Contactless ultrasonic treatment of melts using EM induction

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Abstract. Ultrasound Treatment (UT) is commonly used in light alloys during solidification to refine microstructure, or disperse immersed particles. A sonotrode probe introduced into the melt generates sound waves that are strong enough to produce cavitation of dissolved gases. The same method cannot be used in high temperature melts, or for highly reactive alloys, due to probe erosion and melt contamination. An alternative, contactless method of generating sound waves is proposed and investigated theoretically in this paper, using electromagnetic (EM) induction. In addition to strong vibration, the EM induction currents generate strong stirring in the melt that aids distribution of the UT effect to large volumes of material. In a typical application, the same induction coil surrounding the crucible used to melt the alloy may be adopted for UT with suitable frequency tuning. Alternatively - or in addition - a top coil may be used. For industrial use, instead of multiple sonotrodes as has been the practice in scaling up, modelling shows that one simply has to alter the coil geometry and current to suit. To reach sinusoidal pressure fluctuations suitable for cavitation it may be necessary to tune the induction coil frequency for resonance, given the crucible dimensions.

1. Introduction

Intense vibration of the liquid metal during solidification is known to refine microstructure, remove trapped gas and reduce porosity [1-4]. Vibration can be achieved in various ways: shaking the crucible, inserting a mechanical stirrer in the melt or, more commonly, using an ultrasonic horn e.g. in the DC casting of aluminium ingots [3]. During ultrasonic treatment (UT), frequencies around 20 kHz were found to be the most effective [3], a fact attributed to the onset of cavitation. Gas micro-bubbles exist in the liquid either due to dissolved gases coming out of solution as the melt cools (e.g. H₂ in Al), air trapped with oxides during mould filling, or gas attached to the surface of immersed particles. Bubbles, subjected to an imposed pressure sine-wave, first expand to many times their original size at the pressure minimum and then collapse violently as the pressure rises, generating high speed micro-jets and shock waves. These events fragment emerging dendrites, or facilitate the breakup and dispersion of particle clusters to populate nucleation sites. Evidence of cavitation has been seen in situ recently [5], found in post-solidification analyses and further shown to depend on a critical pressure threshold [3]. Of relevance to the present study, ultrasonic processing is one of the candidate techniques for the production of metal-matrix nano-composites (MMNCs).

There are however, several disadvantages in immersive stirring/vibration techniques: contact with the liquid metal leads to contamination of the melt and conversely erosion of the immersed probe surface, requiring frequent replacement. These problems are limiting when the technology is to be applied to high temperature alloys (ODS steel, nickel superalloys) or to highly reactive metals (Ti, Zr,…). Another limiting factor of the immersed sonotrode approach is the localised effect of the cavitation region, which leads to long processing times, high cost/energy usage and therefore it...
remains most suitable for small treatment volumes. EM induction is an attractive alternative. It provides melt stirring and heat. What is overlooked is the ability of the AC component of the induced Lorentz force to generate a strong sound field within the melt, equivalent to that produced by an immersed sonotrode, but without contact. Vives [6] was the first to investigate experimentally such a non-contact technique, using a combination of static and AC magnetic fields. Other investigators followed this lead, using different configurations; for AlSi hypereutectic alloys [3,7], for grey iron melts [8] and aluminium alloys, etc. In each case, different thresholds of pressure amplitude were found to be necessary and frequencies ranging from 50 Hz to 50 kHz were used. There has been no systematic study of the sound field generated in these situations, which led us in a previous publication [9] to examine the sound field generated by the cylindrical induction coil in an induction crucible, coupling the compressible sound wave equations with the pressure source generated by the electromagnetic field and the Rayleigh-Plesset equations for cavitating bubbles. This simulation demonstrated that pressure amplitudes likely to cause cavitation of dissolved gas can be generated, provided the AC frequency is tuned to approach wave resonant conditions – a similar conclusion was reached by Vives, who considered the design of a resonant EM cavity for this purpose (figure 1, [6]). In the present contribution, we extend this idea via the introduction of a tuned top coil (VibroEM patent #PCT/EP2013/067896) inserted into the liquid metal volume, but nevertheless still using EM repulsion to prevent contact with the metal. In this very close proximity to the surface, intense vibrations and melt stirring can be produced which can be controlled via the depth of immersion.

