

5. VALIDATION OF THE EXPERIMENTAL APPROACH & OUTLOOK

Agglomeration exists almost in all molten systems however, it is not easy to detect or analyze. Generally simulation or numerical works are performed but it is important to be able to understand the mechanisms in-situ.

After a detailed literature survey, it was seen that although the existence of clustering of inclusions is known, there is a huge blank about formation mechanisms, isolation or promotion of clustering in melts. This motivation ended up with some preliminary experiments to validate an experimental lay-out which is practical and capable to investigate the mechanisms playing role in clustering.

First results showed that it is possible to observe the effect of bath movement on agglomeration behaviour of particles. Two exemplary images are shown in Figure 12 and different growth tendencies of particles were observed. Experiments were carried out with approximately 0.5wt.% of inclusion amount and image analysis of following agglomerates showed that the agglomerates were quite high concentrated in comparison with starting concentration. Particle concentrations of following agglomerates are 19.37% (left) and 24.7% (right):

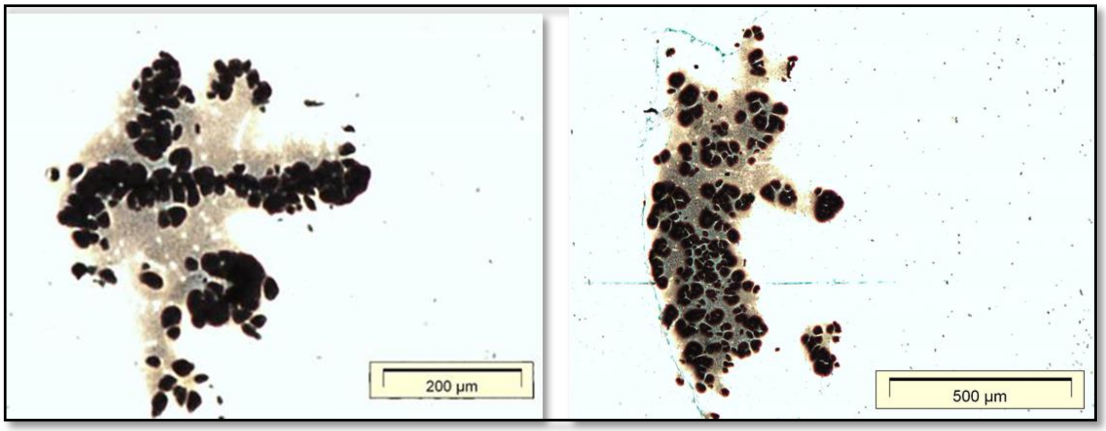

Figure 12. Exemplary images of different agglomeration behaviour of inclusions

Holding and stirring are very important parameters because particles might also decluster after a certain holding time or by very strong turbulences due to intense shearing [22]. Another important parameter is crucible shape. Different diameters of crucible generate different magnetic forces which directly affects the turbulence of melt. Moreover, different crucible shapes might cause different wall effects. Inclusion type and size are also important because of different attractive forces. Those parameters will be deeply investigated by additional experiments and the full-paper will be published with more specific results in a peer review journal after this conference.

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