How to get a smooth ESR Ingot surface?

A. Kharicha [1,2], E. Karimi Sibaki [1], M. Wu [1,2], A. Ludwig [2]

[1] Christian Doppler Laboratory for Advanced Process Simulation of Solidification and Melting,

[2] Department of Metallurgy, University of Leoben, 8700 Leoben, Austria

Contact: abdellah.kharicha@unileoben.ac.at

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Abstract

Thin and homogeneous slag skin is the only known way to obtain a nice ingot surface quality. It is usually believed that surface quality is mainly controled by the slag temperature at the vicinity of the mould. In the present paper considers the effect of the Joule heating on the slag skin energy balance. It will be demonstrated that the magnitude of Joule heating generated within the skin can determine its thickness. The empirical variation of the ingot surface quality with the meltrate, the electrode immersion depth, fill ratio and the resistivity of the slag can be explained by the electric current path and intensity.

Introduction

The surface treatment of ingots produced by the ESR process is expensive. The optimum slag would enable the production of ingots with smooth surfaces, thus reducing the need for surface treatment prior to forming. Mitchel et al. [1] explain the mechanism of slag skin formation by using the phase diagrams of the corresponding phase. A slag skin is formed by the selective solidification of one or more phases on the water cooled copper wall[1]. Its formation plays an important role in controlling the heat transfer to the mould. The phases which solidify and their order of solidification are determined by the composition of the liquid slag and the governing phase relationships. Mitchell [2] has pointed out that the phases present in the slag skin have a direct influence on ingot surface quality. However Korousic and Osterc [3] performed mineralogical analysis of several sample of slag skin, and found that the crystallisation did not follow the path given by the phase diagram.

It has been observed that good quality surface is associated with the presence of a finite depth (few cm) of liquid-metal contact on the slag skin[4] also known as “liquid head” or “standing height”. To achieve this requirements, the melting point of the slag must be higher than that of the metal. For this reason it was stated that a slag with higher Al_2O_3 content than the eutectic will produce good surfaces, while those with lower will not[2]. It was found that two slags with 25 and 10 wt-% gave uniform smooth slag skin. The slag with 1 wt% Al_2O_3 was embedded within the ingot surface. The resistivity of the slag was also mentioned as an important parameter since it controls the heat generated within the slag[2]. Slags with lower fluoride contents (higher electric resistivity) are known to be operationally more efficient in

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achieving good ingot surface quality [5]. A resistive slag is believed to be able to sustain a sufficiently high temperature at the slag/pool interface to sustain the existence of a sufficiently thick depth of liquid metal against the slag skin. However it can be argued that the temperature in a process is primarily determined by the targeted meltrate. A resistive slag needs a smaller amount of imposed current to reach the same melt condition than a more conductive slag. So the temperature might not be the only reason. In addition the explanations given, melting point of the slag versus electric resistivity, are clearly overlapping since slags with higher (Al_2O_3) content have generally higher electric resistivity and simultaneously higher melting point.

It was suggested by industry to run the process with warmed mould may encourage the formation of smooth skin [6]. But in most common industrial practice, the problem with poor surface has been dealt with increasing the power input (and so the meltrate), and by using the highest stable fill-ratio. An explanation based on slag temperature can again be given, a large fill ratios decreases the heat losses at the exposed slag surface, and thus increases the slag temperature near the mould. The thickness of the slag skin is also largely affected by immersion volume of the electrode. Immersing a large volume of electrode into the slag layer increases the amount of heat extracted by the electrode and by the mould, which lowers the temperature of the slag cap and thus increases the thickness of the slag skin. Therefore it is highly recommended to keep the immersion volume of the electrode as small as possible.

The slag viscosity was also mentioned as a parameter that can control the slag skin thickness. Due to similar molecular mechanism of the viscosity with the electric resistivity(ions movement), electrically resistive slags are more viscous than conducting ones. By using a slag with high viscosity the slag flow velocities are lower. Kusamichi et al.[7] reported larger radial temperature gradient in slags with low fluoride content than for larger one. The hottest region was located near the electrode, and the coldest near mould. Low fluoride slags are usually used together with lower applied electric current intensities, which together with a higher viscosity level mean lower magnitude of the electromagnetic forces, which in turn generate less stirring in the slag region. The fact that colder temperatures were found near the slag skin for low fluoride slags is an indication that the slag temperature is not the proper mechanism to explain why resistive slags are more efficient in producing thin slag skins.

