THERMAL STATE OF THE ELECTRODE DURING THE ELECTROSLAG REMELTING PROCESS

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Abstract

This paper presents a numerical investigation on the thermal state of a melting electrode and its influence on the shape of the electrode tip. The first part of this work computes the heat necessary to melt an electrode with a flat tip shape. It is shown that to keep a constant meltrate, heat supplied to the electrode must be continuously changed. The results for different electrode descend velocities, corresponding to different meltrates, are presented. The second part uses a full ESR model to simulate the melting process. It is found that the thermal state of the electrode exerts a great influence on the shape of the electrode tip.

Introduction

The electrode is an important part of the ESR process. The heat provided by the slag to the electrode determines the efficiency of the melting process. Despite its importance, few works focus on the thermal state of the electrode [1-3]. Mitchell et al. [1] described some experiments where the electrode temperature was measured at a laboratory scale of ESR furnace. A complex two dimensional mathematical model based on a steady assumption of the heat balance of the electrode was built. The model provided fairly good results when compared with the experimental temperature profiles. A simpler analytical model has been proposed by Mendrowsky et al. [2] in which both conduction and radiation from the slag surface was taken into account. Based on this model the temperature ranges were found in good agreements with experimental data provided by Mitchell [1]. The computed results also suggested that thermal radiation is unlikely to be important compared to heat conduction. Tacke et al. [3] used a numerical model to analyse the relation between the temperature field and the melting profile of the electrode. This model was able to compute both simultaneously using a false position algorithm. Several experiments were performed where the slag temperature measured and the electrode tip shape reported for different electrode descend velocities. The electrode descend velocity is defined as the electrode velocity relative to the rising slag velocity. To fit the experimental results, the computation needed an empirical slag/electrode heat transfer coefficient. From one experiment to another the heat transfer coefficient was found to vary between 2000 and 4500 W/m^2K.

All these models imposed the room temperature at a certain distance from the electrode tip. This imposition assumes that the electrode is at a steady state, in which the heat diffusion has not the time to reach the other extremity of the electrode. However, the electrode is a finite and closed system, which is strongly heated all along the remelting time. The problem of the electrode melting is clearly a Stefan problem where both the temperature field and the melting front velocity is unknown. Assuming that the electrode is semi-infinite, Zien [4] suggested an approximate analytical solution of this ablation problem with the help of the approximate integral method. This method was suggested to be used in the control system for the melting of electrodes in the VAR process [5].

In the present investigation this Stefan problem is solved numerically with the embedded boundary method for a finite electrode length. In the first part of the analysis, the time dependant heat entering the electrode is calculated. For that a one dimensional thermal analysis is performed on an electrode which is ablated according to quantity of heat received from the slag. In the second part, the influence of the electrode temperature on the electrode tip shape in a real ESR system is numerically and experimentally illustrated.

Energy Necessary to Melt a Flat Electrode

The goal can be stated as follows: P1: "*For a given electrode (density ρ, heat capacity C_p , heat conductivity λ, latent heat of fusion ΔH) and initial electrode length L_0 , how much heat* $Q_{Slag->metal}$ (Watt/m^2) *must be provided* (from the slag) *to the electrode to achieve a constant meltrate and a flat electrode tip*"

The solution of this problem consists of solving the energy equation in a moving boundary domain. A schematic sketch of the electrode is shown in Figure 1. At the time *t*, the electrode has a length of *s(t)* and moves downwards towards the slag at a speed u_e . The electrode is assumed to melt uniformly to form a flat electrode tip. The melting temperature of the electrode, $T_{interface}$, is assumed to be equal to the liquidus temperature of the electrode material (1750K). The origin of the x-referential is fixed at the top of the electrode. If the solid electrode melt uniformly at the level of the slag surface, the referential must move with the electrode at the specified speed $u_e = -\frac{ds}{dt}$.

