

INFLUENCE OF THE FREQUENCY OF THE APPLIED AC CURRENT ON THE ELECTROSLAG REMELTING PROCESS

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Abstract

The influence of the frequency of AC power supply on the magneto-hydrodynamic during the electroslag remelting process is studied. The focus is on the electrodynamic field and its resulting mechanical effects on the flow and liquid interfaces. The possible influence of the electrochemistry on the droplet formation is qualitatively discussed.

Introduction

The electroslag remelting (ESR) process is a secondary melting technique which can be used for a variety of metals and alloys, provided appropriate fluxes (slags) and melting parameters are employed. The ESR process is presently operating mostly with AC current of about 50 Hz. However for reasons primarily of inductive losses in the electric circuit, furnaces for ingots larger than 1 m, use or are projected to use current of very low frequency (< 5 Hz). Effects of lower frequencies (2.5-5Hz) on macrostructure and non-metallic inclusions were recently studied by Chang [1]. Most of investigations were performed either with DC power or with AC of 50-60 Hz [2-4].

In opposite to metals, slags have shown to be ionic, which means that the current must pass across the interfaces by means of Faradaic reaction. Excellent reviews of electrochemical aspects of ESR process were presented by Peover [2] and Mitchell [3]. The fused slag components are dissociated into positively charged cations such as Ca^{2+} , Mg^{2+} , and into negatively charged anions of simple (F^- , O^{2-}) or complex (AlO_3^{3-} , $\text{Al}_2\text{O}_5^{4-}$, SiO_4^{4-}) composition. Large anions of low mobility hinder severely the ionic movement. If the number of large anions increases, the cation mobility decreases and the conductivity of the slag decreases, resulting in an increases in the Joule heating. Electrons flow from the cathode to the anode. In the case that the cathode is the electrode, the slag/pool interface is the anode. An anodic concentration polarization takes place under the electrode, which results in an increase in local resistance for the current. In the case of negative electrode operation, the extra-heat is generated at the slag/metal interface. However due to lower electric current densities at the metal pool the anodic polarization is not as strong as in the case of cathode electrode.

The metal/slag interface exhibits a potential range (0.4 – 1.5 Volt) [3], also called overpotential, where no Faradaic reactions can take place. If the applied potential difference across the double layer is maintained within its Faradaic reaction-free potential window, electrons from the electrode cannot be transferred to the electrolyte and nor can ions from the electrolyte react at the electrode. The only phenomenon occurring at the electrode is a periodic change in charge density on both sides of the interface. Under such circumstances the current flowing through the interface becomes purely capacitive. In other words the polarisation produced due to a high frequency AC current in one direction is neutralised by the effect of current in other direction, no electrochemical reaction takes place.

If the frequency of the AC wave is low, the double layer capacitors of the electrode/slag interfaces charge and discharge periodically. The capacitors can then be fully charged during the rising part of the wave turning on electrochemical reactions. Those reactions involve simultaneous cathodic (i.e. reduction) and anodic (i.e. oxidation) half-reactions; and the overall reactions produce periodic concentration changes of redox species at the electrode surfaces. The extents of those chemical changes primarily depend upon the frequency of the applied AC signal and the chemistry of the used slag. Full electrochemical polarisation was found to occur within 0.2 to 1 seconds [3]. The critical frequency under which chemical effects start can be estimated to be around 5 Hz. In DC operation, in a small scale unit, a large voltage drop was observed at the anodic interface [2]. This was interpreted as to be due to different electrochemical reactions, building larger overpotential at the anodic interface than at the cathodic interface [2]. The voltage drop would produce an extra heat at the anodic interface. In opposite, in electrode positive operation the additional heat is released just under the electrode, thus leading to an improvement of the melting rate. In the same time, a larger portion of the current will flow into the mould in DC electrode negative than in positive operation. These ionic polarizations are considered to be mainly responsible for the variations in melt rates and power dissipation between the DC and the AC configurations.

Another aspect of the electric current frequency lies in the time variation of the generated electromagnetic force, i.e the Lorentz force. This force together with thermal buoyancy is believed to control the flow dynamic in the slag and liquid melt pool region. In the next the expression of the Lorentz force as function of the AC frequency is derived analytically for an axisymmetric system. This force is then applied to a typical ESR system to study the response of the flow in the slag and liquid melt pool.