The remainder of the paper is arranged as follows: In section 2, the problem to be addressed is described, followed by the set of equations for the magnetic and sound fields and bubble evolution. Results of simulations using aluminium and silicon melts are given, followed by discussion and conclusions.

2. Problem setup
A typical ceramic induction crucible is shown in figure 2, together with the two alternative excitation arrangements. The cylindrical induction coil and top coil can be operated independently of each other and at different frequencies. The function of the cylindrical coil remains that of heating/melting and stirring, whilst the top coil is there to provide controlled vibration. The top coil is allowed to move vertically so that it can gradually enter the melt, forming a depression in the free surface. In reality, both coils contribute to the soundfield within the melt. The ceramic crucible is enclosed in a graphite container that is itself surrounded by the coil. The crucible is filled with aluminium.

The flow and thermal fields containing the EM force and Joule heating are solved using an incompressible spectral collocation technique, assuming harmonic averaging for mean values as described in previous publications, e.g. [10]. Time accurate information is extracted within each AC cycle once a pseudo-steady condition is reached, to enable the driving sound source evaluation for the compressible acoustic simulation.

In addition to the aluminium crucible where the main consideration of the study is the uniform distribution of refining particles, a second industrial case has also been simulated, where silicon melt is subjected to AC EM field to expel impurities such as SiC.
3. **Theoretical analysis for the EM force in a cylindrical crucible**

To demonstrate the approach followed, we consider the case of an infinitely long cylindrical crucible coaxially surrounded by a cylindrical coil:

**EM field:**

\[ \mathbf{B} = B_R \cos \omega t + B_I \sin \omega t \]  

(1)

where,

\[ B_R = B_0 e^{-\frac{x}{\delta}} \cos \frac{x}{\delta} ; \quad B_I = -B_0 e^{-\frac{x}{\delta}} \sin \frac{x}{\delta} \]  

(2)

**AC current:**

\[ \mathbf{J} = J_R \cos \omega t + J_I \sin \omega t \]  

(3)

where,

\[ J_R = \frac{\sigma}{2} \delta (B_R + B_I) ; \quad J_I = \frac{\sigma}{2} \delta (-B_R + B_I) \]  

(4)

(Where \( x \) is the cylindrical r-coordinate measured from the external wall inwards and \( \delta \) is the skin layer thickness)

Then, Lorentz force on liquid :

\[ \mathbf{F} = \mathbf{J} \times \mathbf{B} \]  

(5)

**Time averaged force:**

\[ \bar{F} = \frac{1}{2} (J_R B_R + J_I B_I) = \frac{1}{2\mu \delta} B_0^2 e^{-\frac{x}{\delta}} \]  

(6)

**Time-dependent component:**

\[ F = \frac{1}{2\mu \delta} B_0^2 e^{-\frac{x}{\delta}} \left[ 1 + \sqrt{2} \cos(2\omega t - \frac{x}{\delta} + \frac{\pi}{4}) \right] \]  

(7)

*Note, the Lorentz force doubles the supply frequency.*

The resulting sinusoidal force is shown graphically in figure 3. It is evident that the force is only significant in the outermost part of cylinder, in the skin layer, decaying rapidly away from the wall at a frequency of 10 kHz. Amplitude decay is accompanied by a gradual change of phase.

The observations gleaned from this idealised 1D problem are valid for a realistic crucible simulation as shown in figures 4 and 5. Figure 4 shows on the left a schematic representation of an experimental silicon refining crucible [11], together with the resulting flow and temperature field on the right. The quartz crucible is surrounded by graphite, necessary to melt the solid charge using resistance heating. As the silicon melts and its conductivity increases a vigorous flow results due to the induced RMS Lorentz force. The sinusoidal component of this force is shown in figure 5. On the left,
the instantaneous force variation diminishes rapidly in amplitude outside the skin layer (at a frequency of 1 kHz) and although the mean force is always compressive, the resulting pressure troughs reach a significant negative gauge value.

4. Electromagnetic sound generation

The sinusoidal part of the Lorentz force is the source of vibration, hence source of sound in the liquid. A physical manifestation of this can be seen in the mercury experiment depicted in figure 6.

