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INFLUENCE OF ELECTRODE IMMERSION DEPTH IN THE ESR PROCESS: AN EXPERIMENTAL AND NUMERICAL STUDY

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Abstract

In the Electroslag Remelting (ESR) process, the electrode tip is plunged into the slag bath. Its immersion depth is a key parameter that has a strong influence on electromagnetic phenomena and coupled transfers within the slag. Associating trial remeltings and numerical modeling of the process, some specific impacts of electrode immersion depth are highlighted. The link between electrode immersion and slag resistance is discussed about a regime for which electrode excursion plays a specific role. The influence of electrode immersion depth on ingot solidification, especially regarding the quality of ingot skin, is addressed.

Introduction

The Electroslag Remelting (ESR) process is used to cast special steel or superalloy ingots with a higher metallurgical quality than those obtained by conventional casting [1]. The primary ingot – also called the electrode – is plunged into a highly resistive slag bath contained in a water-cooled copper mold. As electrical current flows, the electrode is melted due to the Joule heating occurring in the slag. A liquid film is constituted under the electrode, from which liquid metal droplets form and fall through the slag before being collected into the melt pool of the growing ingot [2].

Despite its critical role, electrode immersion depth (abbreviated thereafter as EID) has been scarcely studied, especially for industrial-sized remeltings [3, 4]. Because of a change in spatial distribution of electrical current, electrode immersion depth influences several phenomena. Among others, the slag equivalent resistance, hence the heat generation, diminishes when the immersion is increased. Ingot solidification, especially for its outer part, is also affected by a change in heat distribution and hydrodynamics of the slag.

In this paper, the influence of EID is assessed through the association of trial remeltings performed at industrial scale by Aubert & Duval and numerical simulations of the process developed at Institut Jean Lamour and Montanuniversität Leoben. The present study is part of a research project dedicated to the improvement of the understanding and the modeling of slag-metal energy transfers in the electroslag remelting process [5].

Experiments and EID Calculation

Three trial remeltings of steel electrodes using a 70/15/15 type slag have been performed to study the influence of the EID on the ESR process. Two process parameters, the electrode feeding velocity and the melting current, need to be controlled during the remelting operation. The first one is related to EID and the second to the heat generated within the slag and therefore to the melt rate. A specific process control has been applied for these trials: voltage was used to control the electrode feeding velocity and was set to a given value. The melt rate was not controlled, as a constant current was aimed. This was intended to ensure a constant immersion depth within a certain period of time. This kind of process regulation has also been discussed by Schlienger [6]. Note that voltage swing is usually used to control electrode feeding, hence EID [7, 8]. Voltage swing is a variation of measured voltage which is not constant with electrode immersion depth.

For all three trials, the voltage aimed value was modified throughout the remelting in order to reach several distinct EIDs, and therefore investigate the effect of this parameter on electrical signals and ingot solidification.

The time evolution of the voltage during one of these remelting operations (trial #2) is plotted on Figure 1. During this trial, the voltage set point was regularly modified in order to progressively reach deep immersion. The lower immersion – i.e. higher voltage – was obtained at 105 minutes, and the higher one – i.e. lower voltage – at 340 minutes. The changes in voltage swing is noticeable: when the electrode was weakly immersed (until 160 min), considerable voltage variations were measured, whereas during the rest of the trial, as the electrode was more and more immersed, voltage signal became flat.

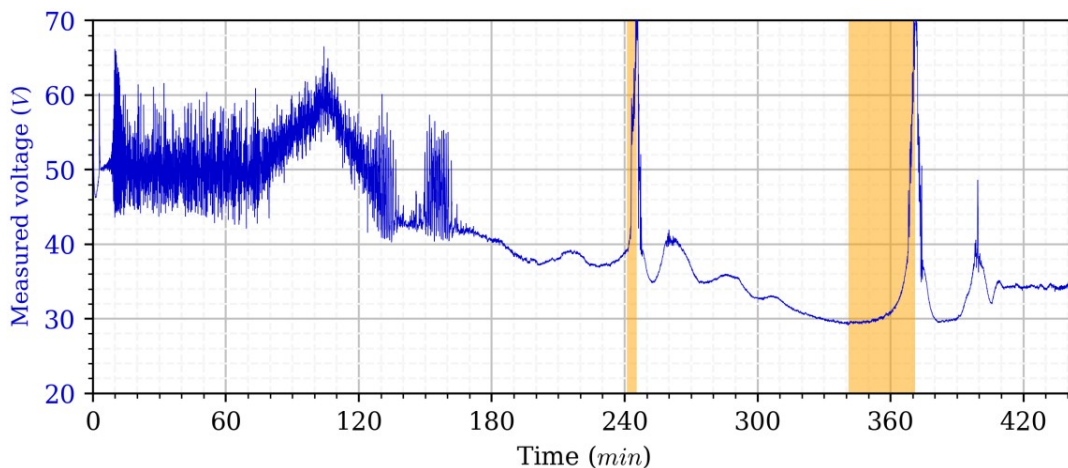


Figure 1: Evolution of measured voltage during trial remelting #2

EID was not directly measured but its variation can be calculated afterwards, using the electrode mass variation, the thermophysical properties of slag and electrode and accounting for the

