

Enhancing the electroslag remelting process: Development and Implementation of a Rotating Electrode Set-up

Martin Schwenk¹, Bernd Friedrich¹

¹IME Process Metallurgy and Metal Recycling, Intzestr. 3, 52072 Aachen, Germany

Keywords: Electroslag Remelting, rotating electrode

Abstract

The electroslag remelting process (ESR) has been investigated thoroughly over the last decades. Yet there is still potential to improve the refining mechanisms during this process with a modification of the electrode movement. In this context the IME is changing its static electrode set-up on its laboratory scaled open atmosphere ESR towards a rotating electrode. Significant improvement is expected concerning solidification structure, ingot quality and energy flow through altered fluid flow phenomena. Besides this, the aims of this project is a better understanding of the electrodes molten metal film, attaining detailed knowledge in terms of droplet detaching from the electrode, investigation of the current flow through ingot and mould and an investigation about the behavior of nonmetallic inclusions. This paper provides an overview on the fundamental principles leading to the before mentioned assumptions as well as the current state of work.

Introduction

The electroslag remelting process (ESR) is a special procedure in the field of metallurgy. Several different refining mechanisms allow the production of metals with a very sharp chemical composition. At the same time, it is possible to ensure a homogeneous texture by controlling the rate of solidification through the cooling rate. The ESR process is mainly used for the desulphurization and nitriding of special steels, refining of titanium alloys as well as the unidirectional and segregation-minimized solidification of nickel-base alloys. [1] [2] [3]

The fundamental scheme of the static ESR process can be seen in figure 1:

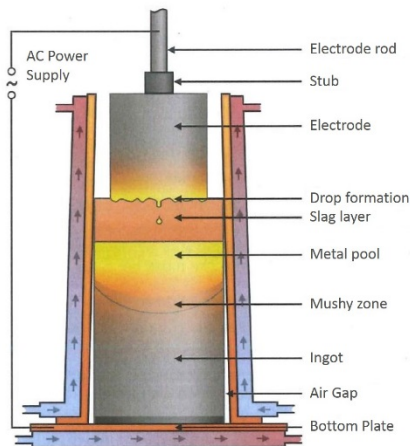


Figure 1: Fundamental scheme of the static ESR process [4]

The metal or alloy to be remelted is cast or forged usually into a cylindrical shape that is used afterwards as a self-consuming electrode. The electrode is connected with a so called stub to the

electrode rod. During the process, this electrode is dipped into a liquid slag medium. Slags as ion-conductors have significantly higher electrical resistances than metals as electron-conductors, even at high temperatures. An applied voltage leads to a flow of current through the electrode rod, stub, electrode, slag layer, ingot and eventually the bottom plate. The mentioned resistance of the slag leads in combination with the applied current to a Joule heating which transforms the slag into the liquid state. Eventually the electrode starts to melt and forms a liquid metal layer at the bottom of the electrode. The liquid metal forms a droplet under the electrode that detaches after gaining a sufficient mass. After detaching, the droplet falls through the slag and aggregates under it forming a liquid metal pool. Because of the high cooling rate, the metal pool solidifies and forms a uniform ingot with a homogeneous texture and high cleanliness. [1]

Refining mechanisms

To clarify the aims of this project, figure 2 shows the main reaction sites of refining during the remelting process.

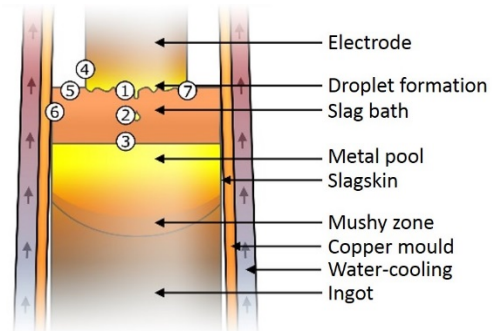


Figure 2: Refining sites during the ESR process [4]

According to Mitchell [5] there are three possible sources for (oxidic) nonmetallic inclusions (NMI):

- Inclusions inside the electrode
- Dissolved oxygen and deoxidation agents (e. g. Al, Si)
- Reactions between electrode and process slag

Concerning steel, the most critical inclusions are oxidic whereas nitrides and carbonitrides are of importance regarding nickel-base alloys. In principle, the chemical compositions of inclusions are influenced by the seven reaction sites shown in figure 2 [1], but the three most discussed ones are reaction sites 1 – 3. [6] [7]

