Dynamic melting and impurity particle tracking in continuously adjustable AC magnetic field

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Abstract. The analysis of semi-levitation melting is extended to account for the presence of particles (impurities, broken metal dendrite agglomerates, bubbles) during the full melting cycle simulated numerically using the pseudo-spectral schemes. The AC coil is dynamically moving with the melt front progress, while the generated Joule heat serves to enhance the melting rate. The electromagnetic force is decomposed into the time average and the oscillating parts. The time average effects on the particle transport are investigated previously using approximations derived for a locally uniform magnetic field. This paper presents expressions for the skin-layer type of the AC force containing also the pulsating part which contributes to the particle drag by the ‘history’ and ‘added mass’ contributions. The intense turbulence in the bulk of molten metal additionally contributes to the particle dispersion. The paper attempts to demonstrate the importance of each of the mentioned effects onto the particle transport during the melting until the final pouring stage. The method could be extended to similar AC field controlled melting/solidification processes.

1. Introduction

Aluminium, magnesium and titanium alloys are the light structural metals attractive for aerospace and automotive applications that offer mechanical properties at a significant weight saving. Research efforts are aimed at developing new casting techniques and practices to ease inherent processing difficulties of aluminium and magnesium alloys to achieve more desirable mechanical properties for critical automotive structural and kinetic components. One major barrier to casting these components is melting and subsequently casting homogeneous alloys free of contamination and severe segregation, which may lead to undesirable properties. These factors can affect the melt microstructural features leading to the poor grain structure, solute segregation and porosity, and eventually the reduced mechanical properties of cast product.

A finer microstructure usually improves the mechanical properties of the solidified alloy. Finer microstructure can be achieved by increasing the cooling rate, adding dispersed micro to nano size particles of other materials serving as grain refiners. The latter technique is preferable if it can be controlled by additional stirring, and it eases the restrictions on the cooling rate during the casting process. It is well known that forced stirring of the melt by electromagnetic forces can significantly promote the detachment of dendrite arms and transporting the crystal fragments in a disperse fashion due to the presence of high turbulence [1]. However, a unidirectional stirring in laminar conditions could induce undesirable channel segmentation in the solidifying material [2]. Therefore the
electromagnetic stirring must be applied in an optimized way, specifically designed for a particular solidification process.

The semi-levitation melting (SM) is a containerless melting process where the electromagnetic confinement force field is generated using induction coils [3,4]. The electromagnetic field induces a strong turbulent flow in the molten pool, which is beneficial for producing a homogeneous melt with uniform temperature. The process combines induction melting and casting into a single self-controlling operation. The charge is gradually melted from top to bottom through movement of the induction coil as illustrated in Figure 1. Pouring of the charge through the hole in the chill block into the mold below occurs when the liquid melting front reaches the base of the metal charge, Figure 2.

The AC coil is dynamically moving with the melt front progress, while the generated Joule heat serves to enhance the melting rate when the coil proximity is adjusted. The electromagnetic force in the liquid melt can be decomposed into the time average over the AC period part, which serves to confine the relatively slower moving melt from leaking and produces intense large scale mixing. The oscillating nature of the total magnetic force means the presence of additional pulsating force component which exerts a significant effect on the microscopic particles in the melt. The particles travel due to the hydrodynamic drag, buoyancy [5], turbulent fluctuations [6] and the electromagnetic force action via the local pressure distribution around the particle [7]. The time average effects are investigated previously [8-11], but an incomplete approximation was used which was derived for a locally uniform electric and magnetic fields. The latter contradicts the skin-layer type of the exponential force distribution in the AC field [12,13]. Moreover, the total force in AC field contains also the pulsating part which contributes to the oscillating particle drag by affecting the ‘history’ and ‘added mass’ contributions [14]. The high mixing rates ensure the intense turbulence in the bulk of molten metal, additionally contributing to the particle dispersion.

