Enhancing the electroslag remelting process: First impressions and results regarding the application of a new current transfer device and electrode control movement

M. Schwenk[1], Prof. Dr.-Ing. Dr. h. c. B. Friedrich[1],*
C. Demirci[2], R. El-Rabati[2], D. Robinson[2], J. Schlüter[2]

The electroslag remelting process (ESR) is an important process for the production of very clean high-tech materials for applications used for example in the aviation- or energy-sector. Although the process itself is well known for decades, there is still potential for improvements. In that regard the IME Institute for Process Metallurgy and Metal Recycling, RWTH Aachen University and SMS Mevac developed a new current transfer device which is implemented in the laboratory scale ESR furnace of the IME. The aim of this new set-up is the enhancement of the ingot quality in terms of an altered shape of the molten metal pool and solidification microstructure as well as a better understanding of chemical and physical refining mechanisms. This paper provides an overview on the new developed current transfer device, the first impressions and results obtained by the control movement of steel electrodes in combination with commonly used slags and concludes with planned subsequent investigations.

Keywords: Electroslag remelting, rotating electrode, solidification structure, electrical behavior of rotating electrodes

1 Introduction

The electroslag remelting process (ESR) is a refining process for metals used for special applications. Applicated for several decades, this process can produce materials with a narrow chemical composition in combination with a very low content of nonmetallic inclusions and especially sulphur. Moreover, a very homogenous solidification structure is ensured due to a high cooling rate of the copper mould, wherein the metal is processed. Nowadays the ESR process is mainly used for the refining of high grade titanium, segregation minimized nickel-base alloys and the desulphurization and nitriding of special steels [1][2][3].

The fundamental principle of the ESR process is shown in figure 1:

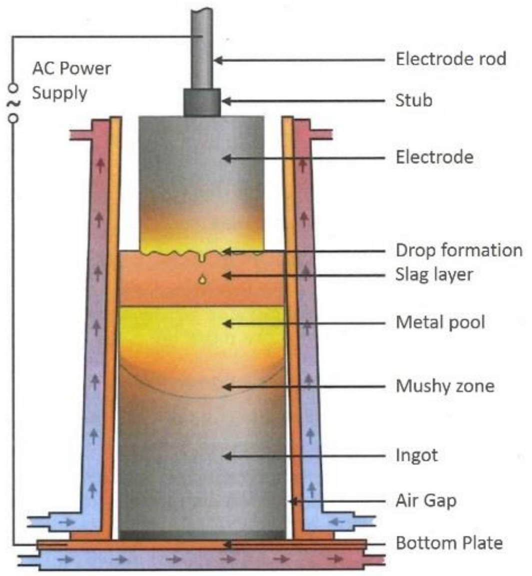

Figure 1: The fundamental principle of the ESR process [4]

A metal or alloy that shall be remelted needs to be cast or forged into an electrode. This electrode usually has a cylindrical shape and consumes itself during the process. A so called stub is mounted onto the electrode to maintain an electrical connection. During the process the electrode dips into a molten slag medium and a high current is applied through stub, electrode, slag, ingot and eventually the bottom plate due to a sufficient voltage. Slags are ion conductors that have a significantly higher electrical resistance compared to metals as electron conductors. When the current flows through the slag medium (resistance),

1) IME Process Metallurgy and Metal Recycling, RWTH Aachen, Germany
2) SMS Mevac GmbH, Essen Germany
**) Corresponding Author, mschwenk@ime-aachen.de*

a part of the energy is transformed into heat, the so called Joule heating. The generated heat is sufficient to keep the slag medium in the liquid state. Eventually that part of the electrode that dips into the slag is transferred into a liquid state, consolidates and detaches as droplet from the bottom of the electrode. The droplets fall through the slag and consolidate under it in the form of a liquid metal pool where the metal solidifies again in a well defined structure. Refining mechanisms, physical as well as chemical ones, occur while the molten or half molten metal is in contact with the slag medium [1].

The main refining mechanisms and different sources of impurities have already been discussed by numerous authors, e. g. [1][5-8]. In general, the most important reaction sites for refining mechanisms to occur are the phase boundaries between the molten metal film underneath the electrode and the slag, the metal droplets and slag during their fall through the slag and the consolidated molten metal pool and the slag. However this article focuses on a rotation of the electrode around its own axis so the general known refining mechanisms shall be skipped at this point.

1.1 Electroslag remelting with rotating electrode

At present time there are just a few authors who investigate the electrode remelting process operating with an rotating electrode. Possible influences are described by Chumanov and Chumanov [9-11] as well as Wang [12], whereas Chang [13-14] investigates a slight different set-up with a rotating mould instead of a rotating electrode.

