Influencing the Electroslag Remelting Process by varying Fluorine Content of the utilized Slag

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Abstract

The influence of slag composition and process parameters on the behavior of electrical parameters and the refining capability with regard to dissolved impurities and non-metallic inclusions of electroslag remelted (ESR) material is currently under investigation at IME, RWTH Aachen University. With regard to an increasing demand of advanced material properties, special attention was given to the behavior of oxygen, sulphur and in correlation with that also to the modification and removal of non-metallic inclusions during ESR.

In order to investigate the influence of fluorine content on the aforementioned objectives, six 110 mm electrodes of the steel 21CrMoV5-7 were remelted in a 400 kW ESR furnace using different mixtures within the slag system CaF_2-CaO-Al_2O_3. At constant remelting conditions (constant melt rate and electrode immersion depth) the fluorine content was successively decreased from 100 to 0 wt.-% keeping the ratio CaO/Al_2O_3 constant.

Beside the evaluation of electrical parameters such as melting power, current density or electrical resistance, the remelted ingots and the various slag partitions (bulk slag, slag skin thickness and flew dust) were subjected to various analysing methods. The determination of matrix and alloying elements at various ingot positions was carried out by spark optical emission spectroscopy. Analysis of oxygen, nitrogen, sulphur, carbon and hydrogen were performed by combustion and inert gas fusion methods. Additionally, microstructure and non-metallic inclusions distribution were characterized by light microscopy as well as SEM-EDX investigations.

It could be summarized, that a decreasing amount of CaF_2 results in a significant decrease of power usage whereas the contents of selected alloying elements such as Al and Si are less influenced. The oxygen amounts are in the range of the electrode values whereas for most slag systems a strong desulphurization was observed.

Introduction

The electroslag-remelting process is commonly used for refining of high grade steels or nickel-, iron- and cobalt-based superalloys. Originally established for achieving ultra-low sulphur contents (< 10 ppm) its main application nowadays shifted to an improvement of the cleanliness level and a homogenization of the solidification structure.

Materials produced by the ESR process are usually utilized for highly stressed components e.g. in the fields of power generation, aerospace, oil and gas extraction, transportation, tool manufacturing or for selected medical applications. [1]

Since the presence of non-metallic inclusions (NMIs) and solidification defects in such materials result in the occurrence of rolling and surface defects during further processing as well as in a decrease of mechanical properties and corrosions resistance, these inhomogeneities need to be minimized.

Fundamentals

In the ESR process a consumable electrode is continuously remelted via a liquid slag in a water-cooled copper mould. The basic principle of the process in the stationary remelting phase is illustrated in Figure 1 (left). As a result of the flow of electric current from the electrode via the liquid slag bath over the remelted ingot into the base plate and due to the fact that liquid slags show much higher electrical resistivities than metallic conductors, most of the applied electric power is transferred into heat in the slag bath. When the temperature of the slag bath exceeds the liquidus temperature of the electrode material, a thin film of liquid metal forms at the electrode tip from which droplets are continuously detached. Due to the density difference, the metal droplets sink through the slag and are collected in a liquid metal pool before solidification. [2]