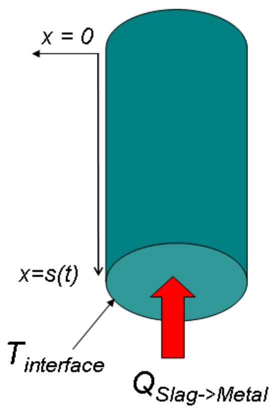


Figure 1. Coordinate set up for the electrode

The set of equations to be solved is:

$$\begin{cases} \frac{\partial(\rho C_p T)}{\partial t} = \frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right) & t > 0, 0 < x < s(t) \\ \frac{\partial T(0,t)}{\partial x} = 0, \quad T(s(t),t) = T_{interface}, & t \geq 0 \\ \lambda \frac{\partial T(s(t),t)}{\partial x} - \rho \Delta H \frac{ds}{dt} = Q_{Slag->Metal}, & t \geq 0 \end{cases} , \qquad (1)$$

Where t is the time, x the Cartesian coordinate and $T(x,t)$ the temperature. The position of the top of the electrode is in $x=0$, the melting front at $x=s(t)$. Thus $s(t)$ is simply the length of the electrode at the time t.
The heat transfers at the lateral and top walls of the electrode, as well as the heat generated by Joule dissipation, are neglected. Usually, the Stefan problem consists in predicting the velocity of the melting front for a given or computed heat flux. In the present problem the unknown quantity is the heat flux $Q_{Slag->metal}$ rather than the meltrate. This heat $Q_{Slag->metal}$ must be equal to the latent heat of fusion $-\rho\Delta H\frac{ds}{dt}$ plus the heat diffused into the electrode by the temperature gradient generated the solid/liquid interface : $q=-\lambda\frac{\partial T(s(t),t)}{\partial x}$. Since the meltrate is set to be constant, the latent heat of fusion is also constant. The real unknown of the problem is the heat diffused into the electrode q, which depends on how much the electrode has been heated during the remelting process. q is then time and u_e dependant, its magnitude varies from the moment when the electrode touch the slag to the moment when the last layer of the electrode disappears.

The moving boundary-value problem governed by Eqs. (1) can be transformed into a fixed one by means of the mapping $(t, x)\rightarrow(\tau, \zeta)$,where $t=\tau$ and $\zeta=x/s(t)$, so that the problem becomes:

$$\begin{cases} \frac{\partial}{\partial\tau}(sT)=\frac{\partial}{\partial\zeta}\left(\frac{\lambda}{\rho C_p}\frac{1}{s}\frac{\partial T}{\partial\zeta}\right)+\xi\frac{\partial}{\partial\zeta}\left(\frac{ds}{d\tau}T\right) \quad \tau>0, 0<\zeta<1, \\ \frac{\partial T(0,\tau)}{\partial\zeta}=0, \quad T(1,\tau)=T_{interface}, \quad \tau\geq 0 \\ \frac{\lambda}{s}\frac{\partial T(1,\tau)}{\partial\zeta}-\rho\Delta H\frac{ds}{d\tau}=Q_{Slag->Metal}, \quad \tau\geq 0 \end{cases} \tag{2}$$

The temperature field is solved for a 1 m long electrode, initially at room temperature (300 K). In Figure 2 the variation of $q(u_e,t)$ is reported as function of the dimensionless remelting time (t/t_0), where $t_0=L_0/u_e$. The profile of q diverges at vicinity of t = 0. To achieve a finite meltrate an infinite heat must be provided to the electrode. Then q decreases, but stays at very high level during the first 5% of the remelting time. After this initial regime, the required heat decreases smoothly during the 80 to 90 % of the remelting time, this stage can be qualified as “steady melting state”. To keep the meltrate constant, the last 5 -10 % of the electrode requires much lower heat than during the steady state.

In the beginning of the process the building of the temperature gradient requires a very high heat input. Theoretically, at t = 0, achieving a non zero meltrate requires an infinite heat input. This means that the desired meltrate cannot be achieved practically from the beginning but should progressively be increased.

At the end of the remelting, the temperature of the top extremity of the electrode is very close to the liquidus temperature, this is why only a small heat flux q is necessary.