In previous numerical works it was shown that the electric current flowing directly towards the mould has a considerable effect on the slag skin thickness [8-9]. For better prediction, the Joule heating generated by the electric current must be added to the heat balance of the slag skin. To our knowledge, Medina et al. [10] were the first to notice experimentally a possible relation between the electric current and slag skin thickness: „..a considerable increase in slag skin weight may be produced when remelting shows wide oscillation in current“. The electric conductivity of the slag skin is a function of the temperature, and in average it has been estimated to be in the order of 1 to 50 Ω/m. This average conductivity must also take into account the existence of a contact resistance at the slag skin/mould interface [11-12]. Just as for the heat transfer, this contact resistance might depend on the slag composition but also and the temperature. For some compositions or/and at high temperatures the slag skin possesses a „ plasticity“ which promotes a very good contact with the mould[12]. According to our own estimations, by taken into account the slag/mould contact resistance, the effective solid slag conductivity lies in the range of 0.1-50 Ω/m .

In the case of „mould isolated“ from the baseplate, J.Cameron et al [13] estimated the amount mould current to be less than 5% of the total current. However, the processes studied were small ESR units (moulds ~2.5-8 cm mould and 2.5-3 cm electrodes diameters) which in normal condition operate with deep electrode immersion depth. The shape of the electrodes tip in such small size ESR are conical, the current path is thus mostly oriented towards the liquid pool. If the electrode tip would have been deepen close to the slag surface the amount of mould current would have probably reached 20 to 40 % of the total current (according to our own calculations). For other ESR scales the amount of mould current can reach up to 90% of the total applied current [8-9].

We propose the hypothesis that the current flowing through the slag/mould and the ingot/mould interfaces is a major key parameter to explain the empirical correlations gathered by industry on the quality of the ingot surface. After having presented some generalities about electric current path, the effect of mould current on the slag skin thickness is investigated.

Electric current path in ESR system

To correctly predict the electric current path, a numerical model based on the potential formulation A-ϕ of the electromagnetic field. The mould and the electrode diameter are 0.75 and 0.5 m respectively. The slag height is 0.15 m, the liquid and solid slag conductivities are taken equal to 140 and 5 $\Omega^{-1}m^{-1}$. The slag skin thickness is assumed constant along the height $\delta = 1\,mm$. The ingot is assumed to be in perfect electric contact over 3 cm under the slag/metal interface. An rms current of 14200 A is applied from the top electrode frequency. The results of calculations shows that different electric current paths can exist in the ESR process(Figures 1-2). The possible paths depend on whether the mould is connected or not to the baseplate :

In the case of a „live“ mould the possible electric current circuits are :