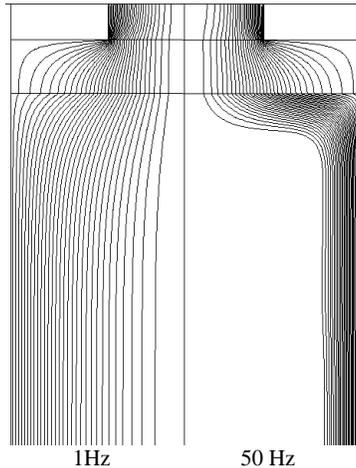


Figure 1: Electric current streamlines in the Electroslag remelting process

Effects on the slag and liquid melt pool flow

The Lorentz force is a body force which results from the interaction of an electric current with a magnetic field:

$$\vec{F} = \vec{j} \times \vec{B}. \quad (1)$$

In the present case the magnetic field is created by the current itself. With the axisymmetric assumption, the induced magnetic field is strictly oriented in the tangential direction $\vec{B} = (0, B_\theta, 0)$. If an AC current is applied the magnetic field will automatically fluctuate. When this happens within a good conductor such as in a liquid metal, the Lenz's law states that eddy currents will be generated in order to oppose the variation of the main magnetic field. This effect is at the origin of the creation of the skin effect in wires under AC conditions. For the sinusoidal AC field, the magnetic field can be expressed in complex notation: $H_\theta = \tilde{H} e^{i\omega t}$. The complex amplitude \tilde{H} is a function of the position (r, z) , and ω is the angular frequency. The equation to be solved can be expressed as:

$$\frac{\partial}{\partial r} \left(\frac{1}{\sigma_1 \cdot r} \frac{\partial}{\partial r} (r\tilde{H}) \right) + \frac{\partial}{\partial z} \left(\frac{1}{\sigma_1 \cdot r} \frac{\partial}{\partial z} (r\tilde{H}) \right) - \frac{\tilde{H}}{\sigma_1 r^2} = i\omega\mu_0\tilde{H}, \quad (2)$$

where μ_0 is the magnetic permeability of vacuum. The local electric conductivity is interpolated by using $1/\sigma = f_1/\sigma_1 + f_2/\sigma_2$. The momentary value for the magnetic field is:

$$B_\theta = \tilde{H}_{Re} \cos(\omega t) - \tilde{H}_{Im} \sin(\omega t). \quad (3)$$

The electric current can be extracted from the Ampere's law:

$$\vec{j} = Re(\mu_0 \vec{\nabla} \times \vec{H}) = \mu_0 \vec{\nabla} \times (\tilde{H}_{Re} \cos(\omega t) \vec{e}_\theta) + \mu_0 \vec{\nabla} \times (\tilde{H}_{Im} \sin(\omega t) \vec{e}_\theta). \quad (4)$$

Examples of electric current distribution are given in Figure 1. The presence of the skin effect is clearly observable in the metal region. After some algebra, the physically effective Lorentz force is:

$$\begin{aligned} \vec{F} = & -\mu_0 (\tilde{H}_{Re} \vec{\nabla} \times (\tilde{H}_{Re} \vec{e}_\theta) \cos^2(\omega t) - \tilde{H}_{Im} \vec{\nabla} \times (\tilde{H}_{Im} \vec{e}_\theta) \sin^2(\omega t)) \\ & - \mu_0 \sin(\omega t) \cos(\omega t) (\tilde{H}_{Re} \vec{\nabla} \times (\tilde{H}_{Im} \vec{e}_\theta) - \tilde{H}_{Im} \vec{\nabla} \times (\tilde{H}_{Re} \vec{e}_\theta)) \end{aligned} \quad (5)$$

The differences between the 1 Hz and 50 Hz Lorentz force vector field are presented in Figure 2, notice the change in direction of the force when the slag/pool interface is crossed. Most simulations of ESR processes did not use Eq. 5, but used the time averaged version:

$$\vec{F} = -\frac{1}{2} \mu_0 (\tilde{H}_{Re} \vec{\nabla} \times (\tilde{H}_{Re} \vec{e}_\theta) - \tilde{H}_{Im} \vec{\nabla} \times (\tilde{H}_{Im} \vec{e}_\theta)) \quad (6)$$

In the present investigation we use the real time dependant expression of Eq.5. Figure 3 presents a typical liquid pool and distribution of the velocity magnitude computed for the application of 14000 Amps 50 Hz current in an industrial scale ESR (60 cm ingot). To illustrate the effect of the AC field, the influence of the fluctuating force (Eq. 5) is studied in term of total kinetic energy contained in the slag and in the liquid pool (Figure 4). For 50 Hz the response of the slag and liquid pool follows strictly the frequency of the applied current. However they are very small compared to the average kinetic energy (1-2 %).

Variation with larger amplitude and lower frequencies are due to flow instabilities naturally present in this turbulent system.