Reaction site 1 is thought to be the phase boundary with the largest refining potential, from a kinetic point of view. [5] [1] [8] While it is proposed that inclusions dissolve into the surrounding material [8], temperatures of around 1800 to 2000 °C would be necessary. According to [1], these temperatures are not reached at this phase boundary. Instead, the metal droplets detach shortly after reaching

the liquidus temperature and are subsequently overheated in the slag bath. However, the dwell time for the molten metal underneath the electrode is with approximately 10 seconds [5] significantly higher than in the slag bath itself (around 0,1 second [9]). Because of this, there is enough time for chemical refining reactions to occur underneath the electrode rather than in the slag bath. Therefore, in static ESR processes, the reaction site 2 plays only an inferior role. Concerning reaction site 3, there have to be considered different phenomena in case of inclusion behavior. On the one hand, there will occur exchanges of oxygen and deoxidizing agents on the interface slag/metal pool. On the other hand, the solubility of oxygen decreases with advancing solidification of the metal in the mushy zone. Therefore there will be inclusions precipitated, especially regarding Al. [7] It is not sure if refining mechanisms such as flotation will occur as this phenomena is governed by different influencing factors, beginning with the transport of these inclusions through the mushy zone and eventually the dissolution in the slag medium. These phenomena have to be further investigated.

If the process is not carried out under a protective gas atmosphere, the other reaction sites (without 6) may be of importance because of a potential oxygen pickup and a subsequent increase of oxygen potential. [5] For a sufficient desulphurization, the reaction site 5 may be of importance because here the sulphur picked up by the slag forms SO_2 that is transferred into the gas phase and removed. [10]

ESR with rotating electrode

At the moment, possible influences of a rotating electrode were only proposed by Chumanov [11] [12], Wang [13] whereas Chang [14] [15] describes the influence of a rotating mould around a static electrode.

The main influencing factor of the proposed improvement of a rotating electrode is based on a change of the energy flow during the process. This change occurs because of three main reasons:

- Changed flow conditions within the slag layer
- Faster detachment of smaller droplets because of horizontal centrifugal force
- Decreased height of the slag layer

The changed flow conditions are the result of the changed place of droplet detachment. Figure 3 shows the expected flow conditions within the slag layer of the static ESR process.

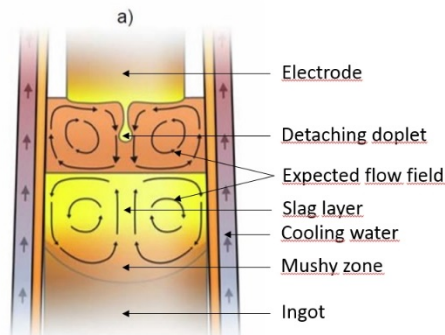


Figure 3: Expected droplet detachment of the static ESR setup

Due to the distribution of the Lorentz force (see equation 1 [16], $F = \text{Lorentz force}$, $q = \text{charge}$, $v = \text{velocity}$, $B = \text{magnetic flow}$

density, $r = \text{location}$), which is directed to the center axis of the electrode, especially on the outer areas, the slag near the mould wall flows in an upward direction. A result of this flow are shear forces also directed to the center of the electrode that move the liquid metal layer towards the center axis of the electrode and therefore promote a droplet formation and eventually detachment in a centered position.

$$F = qv \times B(r) \quad (1)$$

When rotating the electrode the imposed centrifugal force leads to a detachment of the droplets on the edge of the electrode, as can be seen in figure 4:

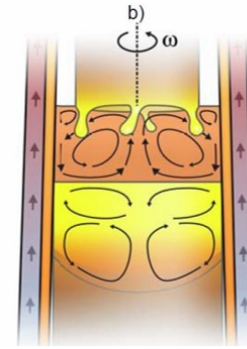


Figure 4: Expected droplet detachment on a rotating electrode ESR process

The result of this flow pattern is an upward stream of the slag in the center of this layer, which promotes itself eventually. According to Wang [13], one of the effects of this flow pattern could be an increased process efficiency up to 25 % and subsequently a smaller demand of power. The reason for this is an increased heat transition from the slag to the electrode under its center axis and eventually a faster melting of the metal or alloy.