The authors promote an increase in the ingot quality made by the ESR process and / or a better energy efficiency, mainly because of the reasons listed below:

- Detachment of smaller droplets due to an extra enforced horizontal centrifugal force
- Altered flow conditions within the slag layer
- Development of a shallower molten metal pool
- Possible reduced height of the slag layer

By letting a cylinder rotate around its own axis, a centrifugal force is imposed in horizontal direction. This way the consolidation of the molten metal film, which leads to the detachment of the electrode, takes place near the outer rim of the electrode, see figure 2b. In contrast to that, the expected detachment pattern of static remelting operations is shown in figure 2a.

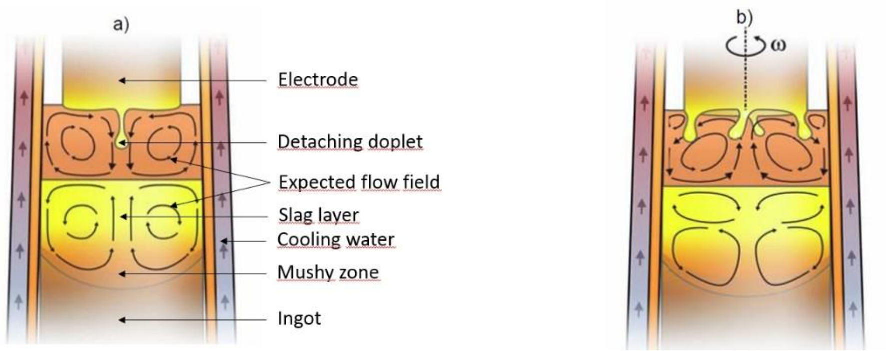

Figure 2: Expected detachment pattern and subsequent slag flow in static (a) and rotating (b) remelting operations.

Not only the place of droplet detachment is altered when rotating the electrode but also the flow pattern within the slag layer, as can be seen in figure 2. In static remelting operations there is a downward stream of slag under the electrode because the droplets detach somewhere underneath the electrode. By applying a centrifugal force the flow is reversed to an upward stream because the droplets are more likely to fall down near the mould wall, causing the downward stream in that region. The upward stream underneath the electrode can also lead to a more planar melting of the electrode, explaining a possible reduced slag height because the electrode does not form a cone pointing downwards as in static remelting operations [11]. This way the same distance electrode - metal pool can be maintained by reducing the height of the slag layer.

The change of slag flow during the process made Wang [12] propose a lower energy consumption when remelting with a rotating electrode because there is a better heat transfer from the slag to the electrode directly underneath the electrode. If so, the demand of energy for the same remelting result could drop 25 % according to the author.

Smaller droplet sizes provide a better surface ratio of molten metal compared to the surrounding slag, giving chance for a better chemical refining. Because of the centrifugal force and a subsequent faster detachment of the droplets, the molten metal film underneath the electrode is prone to get thinner. With a thinner molten metal film, it is also easier for (smaller) non-metallic inclusions to be restrained by the slag, resulting in a better refining efficiency. Another effect of an electrode rotation is a longer path for the droplets to travel through the molten slag in a spiral shape. A longer path could also promote the chemical refining because the droplets get more into contact with "fresh" slag.

The last point Chumanov and Chumanov [11] are proposing is the formation of a shallower liquid metal pool providing an improved solidification structure as the dendrite grow orthogonally to the solidification front. This can also be explained with a droplet detachment at the outer side of the electrode, forcing the droplets to move down near the mould walls and not in the middle of the mould, see figure 3. Here the abbreviations are ω = rotation speed, H and h = heights of the slag phase and the molten metal pool, δ = thickness of slag skin and T_{max} = point with the highest temperature during the process.

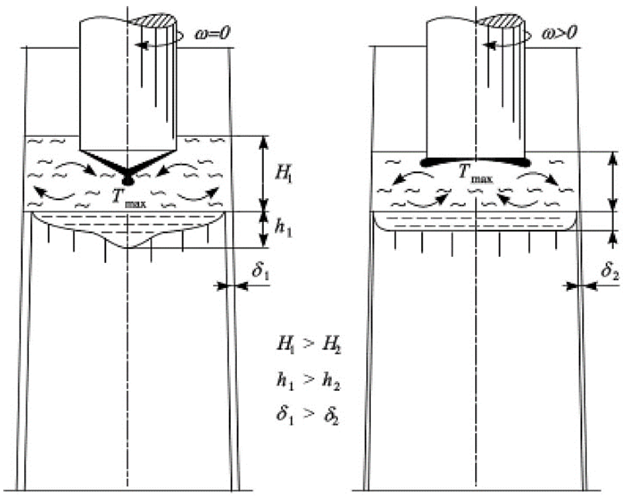

Figure 3: Schemes of the ESR process, without (left) and with rotation (right) [11]

This figure also supports the proposed more planar melting of a rotating because it also shows an upward stream of the slag underneath the electrode on the one hand but also gives the reason for that by proposing the highest temperature directly underneath the center of the electrode.