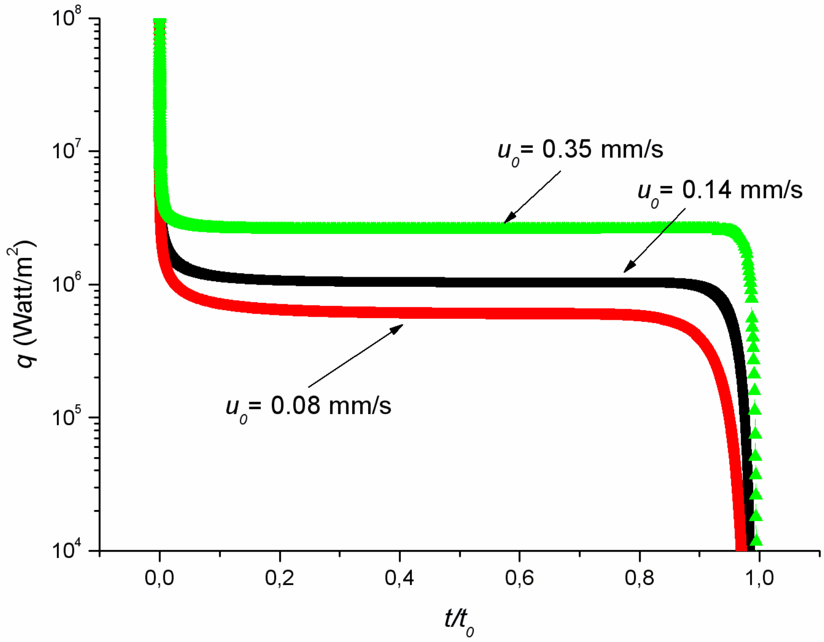


Figure 2: Heat diffused into the electrode versus the dimensionless melting time for three different electrode descend velocities.

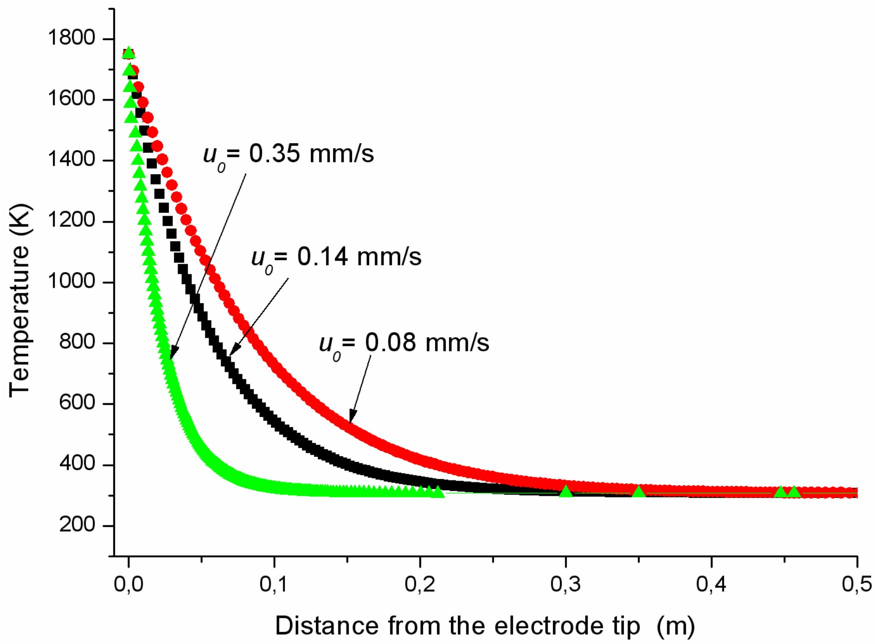


Figure 3: thermal boundary layers during the steady state for three electrode descend velocities.

During the steady state the amplitude of change of q is function of the descend velocity of the electrode. A higher descend velocity means smaller heating time for the electrode. The slower increase of the electrode temperature at the top position promotes quickly the occurrence of a steady heat balance at the electrode tip. This is why the lower variations of q are achieved with higher melt rates.

During the steady state, the heat entering the electrode is equal to the sensitive heat necessary to bring the metal from the room temperature to the melting temperature:

$$q(t,u) = \overline{Q} = u_e \int_{300K}^{T_{interface}} \rho C_p dT \quad (3)$$

The time necessary to build the steady thermal boundary layer can be defined as the time at which q reaches 105% of $\overline{Q}$. This time if of about 142 s for $u_e = 0.35\, mm/s$, 1214 s for $u_e = 0.14\, mm/s$, and 3125 sec for $u_e = 0.088\, mm/s$. The remelting length is 5 cm for $u_e = 0.35\, mm/s$, 17 cm for for $u_e = 0.14\, mm/s$, and 25 cm for $u_e = 0.088\, mm/s$. These calculated results are the smallest theoretical times and distances over which a steady state can be achieved. It assumes that the tip temperature reaches immediately the melting temperature. In practice the electrode preheating operation, which last for several hours, brings the electrode tip temperature from room temperature to about 700-900 K. Only then it is put in contact with the slag.