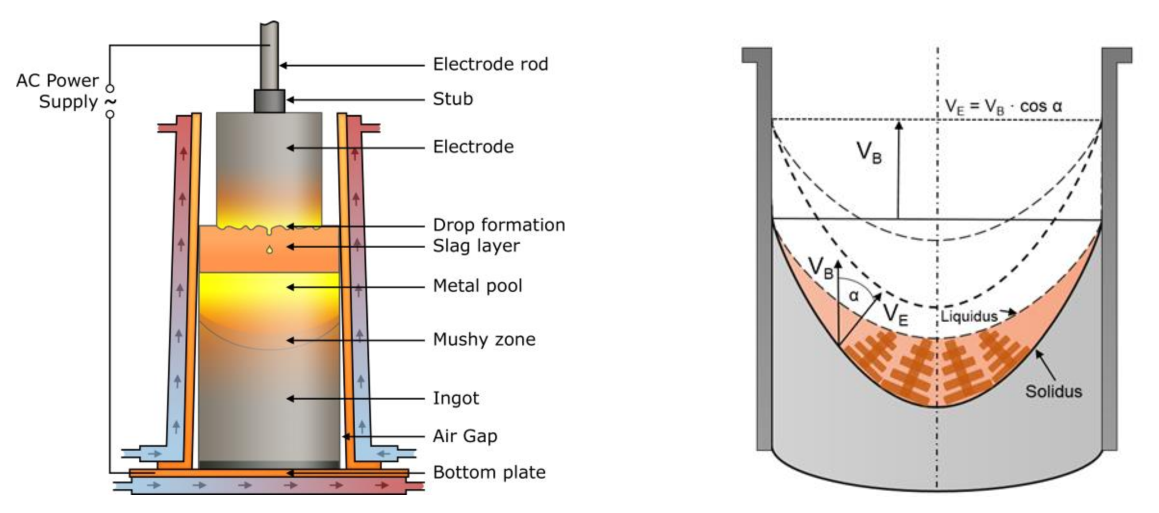

Figure 1: Schematic procedure (left) after [3] and detailed illustration of dendrite formation the mushy zone (right) in the ESR process after [4]

Depending on the ingot diameter, a directional solidification showing a dendritic structure is typically achieved in ESR materials (see Figure 1, right). For heavy forging ingots with diameters up to 3 600 mm, [5] or at high melt rates also equiaxed crystallization is observed in the ingot center.

Typical slags which are utilized in the ER process are based on the ternary system CaF_2-CaO-Al_2O_3. Depending on the material to be remelted or to modify certain slag properties additions of SiO_2, TiO_2 or MgO are added if required.

In the ESR process various chemical and physical interdependencies between the remelted material (alloying elements, dissolved interstitial elements and non-metallic inclusions), the cat- and anions of the slag system and the gas atmosphere are present. An appropriate illustration of these interactions is given by **Fehler! Verweisquelle konnte nicht gefunden werden.**. It is obvious that the refining efficiency of the process is determined by the alloy composition, e.g. by the presence of deoxidizing elements such as Al or Si, the absorption capacity for non-metallic inclusions by the slag, the state of the thermochemical equilibrium between metal and slag and resulting metal-slag interactions as well as evaporation-induced changes of and gas diffusion in the process slag. [6]

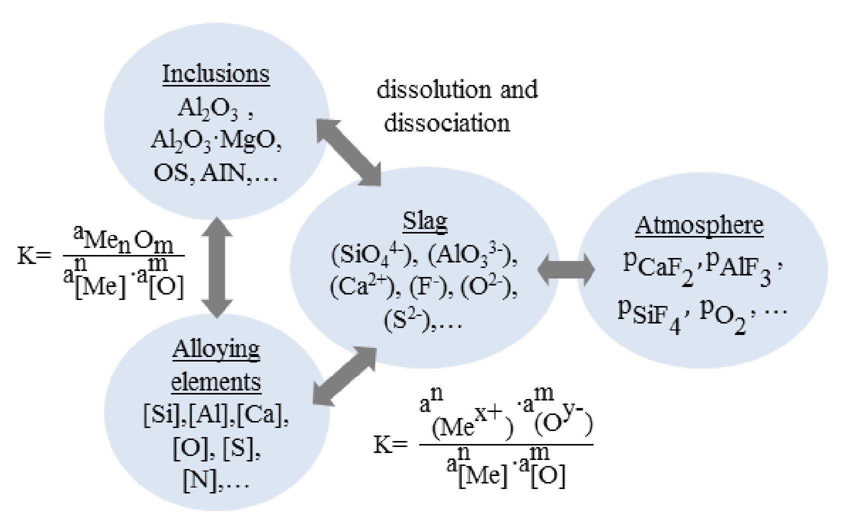

Figure 2: Chemical and physical interactions between alloy, slag and atmosphere during ESR after [6]

Beside the refining properties, the composition of the slag determines its physical attributes, e.g. the electrical conductivity which in turn influences power consumption and process efficiency.

Experimental

In the present study six electrodes of a high-temperature steel 21CrMoV5-7 were remelted in a closed ESR furnace at IME, RWTH Aachen University using various slag compositions. With an average length of 1 100 mm and a diameter of 110 mm the electrode weights were around 84 kg.