a: Electrode->Slag->Mould

b: Electrode->Ingot->Mould

c: Electrode->Ingot ->Baseplate->Mould

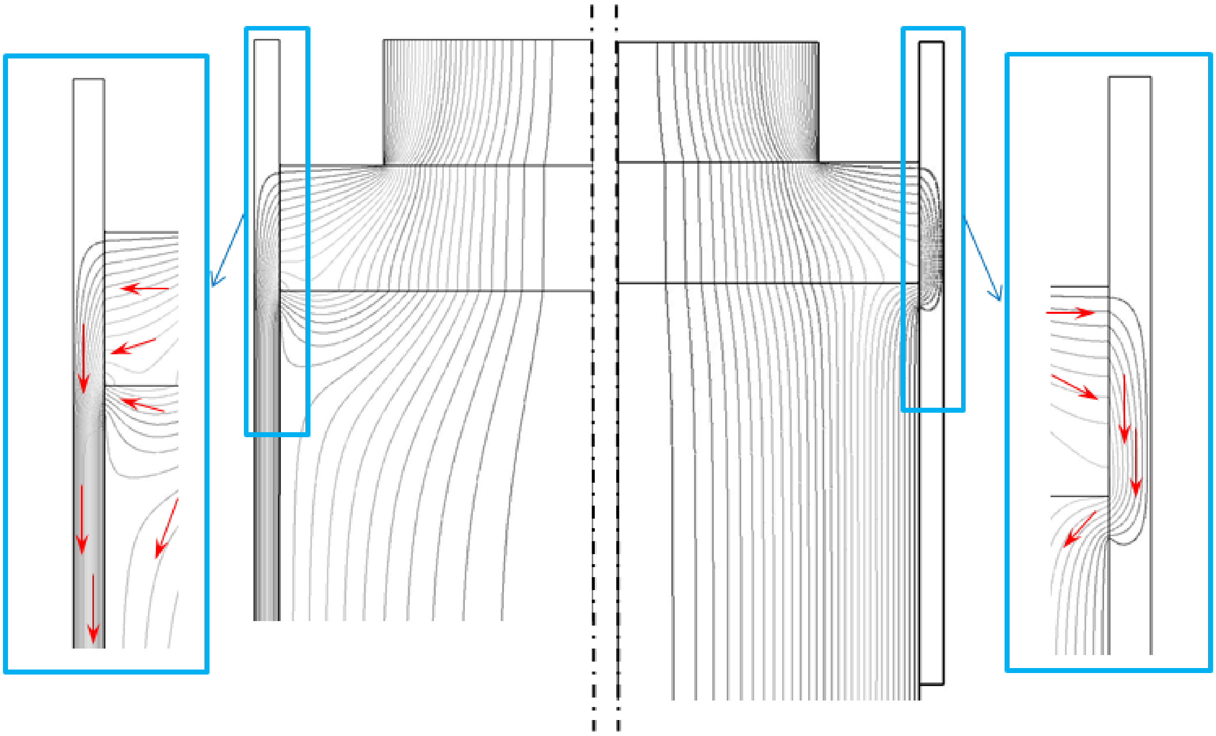
In the case of insulated Mould(or moving mould) :

d: Electrode->Slag->Mould->Ingot->Baseplate

e: Electrode->Ingot-> Baseplate

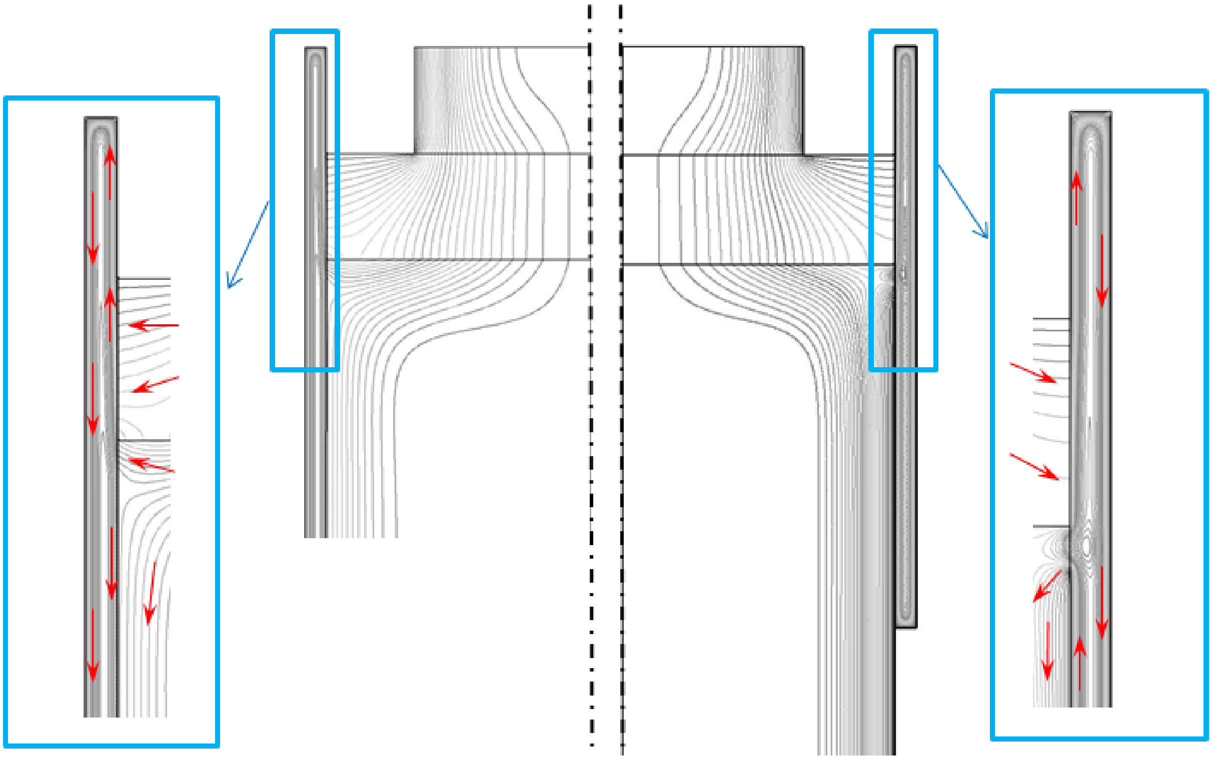
The magnitude of the current flowing in each circuit depends on the electric resistances of each path. In the isolated concept the current in the circuit (d) has to cross two times the skin. Thus if the slag skin covers the entire ingot, less current flows within the mould in the „isolated“ than in the live„ mould. However a distinction must be drawn between the current entering (or leaving) the mould at the slag and at the ingot level. At the slag level, for the present configuration, a small difference exists between the live and insulated mould concept.