2 Experimental

To investigate the behavior of a rotating electrode during the ESR pocess and to examine some of the proposed improvements, SMS Mevac developed a new device to transfer current from a static rod onto a rotating electrode rod. Trials were conducted at the IME Institute for Process Metallurgy and Metal Recycling, RWTH Aachen University. The ESR furnace at the IME is able to operate with a current up to 6 kA and a maximum power of 450 kW. Currently it is equipped with a ~150 mm diameter mould at a height of 800 mm. The maximum electrode dimensions are 100 mm in diameter at a length of 1400 mm, an example of an electrode used for the trials can be seen in figure 4, the new setup in figure 5:

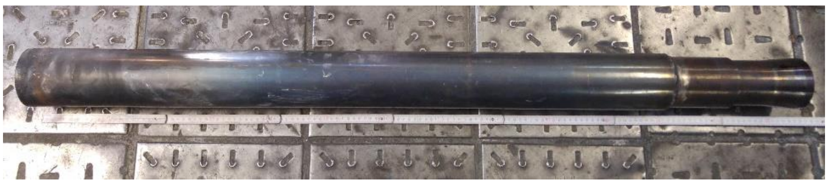

Figure 4: Example of a used electrode; the stub is welded on the right side

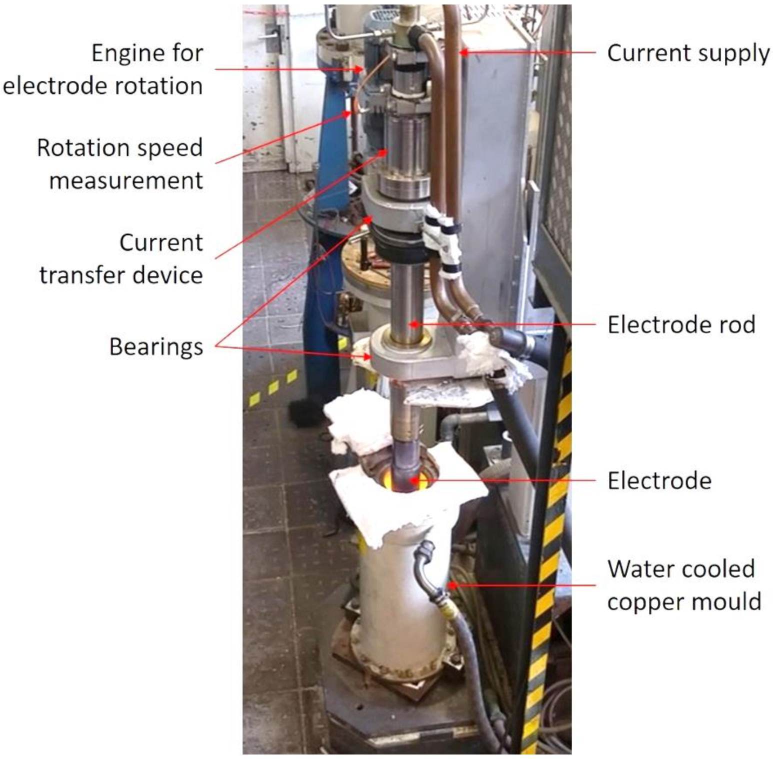

Figure 5: New set-up of the electrode remelting furnace at IME

After setting up this new device test trials were conducted to check the operation ability. In these trials two steel electrodes with diameters of 70 mm and 90 mm were successfully remelted. After these trials two electrodes with properly diameter and length were remelted. To compare the results of these trials, all parameters were kept the same, despite the rotation speed. The used electrodes were made of St37 cold drawn steel, the used slag consisted of 70 % technically prefused CaF_2 mixed with 30 % technically pure Al_2O_3, preheated overnight up to 650 °C. The remelting trials itself were conducted and controlled with fixed power and swing. After half of each electrode was remelted, the rotation was started to compare a non-rotating / rotating remelting trial during one electrode. Rotation speeds were set to 0 / 20 rpm and 0 / 50 rpm, respectively. Finally, after the starting phases and after starting the electrode rotation, FeS was added to enrich the steel with sulphur. This was done to examine the pool profile in the subsequent ingots via the so called Baumann imprint.