The thickness of the steady thermal boundary layer varies strongly with the electrode descend velocity (Figure 3). Smaller is u_e longer is the thermal boundary layer. Simulation targeting the meltrate prediction should include a part of the electrode length larger than the thickness of the thermal boundary layer.

The electric current densities for small experimental electrodes such as those studied by Mitchell[1], Mendryvowski [2] and Tacke[3] were of about 10^6 Amp/m^2. The resulting Joule heating generated in electrode (~10^{6-7} Watt/m^3) is then as strong as the heat diffused into the electrode q (Figure 2). Thus the Joule heat generation should not be neglected if the electrode temperature gradient is of interest. For industrial scale electrodes, the electric current density being lower (~10^4-10^5 Amp/m^2), the Joule heating is rather small (~10^4 Watt/m^2).

To further explore the effect of the thermal state of the electrode on the remelting, it is necessary to consider the cases of non flat electrode shape.

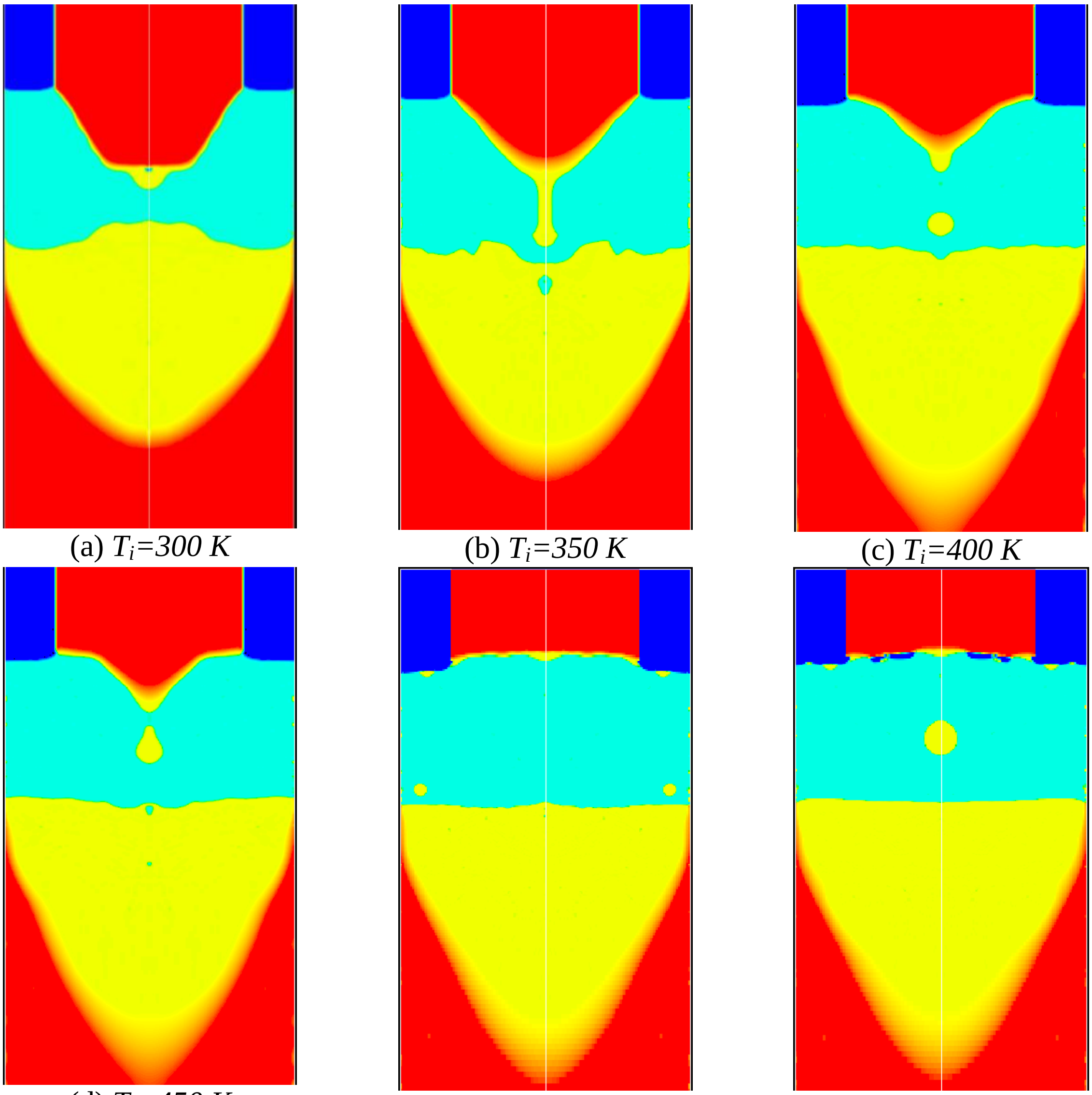
Full Simulation of the Electrode-Slag Coupling