The detachment of the droplets on the edge of the electrode and the described change in the flow pattern is also the argumentation for the proposed decreased height of the slag layer. The flow of the liquid metal from the center of the electrode to the mould wall entails a more planar ablating of the electrode during the ESR process with a rotating electrode instead of a conical shape of the electrode while remelting. Therefore, the electrode does not dip as deep in the slag as in the static ESR setup. This way the whole slag height can be reduced whilst maintaining the same distance for the droplets to travel through the slag.

Chumanov [11] [12] also propose significant improvement concerning the quality of the ingot. The reason is an improvement of the transport of nonmetallic inclusions from the liquid metal to the slag. This is justified with the following assumptions:

- Smaller droplet sizes (as mentioned)
- Longer distance for the inclusions to travel through the slag
- Smaller thickness of the molten metal film under the electrode due to the centrifugal forces and the earlier detachment of the droplets

The smaller droplet sizes cause a better droplet surface to volume ratio. Thus, chemical refining processes, e.g. desulphurization, are carried out better than in the static ESR process with bigger droplets. This increasing refining ability is supported by the longer

distance the droplets travel through the slag, which means there is more time for chemical processes to occur. Even if the slag height is reduced, it is possible to gain longer travel distances through the slag because of the rotation itself. One could easily imagine that the droplets follow a spiral-shaped path due to the centrifugal force and the subsequent movement with an orthogonal component of velocity related to the position of the electrode.

Smaller droplets and the thinner liquid metal layer have also the potential of a physical refining phenomenon. When forming the liquid metal layer, inclusions that are within the metal do not dissolve but are eventually “washed” out of the metal. If the metal film gets thinner, the ability of smaller inclusions to be transferred into the slag increases. The same applies to smaller droplet sizes. Analogical to a thinner metal film, smaller inclusions can be transferred easier to the slag medium when the droplet size decreases.

At this stage, the mentioned, assumed improvements are investigated insufficiently. There is a lack of investigations regarding the cleanliness, the flow patterns within the slag and metal phases as well as the formation of the metal droplets. Furthermore, there are no other authors known who investigated this topic. They have to be questioned as well as the current weak database has to be extended.

Development of the rotation system

The experimental part of this project is carried out at the IME Process Metallurgy and Metal Recycling, Institute and Chair of the RWTH Aachen, Germany. The existing static open atmosphere ESR furnace is shown in figure 5:

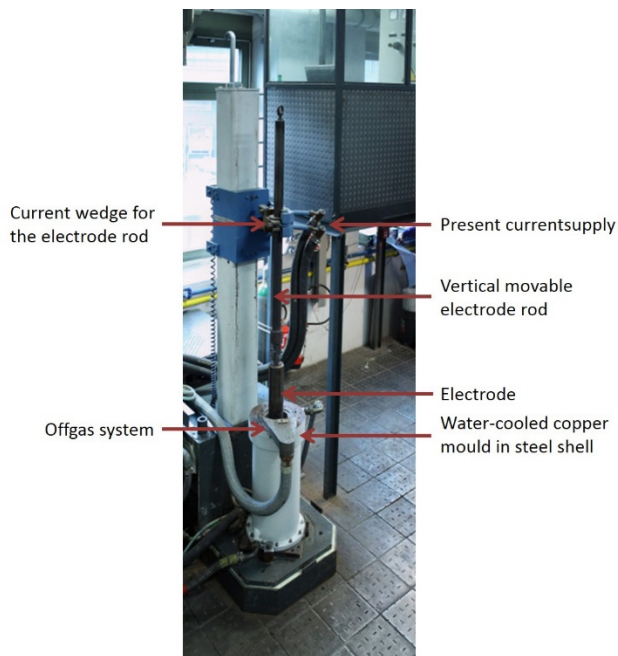


Figure 5: Static ESR furnace at the IME

This simple set-up needs some modification to implement a rotating electrode. Currently the electrode rod is fixed with a wedge to the current supply. In order to get the electrode rotating there has to be an electric insulated driving motor, which is not a big problem. One of the biggest challenges is to conduct the high current of about 6 to 7 kA onto the electrode rod whilst it is rotating. The only option to overcome this is to implement sufficiently large

carbon brushes constructed as a carbon slip ring. Currently the electrode rod is made of simple steel, whose conductivity is not high enough to work with a carbon slip ring in combination with the high current given. That means that the whole electrode rod has to be reconstructed which was done at the IME. The most encouraging solution is shown in figure 6:

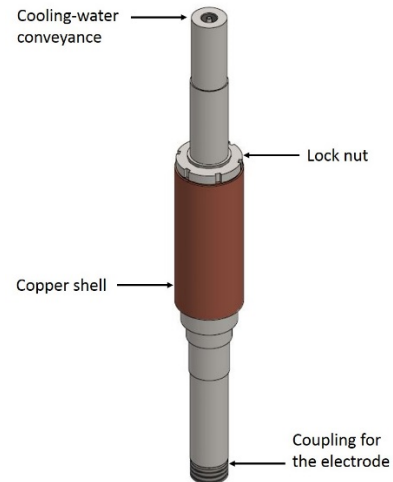


Figure 6: Electrode rod for the rotating electrode ESR setup

To face the problem of the low electrical conductivity of steel it was decided to supply the current through a copper shell, which has a sufficiently high electrical conductivity to work with a current density of almost 2 A per mm². This shell is pressed tight on a conventional steel rod. Secured with a lock nut this setup allows to change the copper shell in the case of damage or maintenance.

Furthermore, the copper shell only operates adequate, in terms of current conduction from the carbon slip ring to the copper, at sufficiently low temperatures of < 90 °C. Therefore, a water-cooling for the electrode rod is implemented, realized with a rotary joint on the top. A detailed draft of the electrode rod can be seen in figure 7.

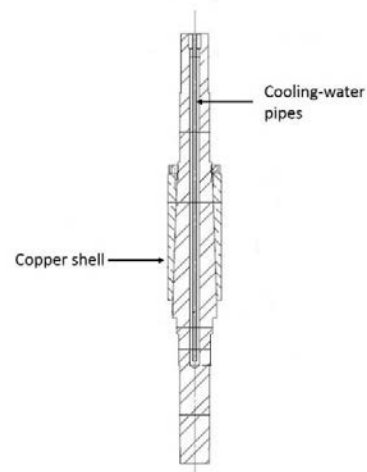


Figure 7: Exposition drawing of the electrode rod

Lastly, a conventional stub is welded on the electrode. This way the electrode can be attached positively to the electrode rod with a coupling.

In order to get the electrode rotating, the existing sleigh (see figure 5) is redesigned. The higher the rotation speed or number of revolutions, respectively, the sensitivity of the electrode in terms of dynamic unbalances rises. In the worst case, the whole furnace gets seriously damaged because of this problem. To minimize this unbalance effect, the electrode rod needs at least two fixing points at different heights. The realization can be seen in figure 8:

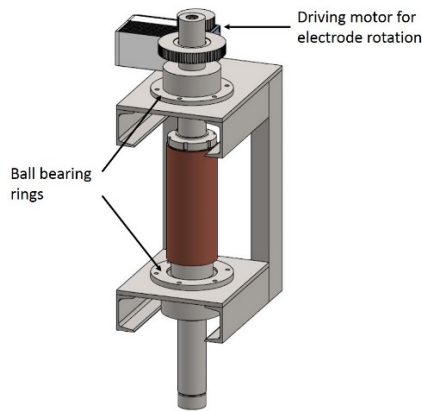


Figure 8: Redesign of the sleigh, which drives the electrode rod

On top of the sleigh is the mentioned electrically insulated driving motor for the rotation installed. A stable, friction reduced movement of the electrode rod is guaranteed using two ball bearing rings, one over and one under the current conduction system. The carbon slip ring itself is installed between those bearings and connected to the high current cords (not pictured in the draft). A draft of the complete set-up including an exemplary slip ring system is pictured in figure 9:

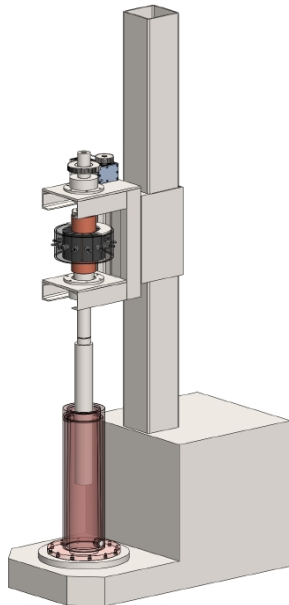


Figure 9: Complete set-up of the rotating electrode ESR construction at the IME.