The utilized ESR furnace is able to operate at maximum 400 kW melting power at 50 Hz under defined atmospheric conditions up to 50 bar.

In order to investigate the influence of varying fluorine contents on the behavior of electrical parameters at a fixed melt rate as well as on the refining capability with regard to oxygen, sulphur and non-metallic inclusions, six slag compositions with a successive decrease in CaF_2 were blended keeping the ratio of CaO/Al_2O_3 constant. The detailed compositions are listed in Table 1. To minimize temperature affected differences with regard to metal-slag interactions, the melt rate was kept constant in all trials at 1.1 kg/min. Additionally, the immersion depth of the electrodes into the liquid slag bath were kept constant by using swing control. To minimize the influence of atmospheric oxygen, remelting was carried out at a slight overpressure (1.2 bar) argon atmosphere.

Table 1: Slag compositions used in the ESR trials

Trial	1	2	3	4	5	6
CaF_2	98,9	79,12	59,34	39,56	19,78	0
CaO	0,35	9,666	18,982	28,298	37,614	46,93
Al_2O_3	0,02	9,33	18,64	27,95	37,26	46,57
MgO	0	1,016	2,032	3,048	4,064	5,08
SiO_2	0,17	0,196	0,222	0,248	0,274	0,3
FeO	0,01	0,028	0,046	0,064	0,082	0,1

After remelting, the bulk slag, slag skin and flew dust were collected for mass balancing, measuring the slag skin thickness und for chemical analysis. The obtained ingots were cut into various sections (see Figure 3) which were subjected to several analyzing methods.

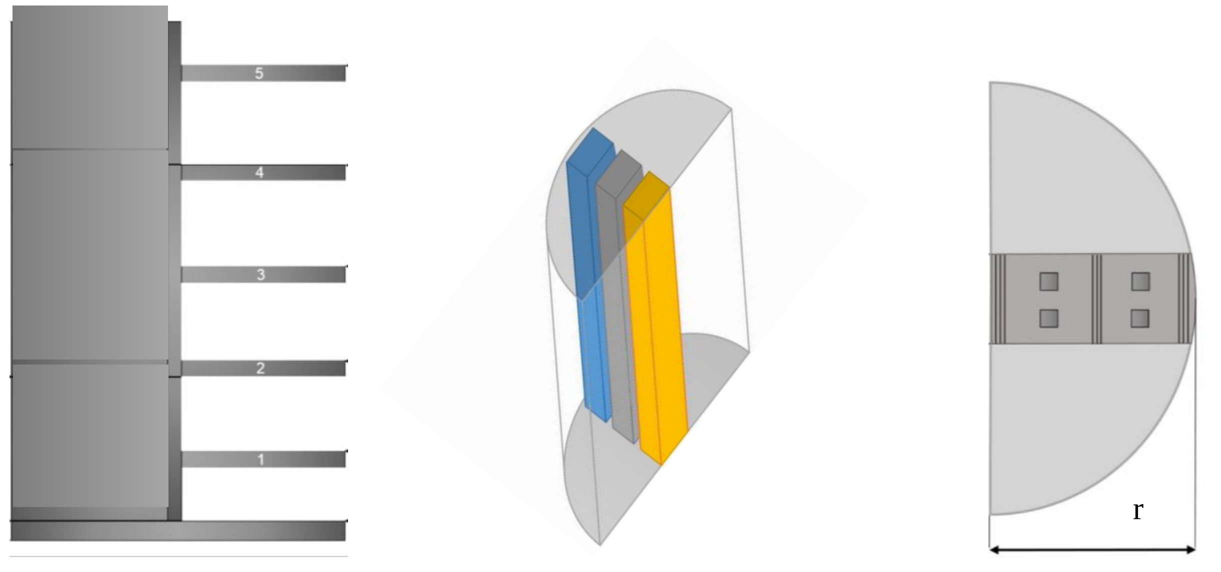

Figure 3: Schematic illustration of sample extraction from the remelted ingots

Longitudinal discs from the ingot center were used to visualize the macro structure and to obtain information about the depth and shape of the liquid metal pool (see Figure 3, left). Stripes from the bottom, middle and top part were used for analyzing the matrix composition over the ingot height and radius (see Figure 3, middle) using optical emission spectroscopy. Additionally, from five horizontal extracted discs stripes for determining O, S, C, N and H by combustion and inert gas fusion methods were taken from positions at the ingot center, half radius and at the surface (radius). Furthermore, microstructure and distribution of non-metallic inclusions was characterized by light microscopy and SEM-EDX at two positions close to the ingot center and surface. The corresponding samples were extracted between the stripes for gas analysis (see Figure 3, right).