In a real system the heat flux to the electrode is related to the slag temperature and velocity field. Due to the good mixing condition occurring within the slag, the slag temperature can be assumed constant. However, the effective slag/electrode heat transfer coefficient controlled by the turbulent velocity field might not be constant over entire electrode/slag surface. The electrode can then melt nonuniformly. Depending on the electrode descend velocity, it can be difficult to develop a flat or constant electrode shape. In order to explore the complex coupling existing between the imposed electric current, the meltrate and the thermal condition of the electrode, it is necessary to build a model in which all coupling mechanism are included. The present study uses a 2D Magneto-hydrodynamic-Multiphase approach to simulate the flow, the temperature field, and the electrodynamics. The interfaces between the three different phases (metal, slag, gas) are tracked with a Volume Of Fluid (VOF) method. The electric current and the induced magnetic field are fully coupled with the phase distribution. The influence of the axial component of the earth magnetic field is added to the magnetic field induced by the electric current. The electrically conducting solid slag layer is modelled with a 1D approach. Joule heating is considered in the entire calculation domain, including the electrode. A large number of problems related to the meltrate can be investigated, the present model is used to solve the following problem:

P2: "During an ESR process, an electrode moves towards the slag with a fixed velocity. The electrode temperature T_i at 8 cm distance from the slag level is constant in time. Assuming the a constant electric current intensity I_0 and electrode descend velocity u_e., what is the influence of T_i on the shape of the electrode tip ? What is the critical temperature under which the melting is no more possible(limited to 300K)? At which temperature the electrode loses full contact with the slag ?"

To provide a solution to this problem the numerical model is applied to a small ESR system. The process parameters are presented in Table I. Figure 4 represents the evolution of the electrode and pool shapes for different electrode inlet temperatures. Lower is the inlet temperature, deeper the electrode must penetrate into the slag to increase the slag/metal heat surface exchange. For Ti <400 K the electrode tip develop a parabolic shape. For the range 400K $<T_i<$450K the electrode starts to flatten from the extremity of the electrode leaving a V shaped volume in the centre. Around 500 K the electrode is just in contact with the slag, and almost not immersed. The electrode develops a slightly concave melting shape corresponding to the type IV of melting profiles in the classification given by Tacke [3]. This concave shape is due to a strong movement of the slag upwards under the electrode, and then outwards towards the slag periphery. This flow expels some of the droplets towards the mould (Figure 4. e-f). At around T_i=520 K the metal melt at faster rate than what the electrode descend velocity can provide. Thus some air gap is created between the electrode and the slag. In this regime the electrode loses full contact with the slag, the electrode is simply floating on the slag surface with a time varying contact area [6]. Each of the electrode melting regimes are characterized by different power generated, resistance swing, slag/pool interface movement, quantity of mould current and velocity fields. Those characteristics are responsible for the electrode and pool depth and shape. For the present process parameters, the electric current is always able to melt the electrode. Nevertheless, since the electrode reached a very close position to the liquid pool (Figure 4a), a small decrease in electric current intensity or an increase of the electrode descend velocity, may lead to a contact between the solid electrode and the liquid pool.