4.1 Linearised Euler Equations in Liquids

The generation of sound waves by the alternating magnetic force was simulated using a Computational Acoustics approach. In 1D, the equation of mass continuity and the simplified momentum equations (no convection or viscous terms), yield the following system:

\[ \begin{align*}
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} &= 0, \\
\frac{\partial (\rho u)}{\partial t} + \frac{\partial (\rho u^2)}{\partial x} &= 0
\end{align*} \]
\[
\frac{\partial p}{\partial t} + \rho c^2 \frac{\partial \vec{u}}{\partial x} = 0
\]

\[
\rho \frac{\partial \vec{u}}{\partial t} + \frac{\partial p}{\partial x} = f; f = |\vec{F}| - \vec{F}
\]

4.2 Bubble evolution and cavitation

The Keller-Miksis equation governs the dynamics of a spherical bubble, including the effects of acoustic radiation and yields satisfactory results with large forcing amplitudes [13]:

\[
\left(1 - \frac{1}{c_\infty} \hat{R}ight) \hat{R}^2 + \frac{3}{2} \left(1 - \frac{1}{3 c_\infty} \hat{R}\right) \hat{R}^2 \\
= \left(1 - \frac{1}{c_\infty} \hat{R}\right)^2 \left[p_B(t) - p_\infty(t) - \frac{R}{\rho_\infty c_\infty} \frac{dp_B}{dt}(t)\right] + \frac{R}{\rho_\infty c_\infty} \frac{dp_B}{dt}(t)
\]

Figure 7 shows the rapid expansion and then collapse of a single bubble placed in the aluminium melt subjected to a driving EM frequency of 10 kHz. The soundfield generated by the bubble collapse, responsible for the breakup of particle agglomerations, is not included in the simulations shown here.
5. Sound field results

In the following figures, samples of computed soundfields using side and top coils are shown, together with the equivalent values for the traditional immersed sonotrode operating at 20 kHz.

Figure 8: Top pair shows instantaneous pressure in a crucible generated by the cylindrical induction coil at (a) 1 kHz, (b) 10 kHz. The corresponding frequency spectra are given below. The 10 kHz coil produces resonance at 20 kHz increasing pressure amplitude by 2 orders of magnitude. Resonance can be easily achieved in the slightly tapering crucible shown in figure 8; in practice and for safety a frequency approaching resonance may be preferable. The figure also highlights the substantial difference in sound pressure patterns between 1 kHz – good for mixing, and 20 kHz, good
for cavitation. Since resonance depends on the relative values of wavelength and crucible dimensions, the frequency will need to be adjusted on a case-by-case basis. Figure 9, depicts the soundfield generated by the immersed vibration coil (RHS) as well as the surface depression and stirring caused by its presence (LHS). The middle pictures show the sound ‘beat’ caused by the near-resonant condition at two different locations in the core of the crucible (top) with the bottom figure showing how the driving frequency excites resonance at three different peaks.

Figure 9: (a) Crucible, inductive melt heating and stirring, (b) Soundwave ‘beat’ as forcing frequency approaches resonance, (c) Acoustic pressure spectrum – multiple peaks due to conical crucible design, (d) Instantaneous sound field

It is instructive to see what the algorithm makes of the sonotrode sound field in the same geometry, and that is given in figure 10. The general patterns of peaks and troughs are similar, but one notes that at the settings given, the vibrating sonotrode produces relatively higher pressure amplitudes (by a factor of 3).

Figure 10: Comparative sound fields generated by the top coil and sonotrode for the same geometrical configuration
6. Conclusions
It has been shown through a combination of MHD and Computational Acoustic simulations that EM induction can be used as a contactless replacement of the mechanical sonotrode. Then,

- The mean EM force acts in a thin skin layer and promotes strong bulk mixing (which a mechanical sonotrode does not!)
- The sinusoidal part of the force generates sound waves
- The AC frequency can be adjusted to produce near resonance pressure amplitudes for cavitation (e.g. so as to disperse particle clusters)

The EM “sonotrode” is contactless, therefore

- It can be used for high temperature or reactive metals (Ni, Ti, Zr, ODS steel, etc.)
- Avoids contamination of the melt
- Can fit in with existing induction coil arrangements

Work is in progress to test this setup experimentally in the near future.

7. References
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Acknowledgments
The authors acknowledge financial support from the ExoMet Project (co-funded by the European Commission (contract FP7-NMP3-LA-2012-280421), by the European Space Agency and by the individual partner organizations).

Dr Bruno Lebon, acknowledges the financial support of the EPSRC (grant EP/K00588X/1) in developing the cavitation model used in this work.