New method for a large-scale levitation melting and casting of Titanium parts

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Abstract

A novel method for the crucible-less large-scale levitation melting (LM) of metals is developed. Numerical simulation has been used to verify the new method and to design a pilot LM furnace capable for a contact-less melting of metallic samples with increased weights. The designed prototype has been successfully validated by experiments with aluminum samples up to 500 g. Levitation melting and casting simulations with Ti-6Al-4V samples (500 g) confirm applicability of the novel concept for Ti-based alloys. This concept is for the first time applied for ALD's newly developed investment casting furnace – called *FastCast*.

Introduction

Crucible-less levitation melting (LM) and single-batch casting of titanium alloys (e. g. for turbocharger impellers up to 500 g) has many advantages over multi-piece castings with induction furnaces using ceramic or cold crucibles.

First of all, electromagnetic (EM) levitation prevents contamination of the melt with the crucible material and results in a superior and reproducible quality of alloy. Heat losses from the liquid metal are reduced and limited to radiation and evaporation that permits fast melting and much higher overheating at less energy consumption. Additionally, contact-less single-shot castings of the levitated melt can be precisely controlled by the current in the coil. Due to the small melt-cast cycle time the process retains productivity comparable with the conventional multi-batch investment castings, while simpler design of the crucible-less LM furnace and utilization of smaller single-batch molds have strong economic benefits. Apart from that, the new method breaks down the statistical nature of a single product quality in case of a multi-piece casting, advances production to the "one-piece-flow" concept and meets requirements for process digitalization.

However, in conventional axisymmetric LM furnaces, already known since 1920's [1], the Lorentz force vanishes on the symmetry axis and the melt leakage can be hindered mainly by the melt surface tension. Therefore, only small molten metal samples up to 50-100 g can be levitated in conventional way and the scale-up needs for the great range of industrial applications remain unsatisfied [2].

We used numerical simulation to develop the new levitation melting method to design and optimize a pilot LM furnace capable for a contact-less melting of metallic samples with increased weights. The designed prototype has been successfully validated by experiments with aluminum samples up to 500 g [3]. Further simulations with Ti-6Al-4V samples (500 g) confirm applicability of the method for Ti alloys and reveal conditions for optimal castings and melt solidification in the mold.

Numerical model and conventional EM levitation melting

Computation of EM induced flow and free surface dynamics is ensured by means of coupling between:

- EM field and Lorentz force recalculation in *ANSYS*,
- Volume of Fluid (VOF) Large Eddy Simulation (LES) of a two-phase turbulent flow in *FLUENT* and
- a free surface shape filtering and reconstruction in *CFD-Post*.

By means of repeating the calculation loop a numerical model for simulation of turbulent flow and free surface dynamics of liquid metal in EM fields of different frequencies has been implemented [4].

First experimental investigations of conventional EM levitation melting of aluminium samples (m = 21.5 g) have been performed by *Okress et al.* in the early 50s [5]. The experimental setup consisted of two coaxial inductors - upper pancake coil and a lower cone-shaped coil. In order to verify the model we have decided to repeat the experiment ourselves. As the sample was completely molten, series of experiment photos were post-processed, and a time-averaged free surface shape of liquid aluminium charge was obtained (Figure 1).

The fine turbulent flow structures resolved with our 3D/VOF/LES model reach up to 1 m/s in instant velocity magnitude and, on account of dynamic pressure, contribute to the free surface fluctuations that are also observed in experiments (Figure 2).

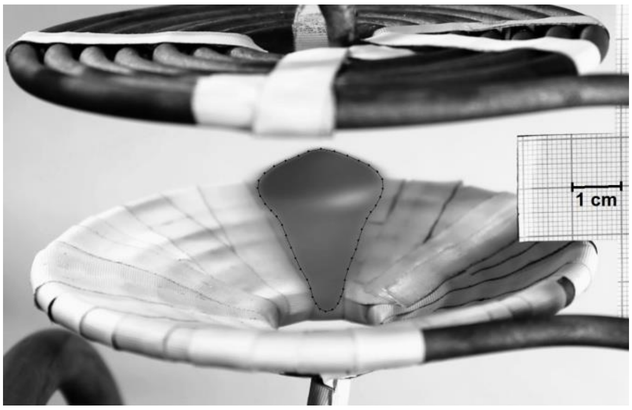


Figure 1. Our experimental setup for repeating of conventional levitation melting experiment with a post-processed time-averaged shape of the molten Al droplet