The electrical and general parameters were logged automatically by the operating system of the furnace.

After remelting the bottom and top parts of the ingots were cut off, followed by a cut in half to separate the non-rotating part of the ingots from the rotating ones. Finally two plates were taken out of the center axis on which the solidification structure of both, non-rotating and rotating parts were examined. A scheme of this sampling can be seen in figure 6, the light blue rectangle shows the plates taken for analysis:

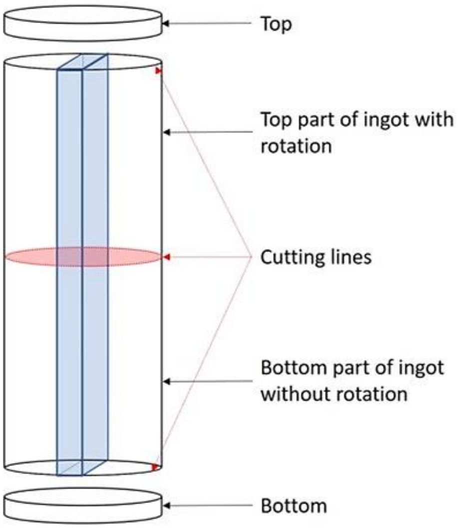

Figure 6: Sampling scheme

3 Results and discussion

Due to a limited space, this article focuses on the formation of the liquid metal during the different remelting operations as well as on selected electrical parameters. Other investigations concerning ingot quality / refining efficiency are going to be published separately.

3.1 Metal pools and droplet detachment

The obtained ingots from the trials conducted at IME can be seen in figure 7:

Figure 7: Obtained ingots; ω = 0 / 20 rpm on the left, ω = 0 / 50 rpm on the right

In the following figure 8 the Baumann imprints of the first ingot are shown. This ingot was made with rotational speeds of 0 rpm and 20 rpm, respectively.

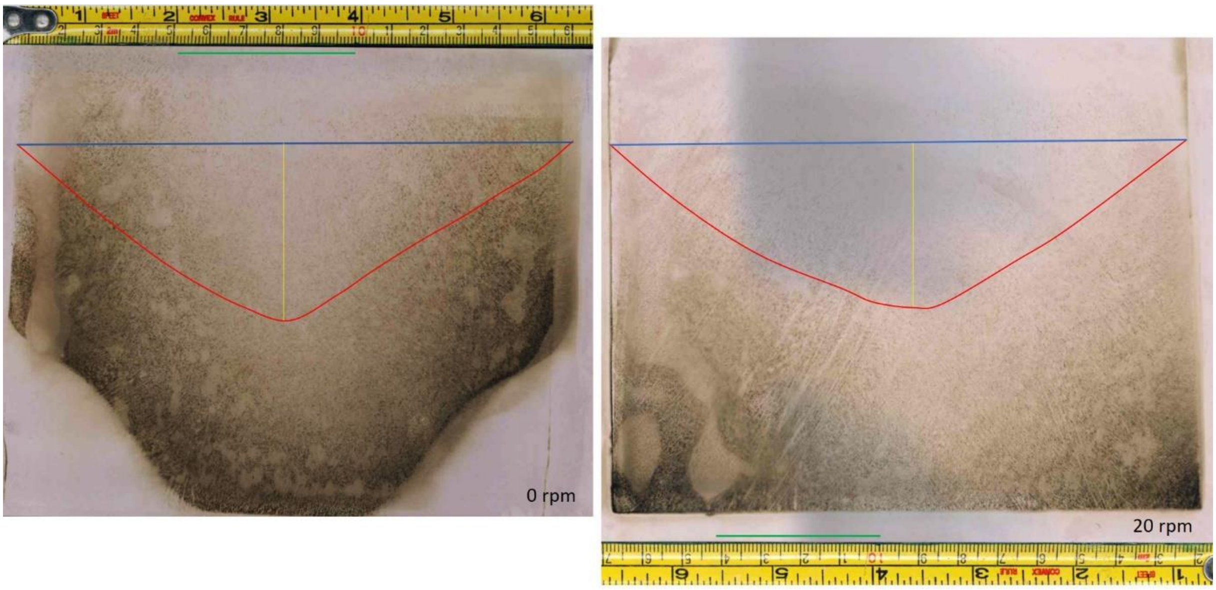

Figure 8: Baumann imprints of the ingot made with a rotational speed of 0 and 20 rpm, respectively

During the solidification of the molten steel the dendrites grow from the mould wall into the center due to the high cooling rate at this wall. A common method to examine the profile of the molten metal pool is to draw lines orthogonally to the orientation of the dendrite growth. This way the profile can be made visible. The result of the first trial shows a metal pool depth of roughly 4,9 cm in the non-rotating part of the ingot (The yellow and green lines have the same lengths, the green ones are rotated 90 ° to compare them with the given scale). Contrarily to this shape, the metal pool gets a little bit shallower after starting the electrode rotate with 20 rpm. In the rotating part the metal pool shows a depth of about 4,2 cm which is a decrease of approximately 14,3 %.