Results and Discussion

After each trial the recorded process data were evaluated and average values for power input, electrical resistance, voltage and current were built for the stationary remelting phase. The dependence of particular process variables on the amount of CaF_2 in the slag is lustrated in Figure 4. A significant decrease of power consumption was found with a reduced amount of CaF_2 accompanied by a strong increase of the electrical resistance.

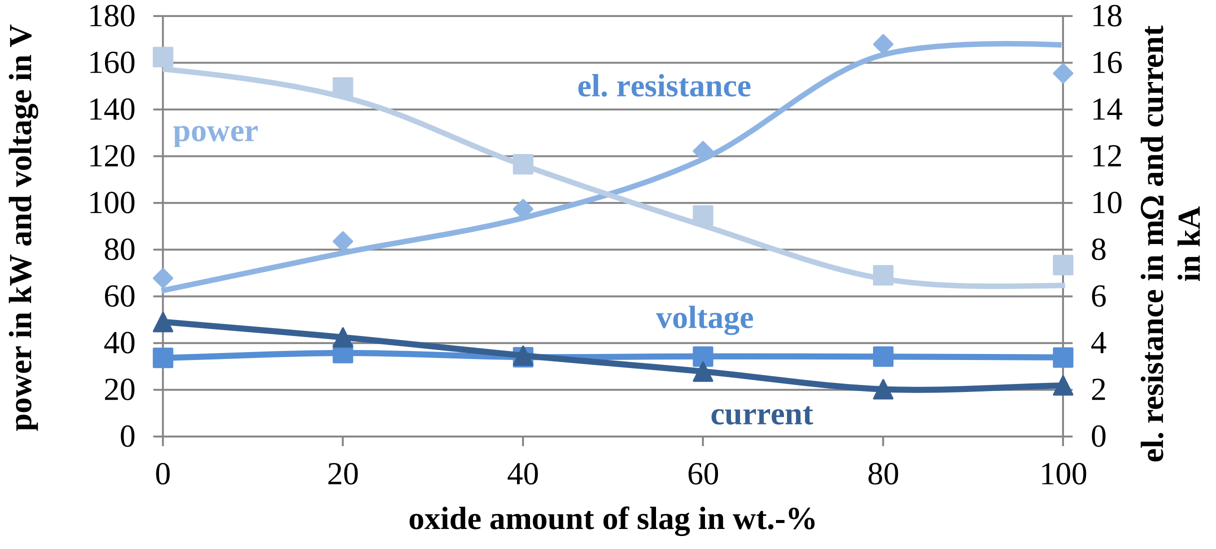

Figure 4: Correlation between the CaF_2 content of the slag and selected process parameters

All remelted ingots showed smooth surfaces (see Figure 5, left) at simultaneously increasing slag skin thicknesses with decreasing amount of CaF_2. Additionally, a decentralization of the droplet formation position at the electrode tip was found with decreasing contents of CaF_2 (see Figure 5, right).