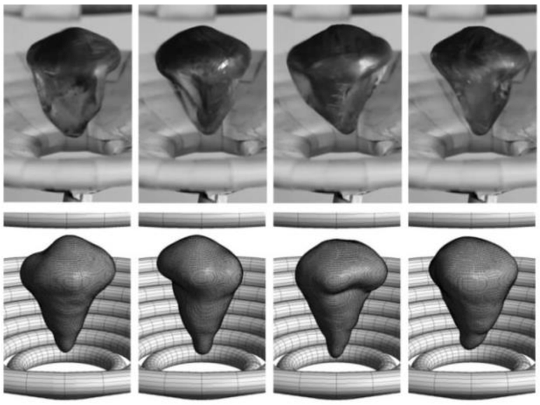
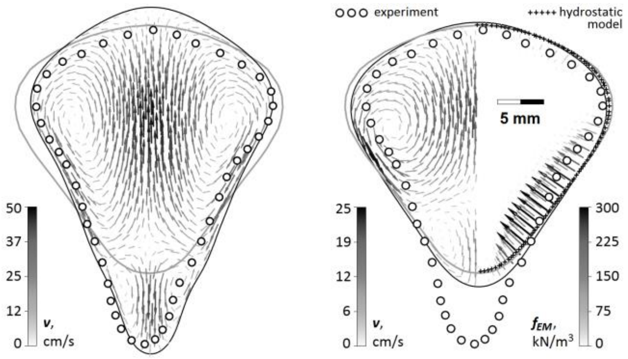


Figure 2. Experimentally observed (upper row) and 3D/VOF/LES simulated (lower row) dynamics of the levitated Al droplet



(a) (b)

Figure 3. Time-averaged droplet shape (black line) and flow calculated with (a) - 3D/VOF/LES and (b) - 3D/VOF/k-ω SST model in comparison with experiment (circles), hydrostatic approach (crosses) and 2D/k-ω model (Bojarevics et al - grey line). Note the typical Lorentz force (f_{EM}) distribution with a zero on the symmetry axis

Maximal velocities of the time-averaged flow, calculated with 3D/VOF/LES model, reached 0.5 m/s and on account of sensible hydrodynamic pressure contributed to a more axially-stretched time-averaged shape of the droplet. Therefore, much better agreement with the experimentally measured time-averaged droplet shape was obtained (Figure 3).

Unlike widely used k-ω and k-ε turbulence models that overestimate eddy viscosity and predict "hydrostatic" steady shape due to less intensive flow, the 3D/VOF/LES model is also able to predict correctly the critical AC current value at which the leakage of the melt will occur on the axis. This is a crucial model capability if it has to be applied for designing new levitation melting equipment.

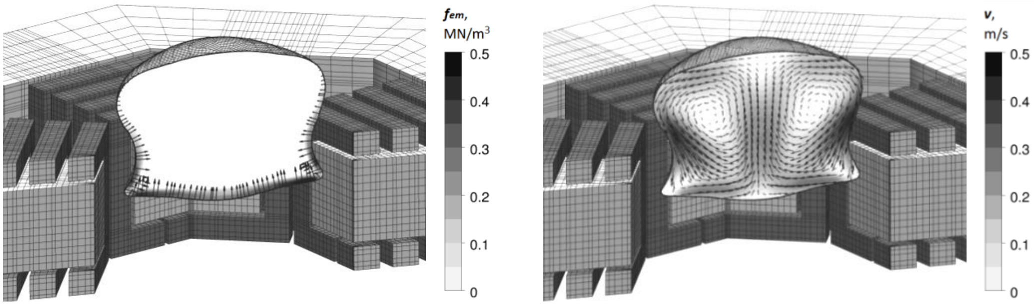
The novel method for the large-scale EM levitation melting and casting

The new method applies two EM fields of different AC frequencies, whose field lines in the absence of a charge are horizontal and orthogonal in order to exert EM lift forces also at the axis of the levitated sample. Therefore, the charge weight can be increased and the charge can be drip- and leakage-free melted. The method for EM levitation melting in horizontal fields has been successfully validated by a series of experiments and simulations with small samples up to 40 g. Using the developed numerical model, the two-frequency EM levitation melting furnace has been scaled-up and redesigned to meet conditions for the levitation melting of 500 g of aluminium.

The 3D transient calculation with LES turbulence model shows that the novel two-frequency EM field configuration enhances the Lorentz force confinement (Figure 4) and allows contact-less levitation of a scaled-up portion of molten aluminium (500 g).