However at the mould level it can be seen that for the live concept the slag skin has only a very limited power of insulation since almost 65% the current enters the mould. At 50 Hz for the insulated mould, eddy currents generated within the cooper media propagate inside the steel media (Figure 2). In the case of live mould, the model predicts that a small amount of current is flowing from the ingot to the mould trough the liquid slag. If the slag skin is totally remelted at the liquid metal level, a good contact metal against the cooper mould can increase considerably the amount of mould current. In the present configuration the mould and the ingot are assumed to be in contact over a height of 3 cm, in reality this height can be much larger especially in the presence of a “liquid head”. So from a process to another this contact height can be very different, so the magnitude of current that can potentially flow through this boundary cannot be clearly defined. In opposite the amount of current flowing from the liquid slag to the mould, topic of the next section, is much more universal.



(a) Live Mould (b) Insulated Mould

Figure 1: Electric current path for a low frequency current (DC or < 5Hz)



(a) Live Mould (b) Insulated Mould

Figure 2: Electric current path for a 50Hz frequency AC current

Effect of a finite slag skin conductivity on power generated

To illustrate the effect of the slag skin electric conductivity on the power generated a parameteric study were performed on the case of a live mould ESR process. The slag skin thickness is still assumed to be constant along the height $\delta = 1\,mm$. Figures 3 shows the evolution of the total power generated in the slag (P_t) with the slag skin conductivity.

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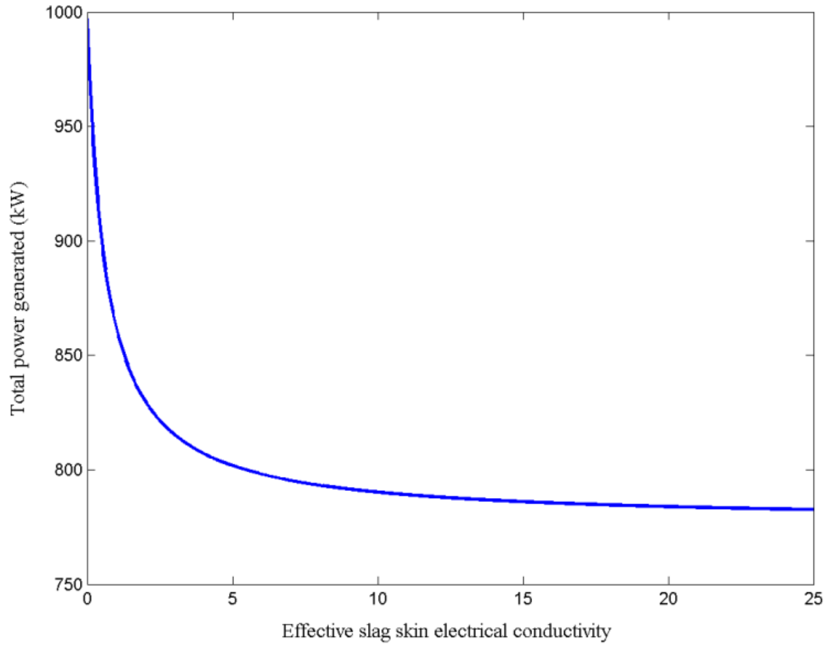