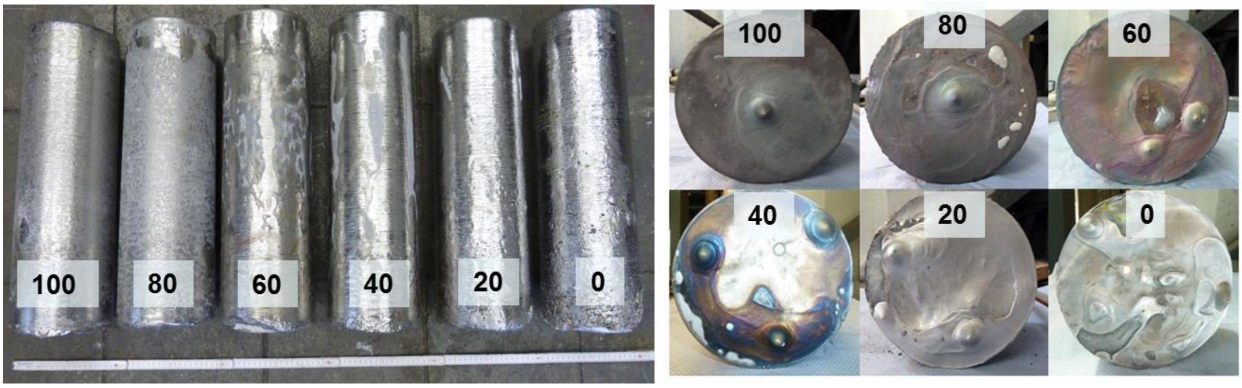

Figure 5: Remelted ingots (left) and droplet formation at the electrode tip (right) with indication of CaF_2 content

With regard to the behavior of selected alloying elements, such as aluminum and silicon, which mainly act as deoxidizing elements, a distinct change was found due to metal-slag interactions. Beside the pure fluorine slag, a high pick-up of aluminum and a simultaneous decrease of silicon contents were found for all slag systems containing oxides. Furthermore, the aluminum pick-up and silicon loss were reduced with increasing ingot height which is illustrated in Figure 6 and Figure 7.

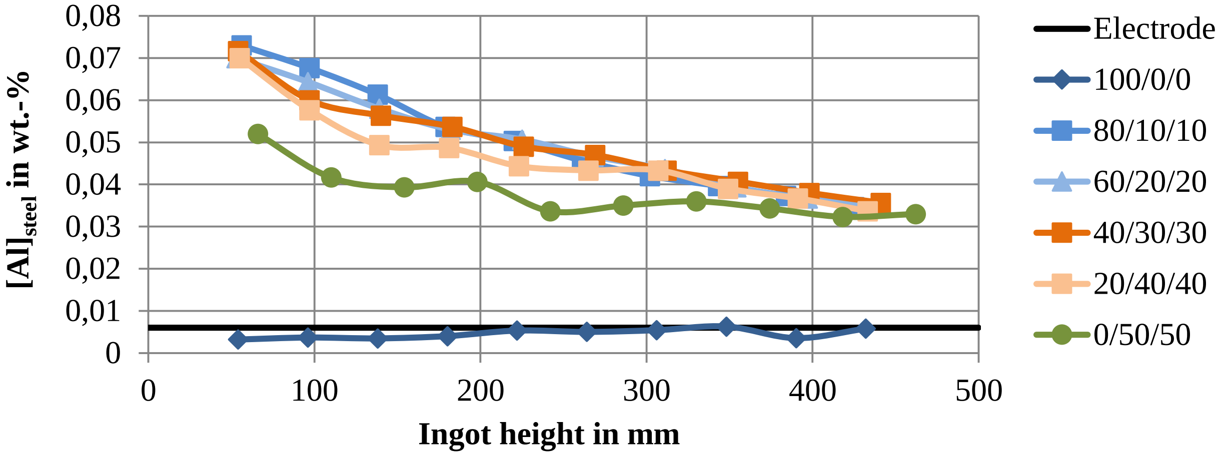

Figure 6: Behavior of aluminum dissolved in the remelted steel in correlation to slag composition

A clear metal-slag interaction, expressed by Equation 1, is visible due to the low activity of SiO_2 and high activity of Al_2O_3 in the slag at process start. The approach to chemical equilibrium between slag- and steel-melt subsequently results in reduced silicon losses and aluminum pick-up with ongoing remelting time and ingot height, respectively.

$$3\,[Si]_{steel} + 2\,[Al_2O_3]_{slag} \leftrightarrow 2\,[Al]_{steel} + 3[SiO_2]_{slag} \qquad (1)$$

It is striking that aluminum pick-up and silicon losses are nearly independent of the amount of oxides in the slag, only the fact that they are present is crucial in the investigated composition range. The detected aluminum contents are even lower when remelting under a pure oxide slag compared to all mixtures of fluorides and oxides. Only by using pure calcium fluoride, no changes with regard to alloying or deoxidizing elements were found. Beside the contents of aluminum and silicon, the amounts of further alloying elements, e.g. chromium, vanadium or molybdenum did not show any changes when compared to the electrode contents or any variations over the ingot height.