It is difficult to design an experiment which could solve the problem *P2*. During the process the temperature of the electrode at 8cm from the slag surface cannot be fixed. In addition the control system is continuously changing the intensity of the supplied current in order to achieve the targeted meltrate. However, some of the shapes computed can clearly be identified in experimentally melted electrode (Figure 5). The experiments were performed on the same ESR process geometry (Kharicha [7]) as that used for simulation (Table I). The remaining electrode lengths are smaller than the corresponding thermal boundary layer thickness(~20 cm see Figure 3). Thus, these electrode tip shapes can probably not be the result of a steady state, the temperature at the top of the electrode is larger than the room temperature. Figures 5a-b shows relatively flat electrode with clear surface depression of about 0.5 to 1 cm in the centre. These electrodes can be compared with computed shapes given in Figures 4e-f. In Figure 5c-d the electrodes develop a conical or a parabolic shape similar to those of figure 4b-c-d. It is probable that the curved electrode shapes results in droplets falling mostly in the centre, while electrodes such as those in Figure 5.a-b probably release some droplets at positions close to the electrode extremity (see Figure 4.e-f).

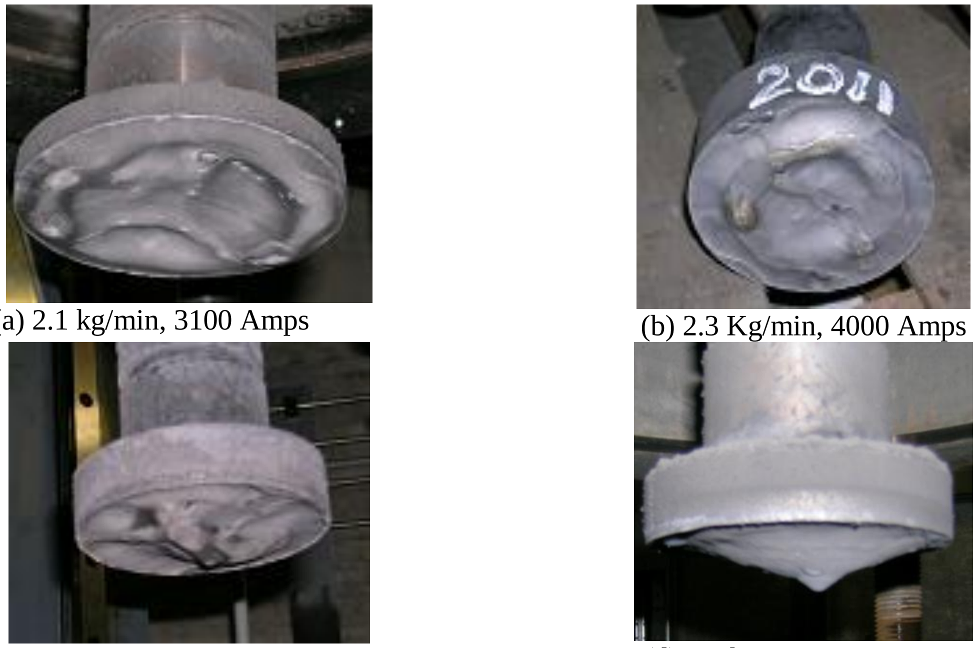


(a) T_i=300 K (b) T_i=350 K (c) T_i=400 K (d) T_i=450 K (e) T_i=500 K (f) T_i=525 K

Figure 4: Computed electrode shape for different electrode inlet temperatures (red: solid steel, yellow: liquid steel, blue: slag, dark blue: Nitrogen)

Table I: Geometry and process parameters

Physical condition	
Current intensity, frequency	4000 Amps, 5Hz
Meltrate	2 Kg/min
Electrode descent velocity u_e	0.35 mm/s
Geometry	
Mould thickness	3 cm
Slag height, metal height	100 mm
Electrode diameter	130 mm
Ingot diameter	200 mm



(a) 2.1 kg/min, 3100 Amps (b) 2.3 Kg/min, 4000 Amps

(c) 2.8 kg/min, 4800 Amp (d) 2.6 kg/min, 4400 Amps

Figure 5: Experimental electrode tip shapes. The reported melt rates and currents are those recorded at the time of interruption of the process [7].

Conclusions

A numerical analysis of the energy balance of the electrode has been performed to explore the different thermal states of electrode during remelting process. In order to melt an electrode with a constant melting rate, a time varying heat flux must exists between the slag and the electrode. The required heat flux follows three regimes. The first regime is characterised by extremely strong heat fluxes. Then a steady state regime starts with a smooth decrease in heat flux intensity. During the melting the average temperature of the electrode is continuously increasing. At the last regime, the electrode is warm enough to be melted with only small heat input. In addition to the imposed current and meltrate, the thermal state of the electrode exerts a great influence on the shape of the melting electrode tip.

Acknowledgements

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