Figure 3 : Total power generated versus slag skin electrical conductivity

The power decreases almost exponentially with the slag skin electric conductivity, which means that opening the path to the mould decreases the overall resistance. The power reaches 1000 kW for the case of perfectly insulating slag skin, for conductivities larger than 15 Ω/m the power almost reached its asymptotic level (~775kW).

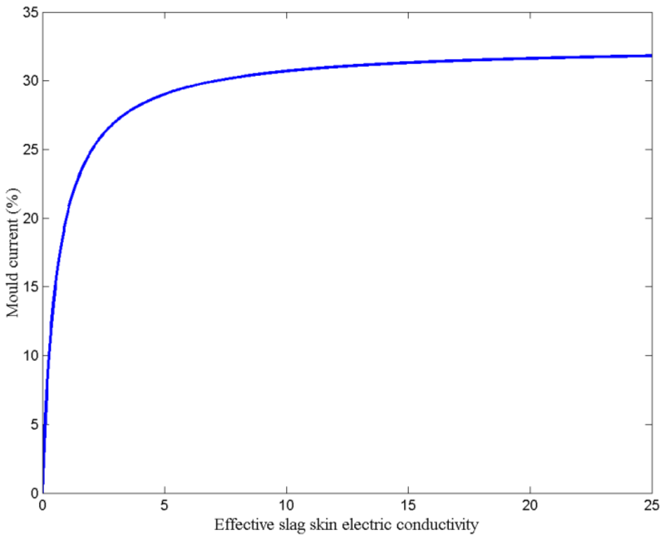


Figure 4 : Proportion of electric current entering the mould at the slag level

The proportion of mould current I_m/I_t increases strongly for conductivities smaller than 3, for $\sigma > 15$ the proportion increases asymptotically towards a maximum of about 32 %(Figure4).

The proportion of power generated within the slag skin reaches a maximum of 27 % for slag skin electric conductivities $\sigma \sim 1 - 2$ Ω/m (Figure 5). The existence of a maximum can be expalined by the fact that j_m^2 increases while $1/\sigma$ decreases with σ. Due to the lack of knowledge of the actual slag skin electric conductivity it is difficult to determine the actual state of the process. However in the real ESR plant the experimental power was found to fluctuate from 790 to 830 kW. This indicates that the actual slag skin conductivity might be arround 2 to 3 Ω/m. If uncertainty about actual liquid slag conductivity is taken into account ($\sigma_l \sim 120 - 180$ Ω/m), the slag skin conductivity can be assumed to be within the range of 1 to 5 Ω/m.

Within this range the power generated within the slag skin (Ps) is high 80-220 kW, it represents 10 to 27 % of the total power. This power must be compared with the heat lost through the mould, which is in the order of 350 kW (assuming 10^6 Watt/m^2). Even in the largest case the Joule heating generated in the slag skin contributes for 2/3 of the heat received by the mould. So it can be stated that having 27% of the total power generated within the slag skin cannot be considered as unphysical. However this large amount of power generated in a so thin volume will definitively modify the actual slag thickness.

Effect of slag height and fill ratio on the mould current

The larger is the slag height, the higher is the resistance of the electrode/liquid pool path. For the case of slag skin conductivity of about $\sigma = 15$ and slag height of about 30 cm, 66% of the current flows to the mould in the live mould concept, and 50% in the insulated mould concept (figure 5). Similarly the fill ratio controls the ratio between the electrode/mould and the electrode/pool distances. Smaller is the electrode radius, less current flows into the mould.