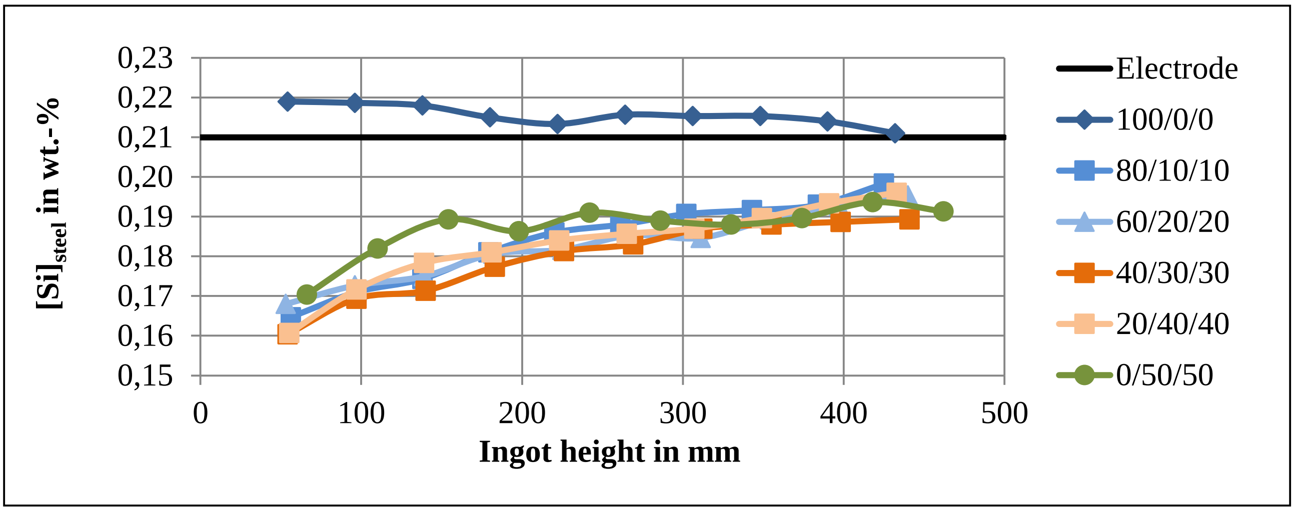

Figure 7: Development of silicon contents in the remelted steel depending on process slag composition

The clear correlation between the aluminum and silicon contents dissolved in the steel is furthermore illustrated in Figure 8 in dependence of slag composition.