The obtained results from the second trial can be seen in figure 9. Unlike the first trial, the metal pool has a depth of approximately 6,1 cm in the non-rotating part, but a small 3,4 cm in the part which was remelted with 50 rpm. This entails a decrease of approximately 44,3 % of the depth of the metal pool during remelting. One possible explanation for a shallower metal pool during remelting with an electrode rotation is given by Chumanov [11], see chapter 1.1. Without an electrode rotation, the molten metal film under the electrode consolidates at a certain point under the electrode, detaches after reaching a critical mass and drips only under gravitational force through the slag phase till it reaches the molten metal pool eventually. When applying an electrode rotation, the centrifugal force becomes important for a droplet detachment at the outer rim of the electrode. The droplets then travel a longer path near the mould wall into the metal pool, letting the dendrites grow more axially, thus creating a shallower pool. According to the results in this paper, this theory can be agreed on, but of course need further confirmation.

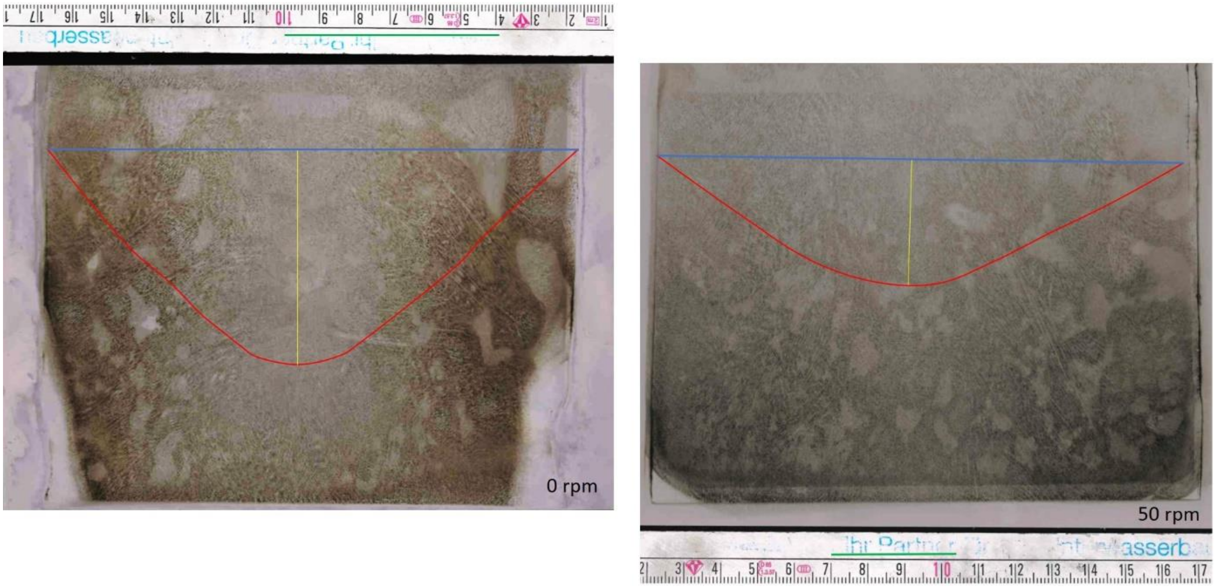

Figure 9: Baumann imprints of the ingot made with a rotational speed of 0 and 50 rpm, respectively

The electrodes where drawn out of the slag directly after the end of the remelting trials with an ongoing rotation. Shortly after this the droplets freeze underneath the electrode and give an impression of the detachment sites. The bottoms of the electrodes after remelting can be seen in figure 10:

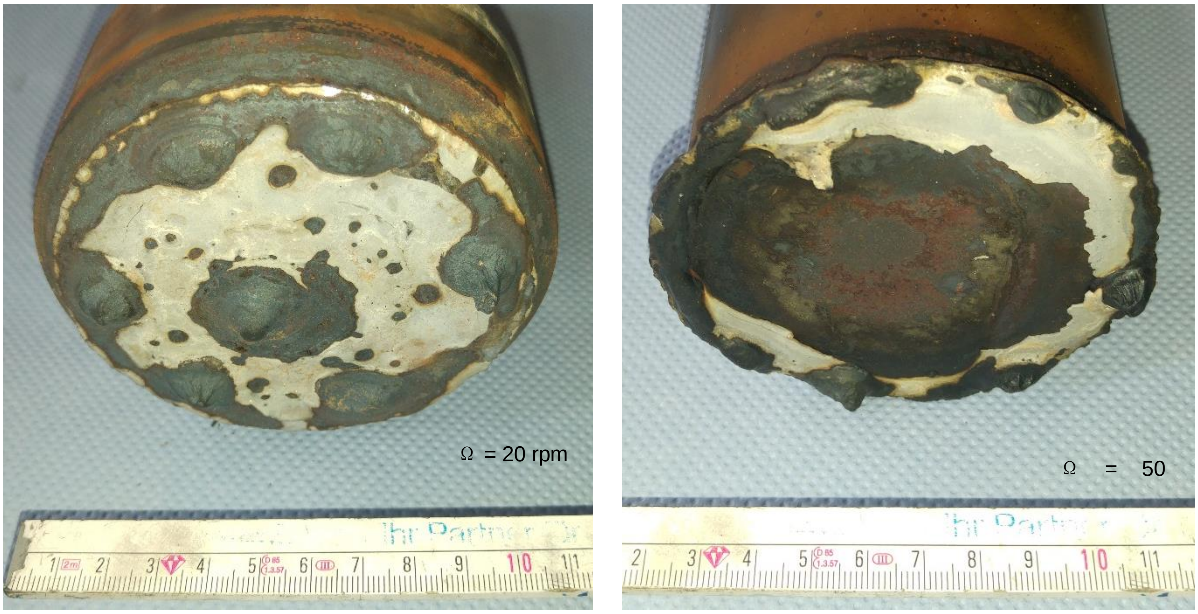

Figure 10: Bottoms of the electrodes after remelting

As can be seen in the previous figure the electrode with the lower rotation speed of 20 rpm has a droplet detachment both, roughly in the middle as well as at the outer diameter. In contrast to that, the bottom of the electrode remelted with 50 rpm does not show a droplet detachment site somewhere in the middle of the electrode. This indicates that a rotation speed of 20 rpm is not as beneficial as 50 rpm is. The finding that there is no droplet detachment in the middle under the electrode during the 50 rpm rotation during remelting supports the formation of a shallower pool as stated out earlier in this chapter.

3.2 Electrical and melting parameters

Electrical and melting parameters are important for the operating of an ESR furnace. Thus the examination of these parameters for remelting operations with a rotating electrode can be crucial for industrial applications in the future. Besides a safe and reasonable operation of such a furnace, the proposed decrease in energy consumption or higher remelting efficiency at a given power are of interest.

From the operating point of view, the ESR furnace at the IME Institute works with two different controlling systems. The first one is the melt rate controller (RMC), the second one the electrode feed controller (EFC) which regulates the lowering of the electrode during remelting. The EFC can be operated with a set total slag resistance or with the commonly used swing. Figure 11 shows the resistance for both remelting trials. It should be mentioned here that the possible high values of slag resistance, regarding the slag used, may be caused from altered general resistances after rebuilding the furnace which are not completely investigated at this point.

However, the slope of the resistance for both trials is because not all the amount of slag used for remelting is charged into the furnace prior the beginning. At this point, IME has no possibility to charge liquid slag into the furnace, so a start with a preheated but solid slag mixture has to be performed. After the initial amount of slag is liquid, the rest of the desired amount gets fed into the furnace which raises the resistance. After all slag is liquid, the resistance for both trials are on a comparable level. The resistance of the first trial seems to be slightly but not significantly lower in the non-rotating part. During the rotation the resistance raises a little bit, which may is caused from the movement of the slag. The slag movement when the electrode rotates is different compared to a static remelting operation because of the friction between electrode and slag. However, the difference of the resistance between static and rotating electrode is not significant for both trials, so at this point it can be assumed that a rotating electrode does not have an important influence on the operation of an ESR furnace with such a rotation device.