In contrast, for 1 Hz both slag and liquid pool volume reacts strongly to the oscillating force. The amplitude of oscillations reaches 50 % in the liquid pool, in the slag it is only of about 15 %. While the liquid pool oscillates harmonically, the slag kinetic energy oscillates chaotically. The time periods of the oscillations are far higher than the applied one, about 60 seconds for the liquid pool, and 12 second for the slag. The origin of this phenomenon is not yet clear, further investigations needs to be performed. However, the oscillations within the liquid pool

can have strong consequences in terms of segregation. This forced convection can interfere with the natural interdendritic flow, can carry the solute for larger distance, and possibly suppress the channel formation.

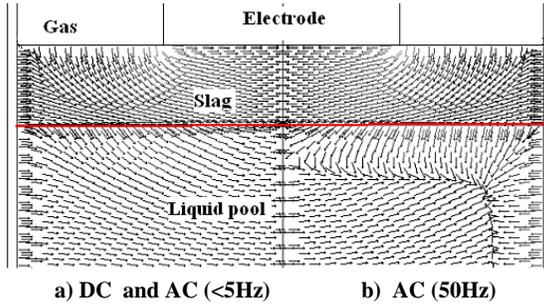


Figure 2: Lorentz force direction in ESR

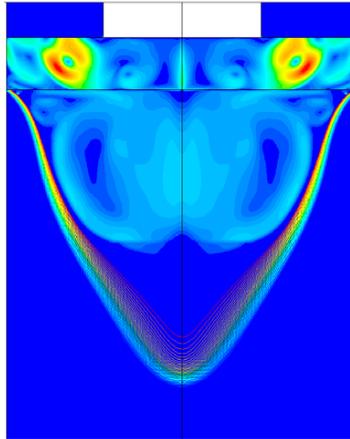


Figure 3: Typical ESR velocity and solid fraction distribution (14000 Amp, 50Hz).

Effects on the liquid Slag/metal interfaces

Liquid-Liquid Interfaces are known to become unstable when MHD forces are present. In the present case the slag/liquid pool interface is stabilized by the fact that the metal is about 2 to 3 times heavier than the slag. However during the process the falling droplets impact on the interface at a speed of about 0.2 to 0.7 m/s. Depending on the melting rate the impacts frequency will give rise to waves. Aside to the influence of the droplets, the interface dynamic is controlled by the equilibrium between the gravity, the shear stress and the Lorentz force. Due to relative difference of steel and slag motion, and to the relative value of the dynamical viscosity, the interface is submitted to a shear stress force. But the discrete change of the Lorentz force through the slag/steel interface introduces a special effect. Due to the low electrical conductivity of the slag and the high electrical conductivity of the molten metal, there is a jump of the electrical field at the metal/slag interface. When crossing the slag/metal interface, the current changes its direction. It is already observable in DC conditions, but

under AC fields the skin effects amplifies strongly this effect (Figure 2). While it is mainly vertical in the slag, the current has a large horizontal component. The Lorentz force is then mainly horizontal in the slag and mainly vertical in the under the interface. This effect is already observable in quasi DC fields, but it is more pronounced at 50 Hz. Thus, the Lorentz force possesses strong rotational components which can generate waves at the interface. The strength of this force can be estimated with:

$$\Delta F_z = (j_r|_{slag} - j_r|_{Metal})b_\theta \sim -\frac{\mu_0}{2R^3} \left(\frac{I_0}{\pi}\right)^2 \quad (7)$$

This force can displace vertically the interface until balance with gravity is reached:

$$\Delta F_z \sim (\rho_{slag} - \rho_{metal})g\Delta h \quad (8)$$

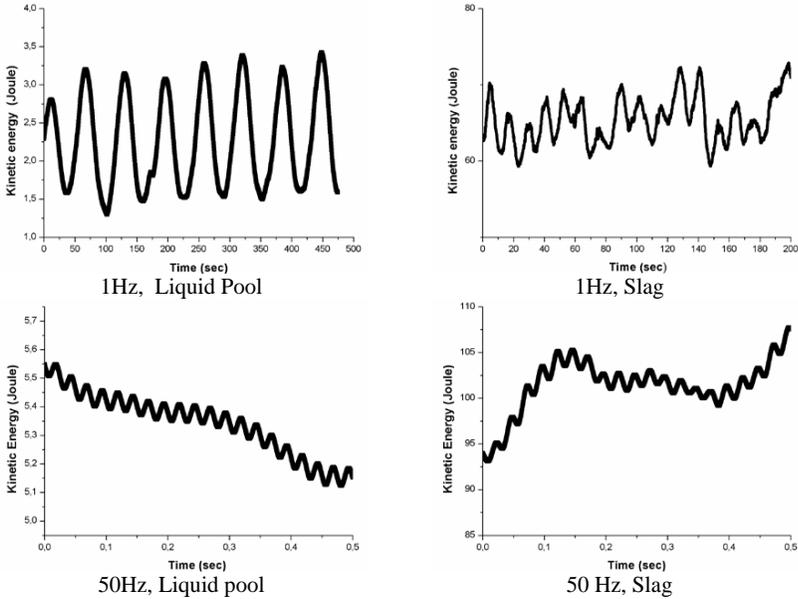


Figure 4: Evolution of the kinetic energy in the slag and liquid pool volume.

In a typical industrial ESR uses $I_0 \sim 14500$ Amps, a mould radius of $R \sim 0.3m$, $(\rho_{slag} - \rho_{metal}) \sim 4000 \text{ Kg/m}^3$, (Eq.8) gives $\Delta h \sim 1.3 \text{ cm}$. This is small but enough to give birth to an instability which can either growth or damp depending to the magnetohydrodynamic conditions generated by the new interface position. A simulation of the interface dynamic (Figure 5) was performed on an 50Hz operating ESR system similar to that presented in Figure 3. The simulation uses a model that couples the electromagnetic field with the multiphase distribution. Indeed, the interface shows larger amplitude oscillation than

expected from Eq.8. It is clear that a moving interface continuously modify the magnitude of the Lorentz force which in turn modifies the interface dynamic through the flow velocity. Due to the axisymmetric assumption, the model predicted the largest amplitude (~2.5 cm) at the centre. A three dimensional computation needs still to be performed, however it is unlikely that this MHD related to alternating current develop in large scale ESR a 2D axisymmetric pattern. In low frequency current the amplitude of the oscillations are expected to be smaller.

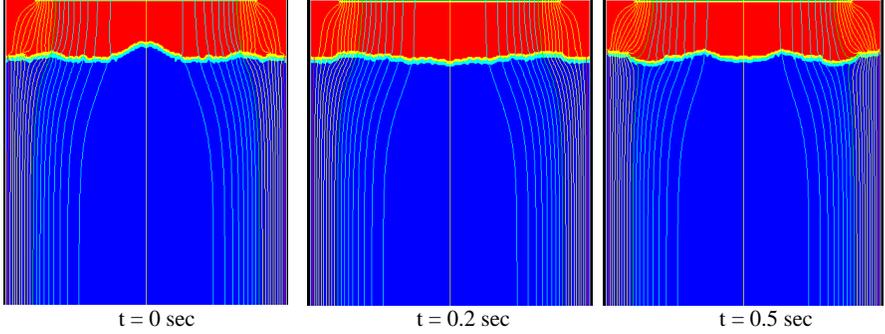


Figure 5: Slag/pool interface position at different time and corresponding electric current streamlines (50Hz).

Effects on the liquid droplets

A difference in dripping phenomena was observed between negative and positive electrode operation. According to Mitchel [3] and Campbell [4], the analysis of the drop size indicates that the interfacial tension is larger for a negative electrode drop than that of an electrode positive drop.

When electrochemistry is not taken into account, the electric current distribution is purely controlled by the ratio of electric conductivities between the metal and slag phase. The electric current density will be higher within a conducting droplet than in the surrounding low conductivity liquid. For any droplet σ and liquid σ_l conductivity, the Andres' formula [5] describes the effective Lorentz force that applies to the droplet body:

$$\vec{F} = \frac{3}{2} \frac{\sigma - \sigma_l}{\sigma + 2\sigma_l} \vec{j} \times \vec{B} \quad (9)$$

When the droplet is much more conducting than the surrounding liquid:

$$\vec{F} = \frac{3}{2} \vec{j} \times \vec{B} \quad (10)$$

The effective Lorentz force is then 50% stronger than within the liquid. If the droplet conductivity is negligible compared to the liquid one:

$$\vec{F} = -\frac{3}{4} \vec{j} \times \vec{B}. \quad (11)$$

Thus, the effective Lorentz force (acting on the droplet) is acting in the opposite direction than the normal Lorentz force acting on the surrounding liquid. This can be considered as a paradox as no current is flowing within the insulating droplet. The existence of this force

results from the balance of the static pressure force induced by the deviation of the current around the droplet volume. The validity of expressions (Eq.9-11) is limited to spherical droplets which are far from each other.