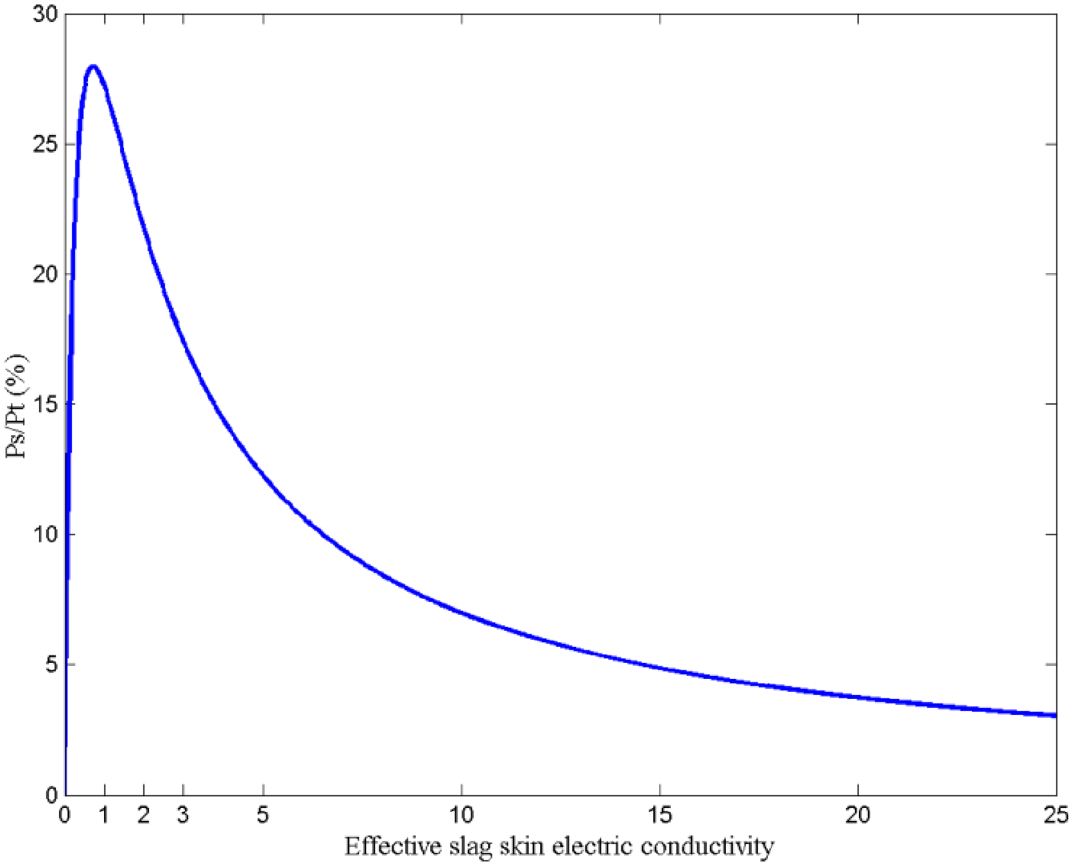
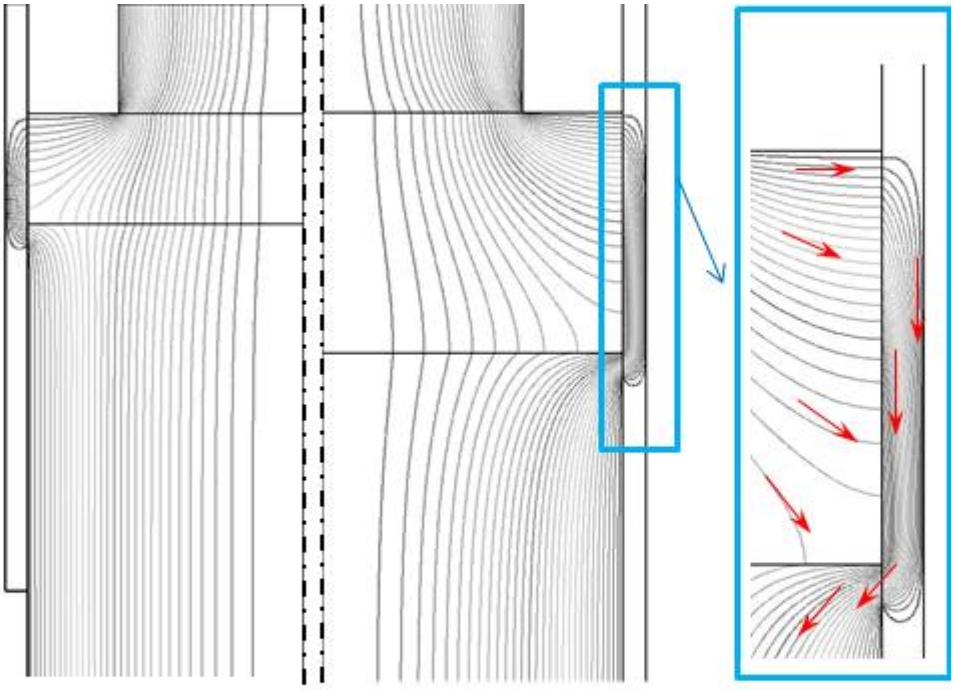