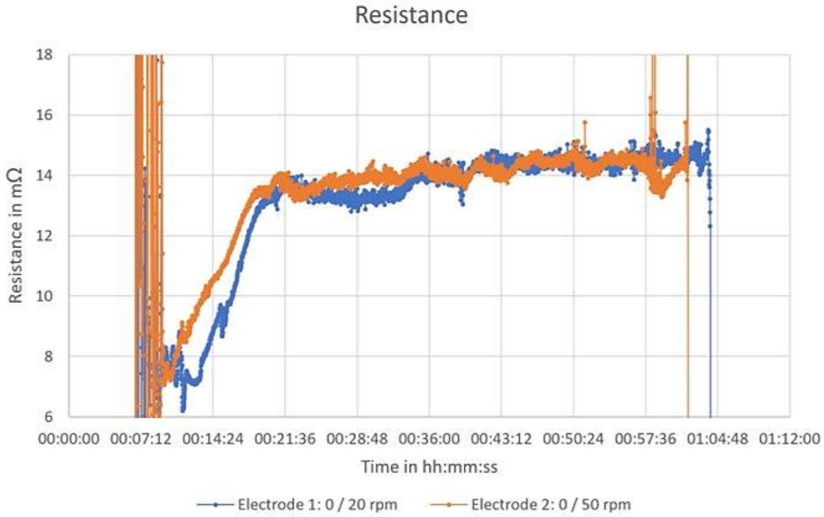

Figure 11: Resistances of the slag during remelting

Besides the resistance of the slag it is more common to operate an ESR furnace with a derivation of the restistance, the so called swing. Basically operating with the swing allows it to control the immersion depth of the electrode into the slag. To remelt at a set swing value guarantees to a certain extend a stable immersion depth. Comparable to the normal resistance, the swing does not show any dependence whether the electrode rotates or not, according to these findings, see figure 12. The high peak of the graph of electrode 2 at the end does not make much sense and can, at the moment, only be explained as a detection failure of the operating system.

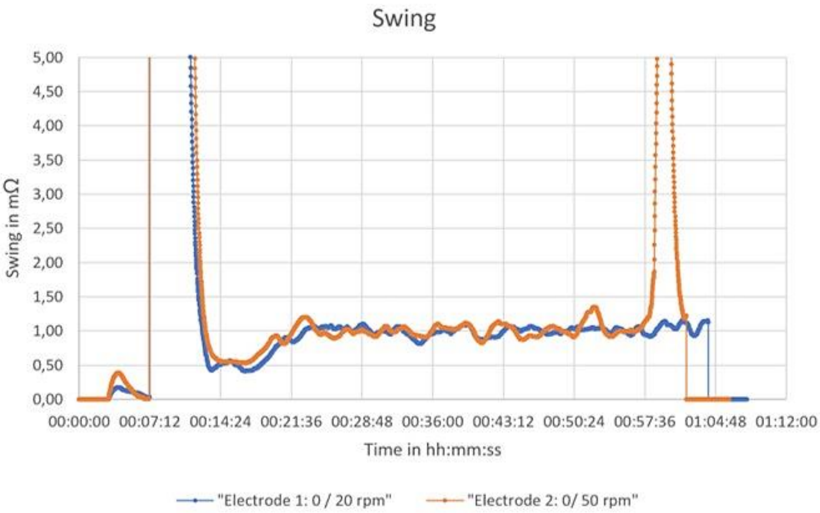

Figure 12: Swings during remelting

From the data obtained it can be assumed that it is very likely not to have any operating problems while remelting an electrode that rotates around the own axis.

The second controlling system at the IME Institute is the RMC. Controlling the melt rate results in a homogenous solidification structure and thus a high quality ingot. Again there are two options of controlling the melt rate. First the melt rate can be calculated with the geometrical dimensions of both, electrode and mould, in combination with the lowering of the electrode over time. Subsequently the constancy of volume determines the melt rate. The second, simpler method is to set a constant melt power with which the furnace operates. To compensate for the gradually melting electrode, the set power is gradually decreased over time. For the trials described in this article, the latter technique was used because this way the behavior of the melt rate at a given melting power can be examined. Figure 13 shows the melt rate of both trials over the complete remelting time. Firstly, the drop of the melt rate at the beginning of both graphs shows the described adding of the remaining slag mixture where the electrodes does not move down and the melt rate cannot be calculated properly. This problem needs a few minutes to be equalized. During static remelting the melt rate constantly decreases in both trials which indicates that the given power is not sufficient to generate enough heat for a constant melt rate. However this is not a new finding. On the contrary, when initializing the rotation, the melt rate initially drops in both trials and then increases afterwards. The drop in the first trial with 20 rpm seems not to be as large as in the second trial with 50 rpm. On the other hand the increase in the melt rate over time is not as large in the 20 rpm trial compared to the 50 rpm trial. In the theory, Wang [12] proposed less energy consumption for the same quality of remelted material while rotating the electrode. This theory can be agreed on, based on the data obtained. Nevertheless it seems that the optimum parameter regarding rotation speed is not reached because there is no peak or stagnation visible in the data given for the 50 rpm trial, especially regarding the 20 rpm trial.