Archimedes' principle. In order to estimate it at specific times, but also to characterize the moment when the immersion is zero, the electrode motion was stopped while the electrical current was kept as its reference value. Therefore, the immersed part of the electrode was progressively melted until the tip reaches the slag surface. For instance, during trial #2, two EID determinations have been performed. The evolution of measured voltage during these specific procedures is highlighted in yellow on Figure 1.

Figure 2 shows the evolution of the electrical resistance measured during one of these procedures and compares it to the simulation of the evolution of slag equivalent resistance while decreasing the immersion. The latter is computed using a 2D axisymmetric electromagnetic model of the ESR process similar to the one described previously by the authors [9].

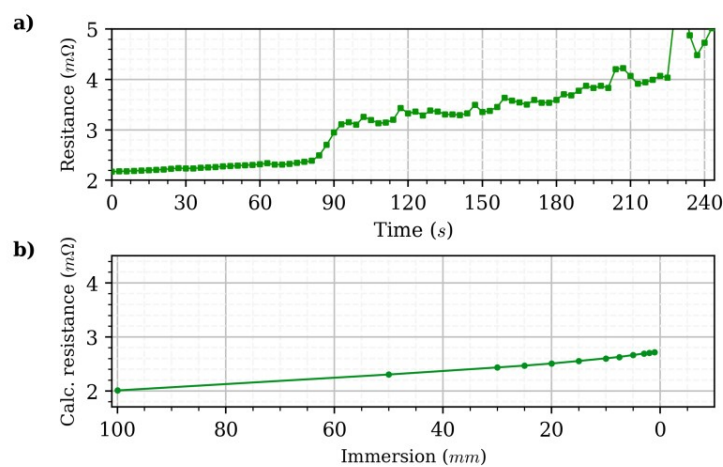


Figure 2: a) electrical resistance measured during the procedure for zero-immersion determination and b) evolution of the calculated resistance vs. immersion

As stated before, when the EID decreases, the slag equivalent electrical resistance increases: this is mainly due to the fact that, considering a constant amount of slag, the distance between the electrode bottom and the top of the ingot – which is the main contribution to the slag equivalent electrical resistance – is greater.

Nonetheless, the voltage point marking “zero” immersion – i.e. the electrode is flush with the slag – is not that clear. We can see on Figure 2 a) that the maximum resistance reaches 5.0 mΩ, while the extrapolated calculation for 0 mm immersion is around 2.8 mΩ (Figure 2 b)). The latter will be taken as the value for the “zero immersion” point. Any higher experimental value reflects a partial contact between the slag and the electrode tip. This may be due to partial immersion (if the tip is not perfectly flat), slag surface swaying, or the presence of liquid metal faucets and drops forming from the liquid film. All these phenomena may be responsible for a restricted electrical contact surface, therefore a higher resistance.

Considering this description, on Figure 2 a), the “zero immersion” point is obtained after around 90 s. One can note that it is also the moment when a steep rise in measured resistance is seen.

Thanks to the definition of this “zero immersion”, and knowing the instantaneous melt rate during the electrode motion stopping procedure, EID can be calculated for every data point before this specific one. The evolution of measured resistance as a function of the calculated EID is given on Figure 3. *To ensure the confidentiality of industrial data, only the ratio between EID and the maximum EID can be given.* As stated previously, electrical resistance is lower when the electrode is deeply immersed. Then, the resistance increases in a quasi-linear way. The deviation from linearity for shallow immersions is more noticeable than the one simulated.