Figure 5: Proportion of the total power generated within the slag skin



(a) 15 cm slag cap (b) 30 cm slag cap

Figure 6: Electric current path for two slag heights for the case of mould insulated from the baseplate . On the right the electric current vectors are shown in a the region near the mould

Effect of the mould current on the slag skin thickness

Let us consider the energy balance within the slag skin. The warmer liquid slag (or liquid metal) provides a heat flux Q_{Slag} wich enters the slag skin. At equilibrium the heat entering the mould Q_{Mould} consists in the sum of Q_{Slag} and the heat generated by the Joule heating within the slag skin Q_{Joule} :

$$Q_{Slag} + Q_{Joule} = Q_{Mould} \tag{1}$$

The thin attribute of the slag skin allows us to rewrite it in the following form :

$$\delta^2 \frac{j^2}{\sigma} + \delta Q_{Slag} - k_s \Delta T = 0 \tag{2}$$

Where j is the electric current crossing the skin, σ is the effective slag skin electric conductivity, and $\Delta T = T_{liq} - T_{mould}$ is the drop in temperature across the slag skin. In the present analysis consider the hot side of the skin to be a the slag liquidus temperature. k_s is an average heat conductivity of the solid slag . The magnitude of the temperature drop across the slag skin depends on the quality of the heat contact with the cooper mould. In the case of a perfect contact, $\Delta T \sim 1650 - 500 \sim 1000\, K$. In real process a jump in temperature exists at the interface with the mould, so the temperature drop across the skin is probably smaller $\Delta T \sim 400 - 900\, K$.

Without mould current (*j*=0) the thickness is simply inversely proportional to the heat flux:

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$$\delta_0 = \frac{k_s \Delta T}{Q_{Slag}} \tag{3}$$

In the presence of mould current the solution is:

$$\delta(j) = Q_{Slag} \frac{\sqrt[2]{1+\frac{j^2}{j_c^2}}-1}{2\frac{j^2}{\sigma}} \tag{4}$$

with j_c defined as:

$$j_c^2 = \frac{\sigma Q_{Slag}^2}{4 k_s \Delta T} = \frac{\sigma}{4\delta_0^2} k_s \Delta T \tag{5}$$

When $j \ll j_c$, the slag skin thickness decreases quadratically with the intensity of mould current :

$$\delta(j) \approx \quad \delta_0 (1 - \frac{j^2}{2 j_c^2}) \tag{6}$$

For very large electric current density $j \gg j_c$, the thickness decreases with the inverse of the electric current density :

$$\delta(j) = Q_{Slag} \frac{\sqrt[2]{1+\frac{j^2}{j_c^2}}-1}{2\frac{j^2}{\sigma}} \approx \quad \frac{\sigma Q_{Slag}}{2 j_c \; j} \tag{7}$$

In the ESR process the current j is function of the difference in electric potential across the skin thickness is not independent of δ :

$$\mathrm{j} \sim \sigma \frac{\varphi_{liq} - \varphi_{Mould}}{\delta} = \sigma \frac{\Delta\varphi}{\delta} \tag{8}$$