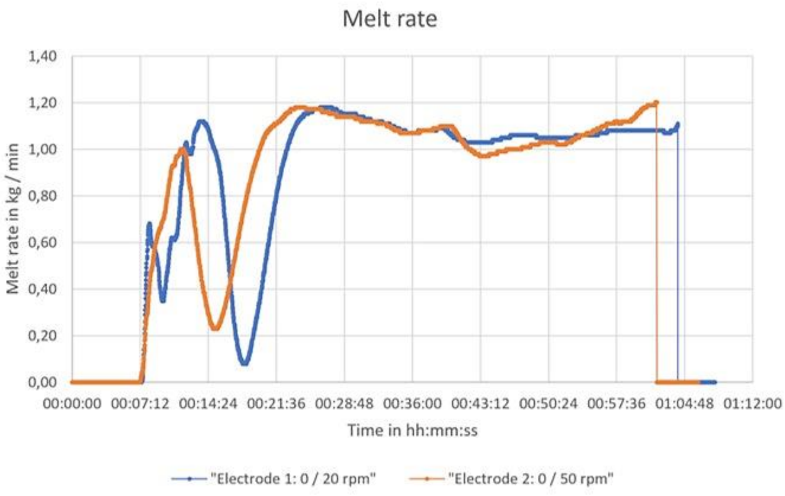

Figure 13: Melt rates during remelting

Another attempt in comparing both trials for their efficiency was made in figure 14, where the melt rate is set in direct correlation to the actual melting power at given moments. Again, for the static remelting both trials consumed comparable energy for the same melt rate. As well as in figure 13 there is a drop in both graphs indicating that the beginning of an electrode rotation at first disturbs a consistent remelting but after a few minutes of adjusting the positive aspects prevail. After a certain amount of time a higher rotation speed seems to result in a lower energy consumption due to a shorter remelting time with better ingot quality considering the solidification structure described in chapter 1.1.

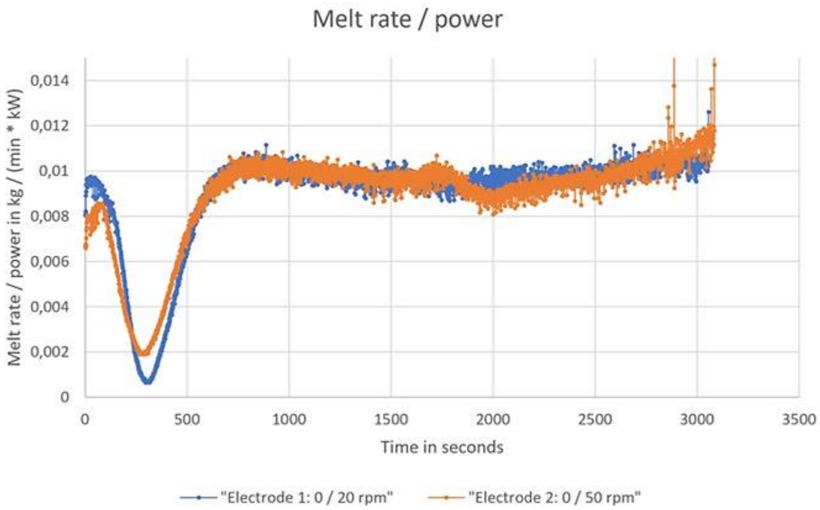

Figure 14: Melt rates during remelting compared with their required power

4 Conclusions and outlook

The characteristics and influences of a rotating electrode implemented in an ESR furnace at the IME Process Metallurgy and Metalrecycling, RWTH Aachen University were investigated. Two electrodes were remelted, both without rotation in the first half of the electrodes. Subsequently rotation was initialized in the second half. One electrode was remelted with 20 rpm, the other one with 50 rpm. The following conclusions can be made:

- The new developed design of the current transfer can remelt electrodes, both static and rotating ones, properly and reliable.
- The molten metal pool gets shallower when remelting electrodes which rotate around their axis. When increasing the rotation speed, the metal pool gets more shallow.
- Droplet detachment is forced to occur more on the outer rim of the electrode when increasing the rotation speed.
- Electrical parameters used for the electrode feed control do not get significantly influenced when remelting with a rotating electrode, compared to static ones.
- At a given remelting power, a higher rotation speed leads to an increase in melt rate.
- Vice versa energy consumption may be lowered using a rotating electrode because it remelts faster with improved ingot structure.

In the near future more trials are conducted to verify the made assumptions and to enlarge the data pool on remelting electrodes that rotate. Besides the investigation of emerged questions (the drop in melt rate when initializing rotation for example) the focus will be on different rotation speeds, a wider range on slag systems as well as different electrical remelting parameters.

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