This paper attempts to demonstrate the importance of each of the mentioned effects to the organized particle ‘swarm’ like transport and the eventual distribution when pouring melt in the bottom hole after the complete melting is reached. The semi-levitation dynamic melting principles could be extended to the similar AC field controlled melting processes, like the electrode melting for gas atomization, the contactless top coil ‘immersion’ mixing [15] and possibly other arrangements involving the dynamic AC field adjustment for high proximity electromagnetic interaction. The Lagrangian particle tracking in the presence of strong electromagnetic force field brings new perspectives to the understanding of the melting and casting processes.

2. Mathematical modelling

The mathematical modelling of the complex time dependent problem describing initially a solid body heating due to the AC electromagnetic field, then the melting process and subsequent liquid metal shape adjustment to the imposed force balance. The free surface confinement, internal fluid flow and the temperature evolution is accomplished using the SPHINX code developed at the University of Greenwich [16-18]. The time dependent Joule heating and the gradual melting requires the model to account for the phase transition and the following liquid material shape change by the action of the EM force time variable distribution.

The fluid flow is solved using the Reynolds averaged turbulent flow model for an incompressible fluid with the effective viscosity \( \nu_e \) and the turbulent diffusivity \( \alpha_e \) modified heat transfer equations:

\[
\partial_t \mathbf{v} + (\mathbf{v} \cdot \nabla) \mathbf{v} = -\rho^{-1} \nabla p + \nabla \cdot (\nu_e (\nabla \mathbf{v} + (\nabla \mathbf{v})^T)) + \rho^{-1} \mathbf{f}_{AC,DC} + \mathbf{g} ,
\]

\[
\nabla \cdot \mathbf{v} = 0 ,
\]

\[
C_p \alpha_e (\partial_t T + \mathbf{v} \cdot \nabla T) = \nabla \cdot (C_p \alpha_e \nabla T) + \rho^{-1} |\mathbf{J}|^2 / \sigma ,
\]
where the usual notation is used, given in detail elsewhere [17]. The boundary conditions are prescribed dynamically on the liquid interface defined in spherical coordinates with the transformation function:

\[ \mathbf{R} = \mathbf{e}_R R(\theta, \varphi, t) \]  \hspace{1cm} (4)

The surface dynamics are resolved following the velocity on the interface by the kinematic condition:

\[ \mathbf{e}_n \cdot \mathbf{v} = \mathbf{e}_n \cdot \mathbf{\partial}_n \mathbf{R} \]  \hspace{1cm} (5)

The free surface boundary conditions are determined by the tangential and normal stress components accounting for the temperature dependent surface tension \( \gamma(T) = \gamma(T_m) + \gamma_T(T - T_m) \):

\[ \Pi_{nt} = \gamma_T \mathbf{e}_r \nabla T ; \quad \Pi_{nn} = \gamma K ; \quad K = \nabla \cdot \mathbf{e}_n \]  \hspace{1cm} (6)

Note, that to preserve the momentum conservation the temperature dependent surface tension is used both for the normal and the tangential stress (Marangoni effect).

The solution method is based on the continuous co-ordinate transformation adapting to the free surface and the containing vessel shape. The present implementation adds the Lagrangian passive particle tracking algorithm. The position \( \mathbf{R}_p(x, y, z, t) \) of an individual particle can be determined following its path and the variable total force \( \mathbf{F}_p(x, y, z, t) \) acting on the particle by solving the set of two equations [5,6]:

\[ \mathbf{\partial}_t \mathbf{R} = \mathbf{u}_p, \quad m_p \mathbf{\partial}_t \mathbf{u}_p = \mathbf{F}, \]  \hspace{1cm} (7)

where \( \mathbf{u}_p \) is the particle velocity and \( m_p \) its mass. The force \( \mathbf{F}_p \) acting locally on a spherical particle can be decomposed into the fluid drag force \( \mathbf{F}_d \), the buoyancy force \( \mathbf{F}_b \) and the effective electromagnetic force \( \mathbf{F}_e \). The drag force depends on the Reynolds number \( \text{Re}_p = r_p |\Delta \mathbf{u}| / \nu \), where \( r_p \) is the particle radius, \( \Delta \mathbf{u} = \mathbf{u} - \mathbf{u}_p \) is the (slip) velocity relative to the fluid velocity \( \mathbf{u}, \nu \) – the kinematic viscosity. For small particles (1nm -100 µm) the Reynolds number \( \text{Re}_p \) is rather small, of the order 0.1 - 10, therefore the drag force can be approximated as instantaneous modified Stokes formula [5,14]