Following the simulation-aided design of the coil arrangement (Figure 4) we have manufactured an experimental setup for the levitation melting of Al samples with increased mass and carried out series of tests at air. Good agreement between experiments (Figure 5 and 6, a) and 3D simulations (Figure 5 and 6, b) has been obtained for the liquid metal position and shape. Oscillations of the free surface of the melt indicated on the intensive turbulent flow caused by the Lorentz forces.

Using numerical modelling the coil arrangement was further optimised since the levitation melting of Titanium alloys face advanced requirements. Additionally, the problem of ferrite heat-up has been solved. Simulations have also helped to design the pouring of the levitated melt in a safe, controlled and contact-free way.

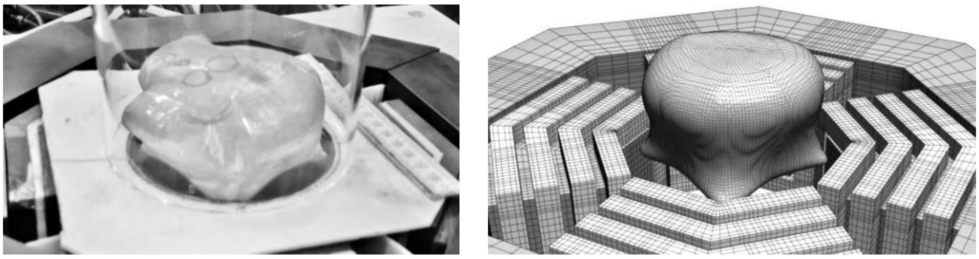


(a) (b)

Figure 4. 3D/VOF/LES model of the two-frequency EM levitation melting furnace with levitating molten Al sample (m = 500 g). Lorentz force (a) and time-averaged flow (b) are shown on the vertical cross-section

(a) (b)

Figure 5. Levitation of solid and fully molten Al sample (m = 250 g) in experiment (a) and predicted by our 3D numerical simulation (b)



(a) (b)

Figure 6. Levitation melting of 500 g of Al in a two-frequency setup: (a) experiment and (b) 3D simulation

Besides extensive investigations around the melting conditions, simulations for different mold filling scenarios were conducted by Access e.V. in Aachen, Germany (Figure 7). It provided valuable information how to release the molten material and how to catch it by the ceramic mould in order to ensure best filling capabilities. These results were considered in the furnace and mold arm design.

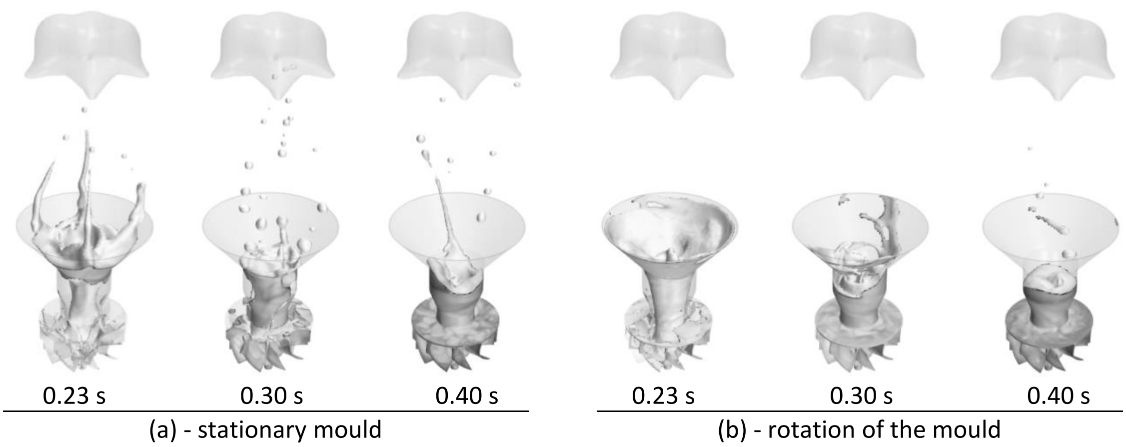


Figure 7. 3D numerical results for the discharge of the Ti64 melt (500 g) due to the AC current switch off, (a) – casting in the stationary mould, (b) – casting in the rotating mould with reduced melt splashing.

New investment casting furnace - *FastCast*

ALD has decided to apply the "state-of-the-art" levitation melting system and advantages of the novel method for real investment castings with ceramic molds and launched "*FastCast"*. Combining all gathered simulation results and ALD's expertise in investment casting, a demonstrator furnace has been designed and manufactured (Figure 8).