Technical enhancements

To gain detailed data about the thermal regime during remelting, a new mould will be obtained. On the outer wall of the mould are five cross-shaped drilled holes in axial and radial direction, containing one thermocouple each, implemented, see figure 10. This is an additional temperature measurement supporting conventional thermocouples that are dipped into the slag at the end of the remelting process.

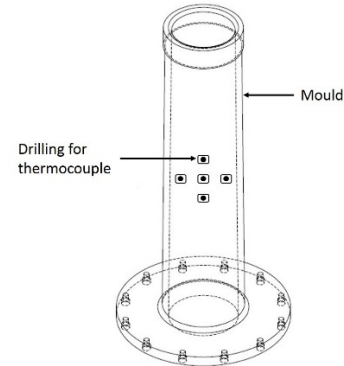


Figure 10: Draft of the new copper mould with the assembly of the thermocouples

With this new arrangement of thermocouples, it is possible to measure the temperature and its distribution on a 2D scale. Furthermore, it is assumed to allow creating a model of the fluid flow inside the slag medium as well as an evaluation of the current flow over the mould wall.

Concerning the proposed earlier detachment of the metal droplets, a significant higher resolution in terms of current, voltage and slag resistance monitoring will be implemented. With a monitoring rate of at least 0,01 s short drops of the resistance will be much more likely to identify. These drops occur when the droplets under the electrode form, grow and eventually detach from the electrode because the distance between molten metal and the metal pool decrease. The needed voltage for the given current to overcome this distance will decrease or the current at a given voltage will increase, respectively. These value changes can indicate the droplet detachment and can therefore serve as an indicator for the metal droplet detachment rate per time unit.

Methodology

The intended investigations will be performed on the nickel base Alloy 718. The IME is highly experienced in remelting this material in the ESR process. Therefore, the effects of remelting using different slag phases and remelting parameters, such as power or melt rate, are well known. For comparability of the experiments, all of the electrodes are taken and forged from one conventional industry scale ESR ingot. This way it can be ensured that all of the electrodes have the same composition and amount of (residual-) impurities. Furthermore, to exclude influences of the atmosphere, a protective gas hood will be implemented.

Alloy 718, besides oxidic inclusions, is prone to enclose nitrides and carbonitrides, as mentioned before. So one focus of the remelting efficiency in terms of refining will be the behavior of these types of inclusions. All of the ingots will be grinded and cut along the vertical and horizontal axes to investigate the distribution

of impurities and dissolved gas. The analysis will be performed via conventional SEM/EDX analysis. Additionally it is planned to use the QUEMSCAN® method to analyze the phase distributions within the remelted ingot. This method is advantageous concerning a relatively large area to be analyzed and it gives, moreover, a visual illustration of the phase distributions, see figure 11. This figure was taken from remelted Alloy 718 ingots during the ESR process at the IME. [17]

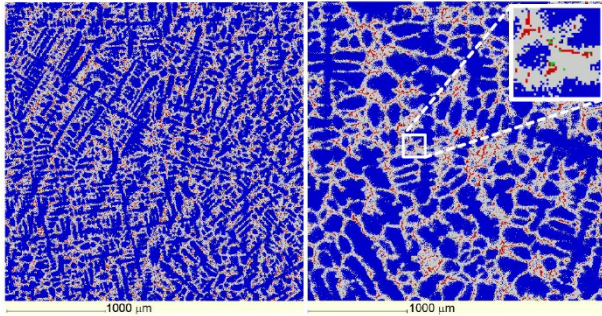


Figure 11: Phase distribution visualized with the QUEMSCAN analysis. Each color represents a certain phase [17]

Conclusion/Summary

The IME is developing and constructing a new set-up for its static, open atmosphere (at this moment) ESR towards a system with an electrode rotating around its vertical axis. For this to achieve, several parts of the furnace need to be reconstructed or renewed because of difficulties in conducting current to a rotating electrode rod and possible unbalances in the electrodes rotating behavior. The main reasons behind this project are presumed enhancements of the ESR process:

- Improved refining abilities due to: smaller droplet sizes and earlier detachment of the droplets, thinner molten metal film under the electrode and a longer path for the droplets to travel through the slag layer
- Improved process efficiency because of altered flow patterns in the slag layer

Acknowledgements

The author likes to thank the German Research Foundation (DFG) for the funding of this project. Furthermore thanks to the constructor of the IME for his effort realizing this project.

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