For the sake of simplicity we assume that the mould is connected with the baseplate, in this case we can assume φ_{Mould} constant and equal to zero. The solution of equation (Eq. 2) simplifies into:

$$\delta \quad = \frac{k_s \Delta T - \sigma \Delta\varphi^2}{Q_{Slag}} \tag{9}$$

The slag skin thickness decreases linearly with σ and quadratically with the jump in potential acros the skin. The maximum possible difference between the liquid slag and the mould electric potential is:

$$\Delta\varphi_{max} = \sqrt{\frac{k_s \Delta T}{\sigma}} \tag{10}$$

This represents a physical limit for the Joule heat released over which the skin layer cannot sustain its solid nature ($\delta \;\; > 0$). As example by using $k_s = 0.5$, $\sigma = 1$, we obtain $\Delta\varphi_{max} \sim 22$ Volt. The maximum difference in potential $\Delta\varphi$ is reached at the gas/slag interface.

The question is whether the limit (Eq. 10) can be reached or not during the process. In both live and insulated mould cases, the potential of the mould φ_{Mould} can be considered as constant. The magnitude of $\Delta\varphi$ varies with the axial position along the mould and reaches its maximum at the top slag/gas interface. This maximum depends directly on the fill ratio and must be compared with$\Delta\varphi_{max}$. By increasing the size of the electrode, $\Delta\varphi$ becomes closer to the operating voltage of the process(typically 30-70 Volts). Therefore depending on the properties and the height of the slag, there

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exists a maximum fill ratio so that $\Delta\varphi \quad < \Delta\varphi_{max}$. It is clear that more resistive is the slag skin, larger can be the fill/ratio. We believe that relation (Eq. 10) explains also why ESR processes are successfully run with large fill ratio only if the slag height is not too high.

Correlation between Electric current distribution and Ingot surface quality

Cases	Empirical correlation towards better ingot surface quality	Explanation based on slag temperature	Explanation based on mould current
A	Higher Slag resistance ↑	Higher slag temperature ↑	I_m/I_t ↑
B	Melt rate ↑	Higher Slag temperature Stronger Liquid pool Stirring	I_m ↑
C	Power, applied current ↑	Higher slag temperature Stronger stirring in the slag and metal	I_m ↑
D	Fill ratio Re/Rm ↑	Heat lost at the exposed slag surface ↓	I_m/I_t ↑
E	Electrode penetration depth ↓	Slag/mould surface ↓ heat lost ↓	I_m/I_t↑

Table 1: Factors influencing the ingot surface quality and possible explanations

The slag skin is first formed at the slag level, then it enters the liquid metal pool where it can eitheir keep its size or melt. Good ingot surface quality is believed to be acheived if the slag skin melt completely or at least partly. For each empirically known correlation, a conventional explanation related to heat transferred to the slag skin (Q_{Slag} in Eq.1.) exists. The proposed explanation based on the Joule heat released within the slag skin $Q_{\quad Joule}$ is related to the magnitude I_m or proportion of the mould current (I_m/I_t) . A summary of concurrent explanations is presented in table1.

The two cases (B-C) are highly related and cannot be separated, higher melt rate are only reached by increasing the magnitude of the applied current and so the power. The cases D and C decrease the heat losses by decreasing the area in contact with the electrode, the air and the mould. However these two cases, as mentioned inprevious sections, are related to the geometrical characteristics which control the amount of mould current. The case A is better related to the electric explanation by the fact that if similar meltrates are obtained with two different slags, resistive slags although using lower electric intensity gives usually better surface quality.

Conclusions

Despite its very small electric conductivity, the solid slag skin can largely conduct a large amount of electric current. The proportion of electric current entering the mould is function of the slag electrical conductivity, the slag height, electrode penetration depth and the fill ratio. These parameters are also known to influence the ingot surface quality. We suggest the hypothesis that the Joule heating generated within the slag skin contributes largely to the ingot surface quality. Results of simulations show that a large amount of Joule heating is generated within the slag skin volume. The electric current that crosses skin at the liquid metal level can easily reach high electric current density. Depending on the heat balance, this additional heat contributes certainly to the melting of the slag skin volume.

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