\[ \mathbf{F}_d = \frac{3C_d \rho \pi d^2}{\text{Re}_p} |\Delta \mathbf{u}| \Delta \mathbf{u} = 3C_d' \nu \rho \pi d^2 \Delta \mathbf{u}, \]  \hspace{1cm} (8)

\[ C_d' = 1 + 0.15 \text{Re}_p^{0.687}, \quad (\text{Re}_p < 1000). \]

The buoyancy force due to the gravity \( \mathbf{g} \) action on the particle and the surrounding fluid is

\[ \mathbf{F}_b = (\rho_p - \rho)V_p \mathbf{g}, \]  \hspace{1cm} (9)

\( \rho \) is the fluid density, \( \rho_p \) – the particle density, \( V_p \) – the particle volume.

The electromagnetic force acts on the induced electric current in the particle and due to the fluid pressure redistribution on the surface of the particle [7]. For the case of electrically non-conducting particles (oxides, carbides, dendrite fragments, bubbles etc.) the electromagnetic force in the AC skin-layer can be derived as

\[ \mathbf{F}_e = -V_p \left( \frac{\partial f_e}{\partial t} + f'(t) \right), \]  \hspace{1cm} (10)
the sum of the time average and the oscillating components of the electromagnetic force computed in the fluid at the location of the particle. Note, the Leenov, Kolin [7] expression derived for DC constant fields,

$$\mathbf{F}_{DC} = -V_p \frac{\lambda^2}{2} \mathbf{f}_e$$

(11)
gives two times smaller force magnitude acting on a non-conducting particle.

The presence of the oscillating force component requires the modified drag expression for an oscillating spherical particle [14]:

$$\mathbf{F}_d = 6\pi \eta r_p [(1 + \varepsilon)\Delta \mathbf{u} + \frac{\varepsilon}{\omega} (1 + \frac{2}{9} \varepsilon) \frac{d\Delta \mathbf{u}}{dt}], \quad \varepsilon = \frac{\omega r_p^2}{2\nu},$$

(12)

where the Stokes number $\varepsilon$ can reach an order 1 in an AC field oscillating at typical frequencies $\omega \sim 10^3 - 10^4$ Hz. The equation (12) contains the instantaneous Stokes drag, the memory term (Basset force) and the added mass force.

The typical mixing flow is turbulent ($Re \sim 10^3 - 10^4$), which further requires a modification due to the stochastic part of velocity in accordance to the resolved turbulent kinetic energy $k$ and the local eddy life time (or the particle transit time in that eddy, whichever is the shortest) [6]. The use of $k-\omega$ turbulence model in the SPHINX code facilitates to obtain these quantities, which are locally interpolated to the particle position at each time step. The numerical integration of equations (7-10, 12) is performed for each individual particle of various properties depending on the initial seeding locations. The time dependent forces $\mathbf{F}_p$ are sensitive to the location and the instantaneous update of local slip velocity $\Delta \mathbf{u}$ (including the stochastic contribution). Therefore, the stability of long term integration along the particle tracks can be adversely affected by the choice of numerical integration scheme. The classical explicit integration schemes are limited to extremely small time steps, which could make the numerical solution difficult for the dynamic flow conditions. The exponential numerical scheme, proposed in [13], permits stable time integration of the particle tracks with the dynamically adjustable time steps of the order 0.1 – 1 ms used for the unsteady fluid flow solution in the examples considered below.