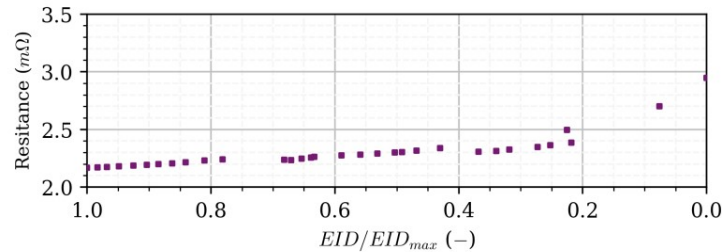


Figure 3: Evolution of measured resistance as a function of calculated EID

Influence of Electrode Immersion Depth on the Slag Equivalent Resistance

As discussed above, one of the main effects of electrode immersion depth can be noticed on the electrical signals recorded during the remelting process, like resistance or voltage. As seen on Figure 2, the increase in resistance when the electrode is immersed is not perfectly linear – which is verified both experimentally and by calculation. Then, a strong rise is visible around the “zero immersion” point, i.e. during the excursion of the electrode. This rise is also visible during a specific regime obtained during the remelting trials, as illustrated by the time evolutions of slag resistance on Figure 4. Periodic spikes are observed, while the baseline between those spikes is slightly increasing between these peaks. Figure 4 a) shows this phenomenon occurring during trial remelting #2 (see Figure 1.), and b) happened during trial #1. In both cases, periodic resistance spikes are seen, whereas the pattern is not exactly the same.

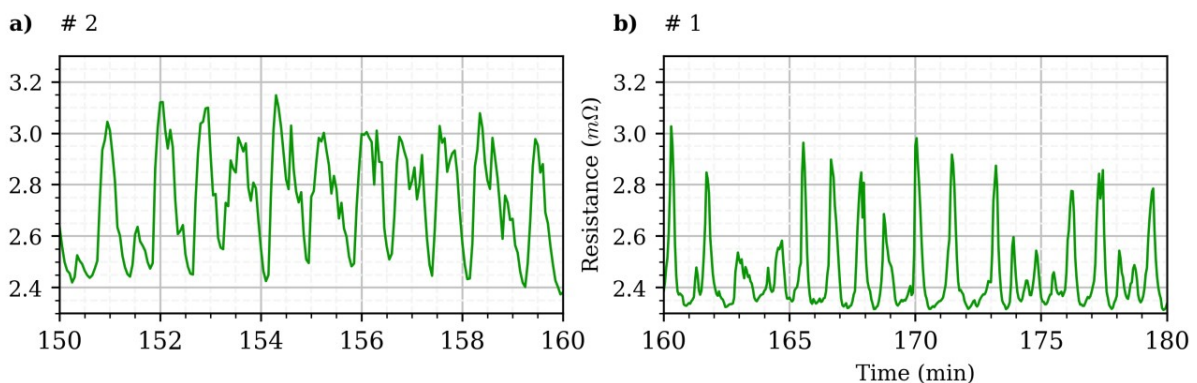


Figure 4: Periodic resistance spikes observed during electrode excursions

This phenomenon corresponds to an instability created by the combination of the melting phenomena and the process control. It is known that, when the immersion is decreased, as the electrical resistance is higher and so is the heat generated by Joule heating, the melt rate increases [6]. Depending on the parameters used within the PID control loops, the reaction of the control system may be delayed because the change in voltage or resistance is unnoticed. Electrode feeding velocity remains therefore the same, and as the electrode melt rate increases, the bottom of the electrode reaches the surface. With this excursion, the resistance spikes. At that moment, the process control reacts and plunges back the electrode into the slag. Such instabilities have also been reported by Melgaard and Shelmidine [10].

Impact on Ingot Skin Formation

Now that the influence of electrode immersion depth on the slag electrical resistance has been discussed, its impacts on the remelted ingot can be addressed. A first effect can be seen on the outer surface of the ingot, called here “ingot skin”.

As the electrical current is aimed constant, a change in the slag resistance – caused by a change in EID – affects the heat generated within the slag, hence the melt rate. The melt rate is known to affect ingot solidification. Indirectly, electrode immersion depth may thus influence ingot solidification.

During the trial remelting #2 (see Figure 1.), wide variations in the electrode immersion depth were performed. A picture of the remelted ingot is reproduced on Figure 5. The immersion was shallow at the beginning of the remelting. As a high amount of heat was generated in the slag because of the high equivalent resistance, the slag skin was thin and possibly partially remelted by the overheated liquid metal head. The ingot then solidified on this partially melted slag skin, ensuring a smooth surface [3], as we can see near the point a) in the figure.

The EID was then continuously increased for the rest of the remelting, to reach a significant immersion depth at point c). Pronounced wrinkles, and even “pancake-like” structures, are observed. When the immersion depth is high, the Joule heating is low, which leads to a thick slag skin and a low overheat of the melted steel. Ingot solidification may start at the meniscus close to this thick slag skin, and some liquid may “overflow”, then creating a pronounced wrinkle. Variation in the mold current may also contribute to the formation of these slag skin structures, as it affects Joule heating in this zone.