The demonstrator is made for 10 consecutive castings. Maximum melt weight is limited to 500 g / 1.1 lbs of Ti-alloy or 250 g / 0.55 lbs of superalloy. The furnace operates under vacuum or inert gas atmosphere. Once the furnace is loaded the castings run fully automated. The furnace concept can be integrated into production lines with fully automated and continuous material flow (Figure 9).

The ingot is guided from the top into the AC magnetic field that ensures levitation. The sample gets molten and overheated by around 100 ^{0}C above the liquidus temperature in less than 30 s (whereas higher superheat is possible). During the melting Lorentz forces lead to intensive stirring and a great level of melt homogenization. In the meantime a ceramic mold is transferred out of the mold chamber right below the AC coils. After a preprogrammed melting sequence the molten material is released into the mold. The mold arm provides the capability for static or spin casting, and a fast withdrawal along with the material drop. After the single-shot casting is completed a new ingot is loaded and the previously casted part is transferred into the lock-out position. Protection measures were thoroughly engineered to keep the production conditions stable.

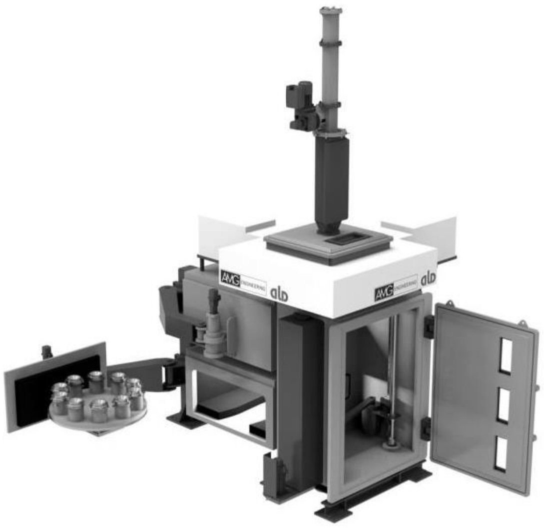


Figure 8. The *FastCast* Demonstrator

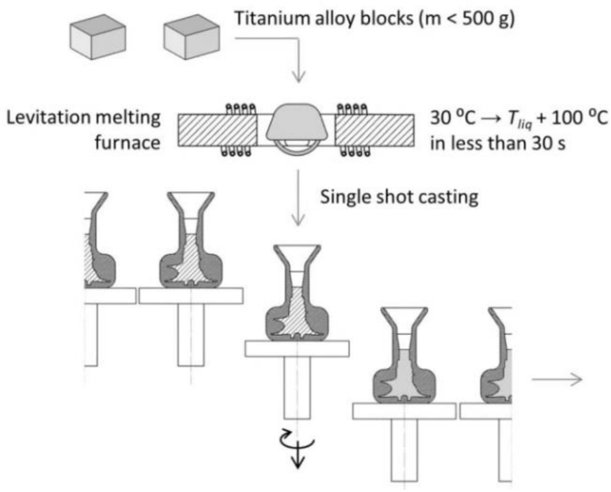


Figure 9. Continuous concept for the *FastCast*

Conclusions

FastCast overcomes boundaries of conventional casting methods with ceramic or copper crucibles. Levitating in a magnetic field, the metal has no contact with or contamination from other materials during heating up to the moment when the melt enters the mold. No crucible or other refractories are used.

In this way, the melt achieves much higher superheat (compared to copper crucibles) that improves mold filling, especially for parts with fine shapes. Moreover, much higher superheat of the melt can compensate the reduced preheating temperature of the mold.

Main applications are parts made of Titanium or other reactive materials for automotive, aviation or general industries. However, other materials like superalloys can be melted as well.

The *FastCast* concept is designed for short cycle times. The furnace can be integrated into your fully automated production system – in terms of material flow and production management – to establish an inline casting route from shell making to a final cast part.

[1] O. Muck, German Patent 422004. (October 30, 1923).
[2] V. Bojarevics et al., "Magnetic levitation of large liquid volume" Magnetohydrodynamics, 46/4 (2010), 317-329.
[3] S. Spitans et al., "Large scale electromagnetic levitation melting of metals" IJAEM, 53 (2017), 61-66.
[4] S. Spitans et al., "Numerical modelling of free surface dynamics of melt in an alternate electromagnetic field. Part II: conventional electromagnetic levitation" Metall. Mater. Trans. B, 47/1 (2015), 522-536.
[5] E. Okress et al., "Electromagnetic Levitation of Solid and Molten Metals" J. Appl. Phys., 23 (1952), 545-552.