3. Numerical results

The electromagnetic field induces a strong turbulent flow in the molten pool, which is beneficial for producing a homogeneous melt with uniform temperature. The process combines induction melting and casting into a single self-controlling operation. The charge is melted from top to bottom through movement of the induction coil as illustrated in the Figures 1 and 2. The electromagnetic force needs continuous adjustment while the free surface moves in the molten state. Figure 1 demonstrates the difference in the distribution of the current and the force at the initial stage and the stage when almost full volume of the melt is liquid just before pouring starts. Pouring of the charge through the hole in the chill block into the mold below occurs when the liquid melting front reaches the base of the metal charge.

In this study the main interest is about the behavior of the particles in the melt. The Figure 3 compares the particle instantaneous positions after the random seeding in the initial solid cylinder, melting and mixing for 340 s, then pouring while the magnetic confinement and mixing is maintained. If the effects of the turbulent fluctuations and the oscillating force component are neglected, the mixing patterns are organized in particle ‘loops’, while the larger size particle loops collapse to concentrated localizations on the free surface. This may indicate a coagulation process for the larger particles. The electromagnetic force effect on the particles of sizes 50 -100 µm is comparable to the drag force, leaving the particles at positions where the gravity (buoyancy) force is balanced by the electromagnetic expulsion and the drag. This corresponds to observations for the small metallic samples (about 2-3 cm in diameter) where, after fast solidification, the particles are localized at certain surface positions depending on their size [8,13].

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Figure 1. The induced electric current density and the time average electromagnetic force distribution in the melting ingot \((d=7.5 \, \text{cm})\) at the initial time (left) and at the final stage when liquid pouring starts (right) for the effective current magnitude in the coil 1094 A at the frequency 3717 Hz.

Figure 2. Melting front progress shown as two snapshots of the simulated results: the flow and the temperature at the intermediate stage 214 s and at the final stage when liquid pouring starts 339 s.

Figure 3. The particle positions at two snapshots of the simulated results: at the initial stage (214 s) and at the intermediate stage when liquid pouring starts (339 s). The particle tracking does not include the oscillating force and the stochastic turbulent fluctuation effects.
The effect of turbulent fluctuations is more pronounced in the semi-levitation case, having a larger size metallic volume (the initial ingot is 7.5 cm in diameter). In addition, the full AC force including the oscillating part contribution creates more realistic particle distribution shown in the sequence of snapshots in the Figure 4. The larger particles are still trapped on the surface, however their position is more dynamic, eventually shifting to lower height closer to the solid front. The larger particles are the last to exit the liquid zone when poured to the hole at the bottom.

Figure 4. The particle positions at 4 stages of the simulated results when the tracking includes the oscillating force and the stochastic turbulent fluctuation effects.

The other type of semi-levitation device was used in [16], where the initial ingot was 12 cm of diameter. To melt such a large piece of metal the frequency was increased to 8000 Hz and the current magnitude to 5500 A. The flow in this situation is more intense and highly turbulent (Figure 5). The particle tracks are more dominated by the stochastic fluctuations and the oscillating force contributes to the drag force difference if compared to the previous case of the original semi-levitation device. The larger size particles tend to agglomerate near the side free surface (similar to the previous) and to the top of the liquid metal column sustained by the magnetic forces. The smaller size particles appear to be removed first from the liquid column to the hole at the bottom when pouring starts, while the large particles are retained until the end stage and reach the exit at the very end of the pouring process (Figure 6).
Figure 5. Melting of the large ingot (d=12 cm) shown as two snapshots of the simulated results: the flow and the temperature at the intermediate stage 179 s and at the final stage when liquid pouring starts 226 s. (For the effective current magnitude in the coil 5500 A at the frequency 8000 Hz).

Figure 6. The particle positions at 4 stages of the simulated results for the large ingot when the tracking includes the oscillating force and the stochastic turbulent fluctuation effects.
Conclusion

The results of modelling show the importance of the electromagnetic effects on the particle distribution when pouring the molten metal in the semi-levitation process, indicating the potentially beneficial feature to supply well dispersed small particles at the initial and mid stages of the mold filling, separating the agglomerates until the last stage when the mold could be already full. This would result in a fine grained casting structure.

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