Periodic resistance spikes (see previous paragraph) were observed near point b). The ingot skin is there marked by faint wrinkles, whose spacing seems to be linked to the time interval between two successive spikes. It may reflect the electrode excursion phenomena.

Note that the influence of EID visible on the ingot skin is also related to the induced change in melt rate. For shallow immersion – point a) –, the melt rate was around 4 times higher than at point c), and 20 % higher than at point b).



Figure 5: Aspect of one of the trial remelting (ingot foot on the left hand side)

Impact on Ingot Solidification

In order to discuss the influence of EID on ingot solidification, some remarkable cases published in the literature can be taken as a starting point.

Experimental works performed by Holzgruber [11] and by Kawakami et al. [12] showed that, using a low voltage – i.e. a high immersion –, the morphology of the melt pool changes drastically. Sump profile obtained by these authors during the remelting of small-size steel ingots are reproduced on Figure 6 and Figure 7.

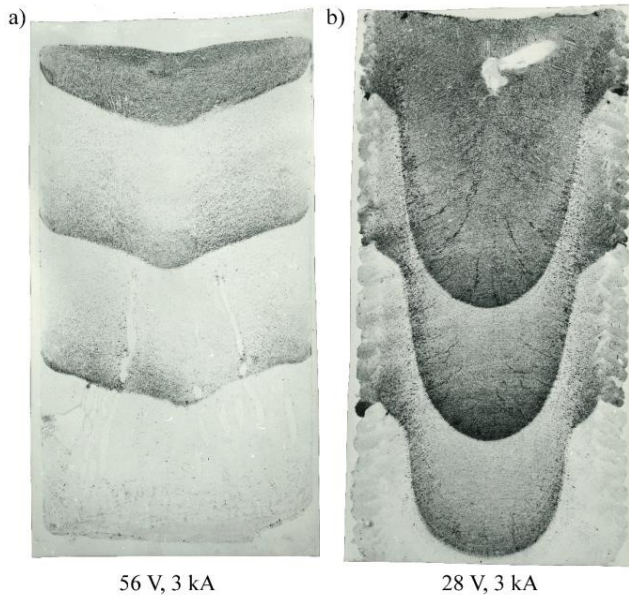


Figure 6: Melt pool profiles for high and low-voltage remeltings, from Holzgruber [11]
 Ø electrode/mold: 100/240 mm, 50/30/20 slag

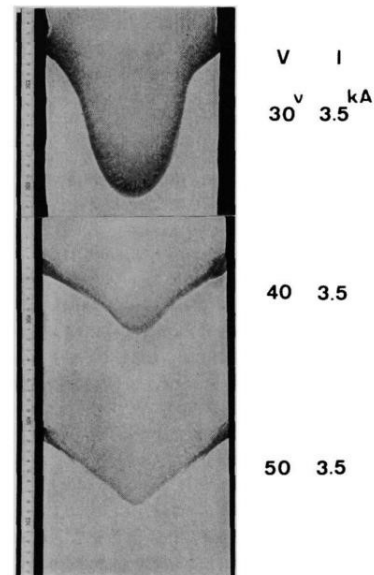


Figure 7: Melt pool profiles for high and low-voltage remeltings, from Kawakami et al. [12]
 Ø electrode/mold: 100/180 mm, 60/25/15 slag

When the voltage is low, i.e. the distance between the electrode and ingot is small, a deep U-shape melt pool replaces the usual shallow V-shape profile. These studies imply that EID (or electrode-ingot gap) might affect ingot solidification because of a change in melt pool morphology.

In order to better understand how EID can influence ingot solidification, numerical simulations of ingots remelted using similar conditions to the ones used by Holzgruber and Kawakami et al. were performed using a transient 2D axisymmetric model of the ESR process, developed by Weber [13] and Hugo [14], then improved by Chaulat [15]. This model simulates the entire growth of the ingot and its solidification. Main parameters and results of these simulations are summarized in Table 1. Two cases were considered: a) a shallow immersion and b) a deep immersion. The slag electrical conductivity was calculated using Ogino's formula [16] to account for the effect of temperature.

Table 1: Main parameters used for the simulations and main results

Parameter	a) Shallow EID	b) Deep EID
Current intensity (kA)		12.4
Electrode radius (m)		0.260
Ingot radius (m)		0.530
EID (mm)	15	150
Results	a) Shallow EID	b) Deep EID
Slag eq. resistance (mΩ)	4.14	1.53
Melt rate (kg.min⁻¹)	5.9	1.5
Melt pool depth at gl=0.5 (mm)	316	185

Figure 8 shows the computed current density distribution, liquid velocity and sump profile for both cases. On the right-hand side of the figures, the melt pool profile distortion between cases a) (shallow immersion) and b) (deep immersion) is obvious. In the second case, the profile adopts a similar U-shape morphology that the one described by Holzgruber and Kawakami et al. This particular pool profile is caused by a counterclockwise (on the right-hand part of the figure) motion in the melt pool, that does not appear in case a). This motion carries hotter liquid deep into the melt pool. Isotherms are then far from their "usual" shape due mainly to the conductive heat transfer within the ingot.