During the droplet fall in the slag, the Lorentz force is mainly radially oriented towards the centre. We can expect that the droplets trajectories will be deviated towards the centre. This effect is observable in the results of a 3D simulation of a DC electroslag remelting process (Figure 6). Depending on the departure position, the droplet impacts the interface at closer position from the centre. Typically 2-3 cm of deviation for a slag height of 10 cm is predicted. Since the Lorentz force continuously act during the droplet fall, in processes that use larger slag height (up to 50 cm) the radial deviation might be much higher.

When electrochemistry is taken into account for low frequency operation, the previous results can be strongly modified. In an electrolyte, in order to be conductive the droplet needs to be polarized at its extremities. At those extremities an oxidation and a reduction reaction needs to take place. In electric terms, the current needs to cross the cathode and anode overpotential barriers (~1Volt). For that the potential drop built by the surrounding resistive slag should exceed 2 Volts over a distance equivalent to the droplet size. It is clear that larger is the droplet larger is the potential drop likely the current will flow through the droplet. The voltage drop can be estimated for a typical slag of conductivity $\sigma_l \sim 300(1/\Omega m)$ in which an electric current density of 10^5 Amp/m^2 flows:

$$\frac{\partial V}{\partial x} = \frac{i}{\sigma_l} \approx 3.33 \text{ Volt/cm} \quad (12)$$

A droplet of about 1 cm diameter will conduct some of the current. A small droplet of about 1 mm diameter will experience only 0.33 Volt potential drop between its extremities, not enough(<2 Volt) to allow any current. However within the electroslag remelting process the electric current density varies strongly. If locally the density of current is too low no Faradaic reactions will take place. In this case although made with conducting material the droplet will behave as made with an electrically insulating material. The droplets will then be expelled towards the mould. A droplet can be conducting in a region of low conductivity (low slag temperature), and behaves as insulating in high conductivity region (hot slag temperature). Similarly, a droplet can be conducting in a region of high current density and behaves as insulating in low electric current density regions. It is clear that strong variations in behaviour of the droplets and the slag flow can be expected from one ESR operation condition to another.

For sufficiently high AC frequencies no (or little) reaction will occur at the interfaces. The only phenomenon occurring at the metal/slag interfaces is a periodic change in charge density on both sides of the interfaces. Under such circumstances the current flowing through the interface becomes purely capacitive, and all droplets of any size will behave as conductor. As observed in Figure 6 in AC fields it can be expected that droplets will be attracted towards the centre.

In sufficiently high frequency (> 30Hz), the occurrence of the electromagnetic skin effect inside the droplets might have a destabilizing effect. If the Lorentz force is strong enough the action can possibly lead to a breaking into smaller droplets. This topic needs further investigations.

Conclusion

This study has numerically investigated the effect of the AC current frequency on the electroslag remelting process. The direction of the time dependant electromagnetic force was computed and applied to the slag and liquid pool volumes. For a 50 Hz current the kinetic energy contained in the systems reacted weakly to the oscillating force, however due to a discrete change in direction of the Lorentz force, waves are generated at the slag/metal pool interface. When the frequency was 1 Hz, spectacular global fluctuations of the liquid pool kinetic energy were predicted. Metallic droplets in the liquid slag experience an additional electromagnetic force which direction depends on whether the droplet is conducting or not. In the lower range of electric current density metallic droplets behave as insulators. If the voltage drop is larger than the sum of the anodic and cathodic potential overpotentials the droplets behaves as conducting droplets. It can be expected that through electrochemical effects, Magnetohydrodynamic phenomena might influence the final ingot properties and quality.

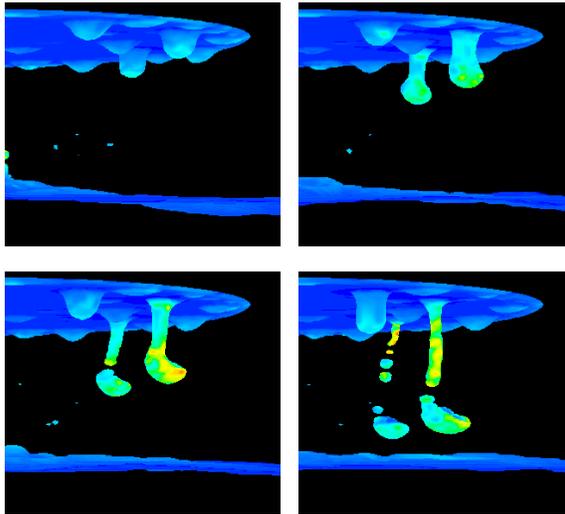


Figure 6: Fall of conducting droplets through a layer of slag.

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