This significant motion of the melt pool in case b) is caused by the difference in current density distribution. As the electrode is closer to the ingot, current density at the top of the melt pool near the center is higher in case b). Because of the deflection of the current lines, strong Lorentz forces are created locally. The U-shape profile is thus caused by an unusual electro-vortex generated in the melt pool.

Furthermore, when the immersion is deep, the immersed part of the electrode does not remain cylindrical but tends to adopt a pencil-like shape. This may reinforce the abovementioned phenomenon, as it would increase again the current density at the top of the melt pool and the divergence of the electrical current lines.

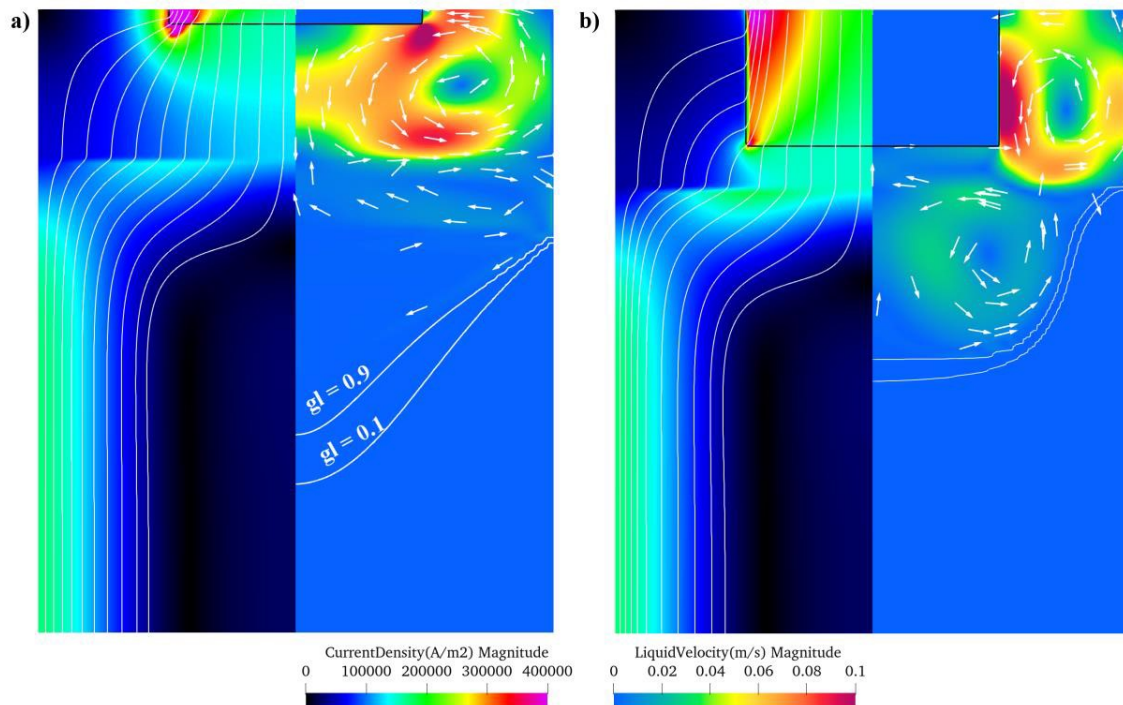


Figure 8: Current density magnitude - current lines (left) and velocity magnitude - normalized vectors (right) for a) a shallow EID; b) a deep EID

Summary and Conclusions

Thanks to the association of trial electroslag remelting operations and numerical simulations of the ESR process, the influence of electrode immersion depth on several issues has been studied. The decrease in electrical resistance predicted by the simulations when EID increases has been verified experimentally. Moreover, EID was shown to have an impact on:

- The electrical resistance level and stability during the remelting (combination of the melting phenomena and the process control),
- The ingot skin formation: because of a change in melt rate and heat distribution, ingot solidification can start at the meniscus,
- The melt pool profile and ingot solidification: the intensity of Lorentz forces in the melt pool depends on electrode immersion depth.

The primary reason underlying all these effects is the impact of EID on the electrical current spatial distribution.

Aknowledgements

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