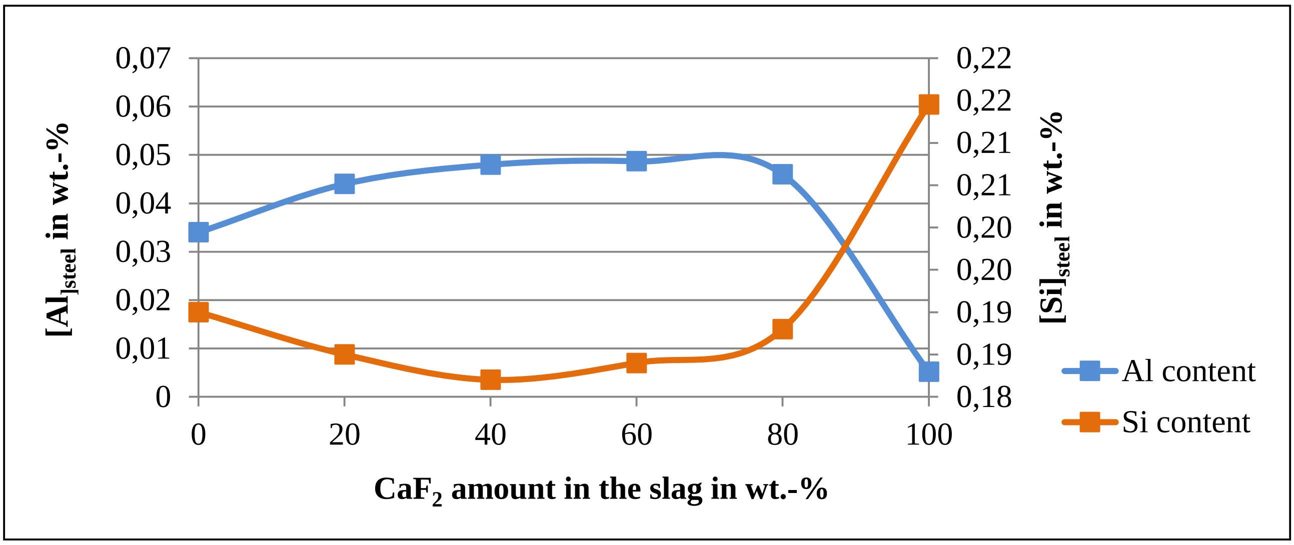

Figure 8: Correlation between aluminum a silicon amount dissolved in the steel with respect to slag composition

In contrast to the variation of aluminum and silicon contents, no changes of total oxygen amount over the ingot length were found, despite different deoxidizing abilities of aluminum and silicon. Additionally, lower oxygen values were achieved by remelting under slags containing high amounts of CaO and Al_2O_3. Compared to the content of total oxygen in the electrode material, remelting under high fluorine slags resulted in slightly higher oxygen contents in the ingots. In contrast to that, it was possible to reduce the total oxygen amount by the utilization of high oxide slags (see Figure 9).

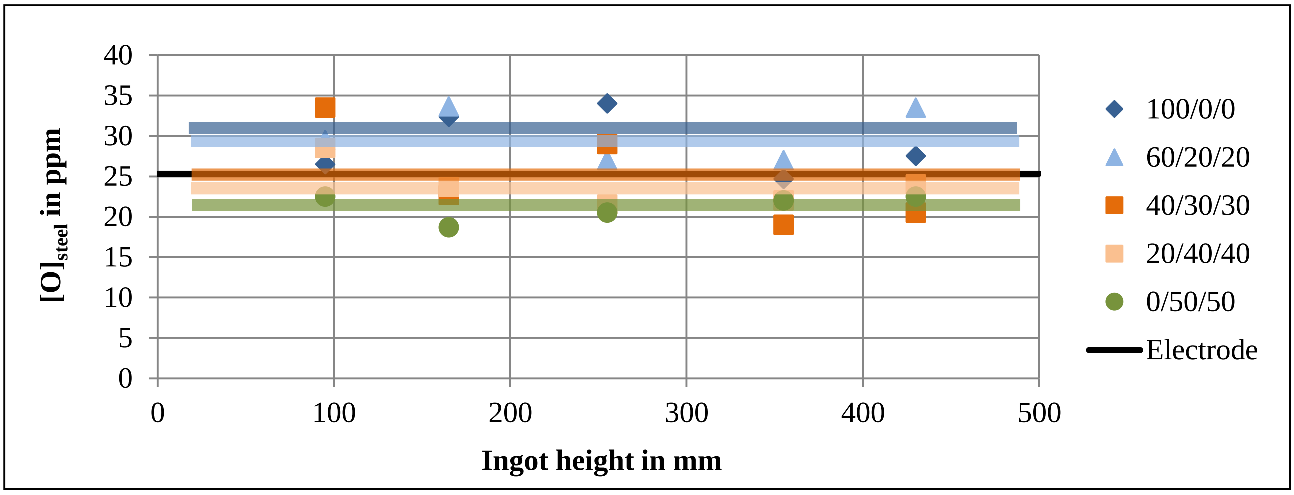

Figure 9: Total content of oxygen after remelting under various slag compositions

Desulphurization was generally possible using all slag systems but only to a very limited degree under an absence of oxides. Since the reduction of sulphur amount in the steel is based on the formation of CaS in the slag, this is only possible if comparatively high contents of CaO are present. With regard to Figure 10, it is obvious that an amount of 20 wt.-% CaO is sufficient to maintain an satisfactory sulphur removal until the end of remelting. However, the increasing amount of CaS dissolved in the slag with increasing process time will lead to higher sulphur contents in the metal with rising electrode length. By remelting under an oxygen containing atmosphere, CaS could further react to SO_2 and therefor desulphurization capacity of the slag could be kept high. On the other hand, these conditions lead to higher oxygen values and amounts of non-metallic inclusions in the remelted material as a result of the oxygen permeability of the slag.

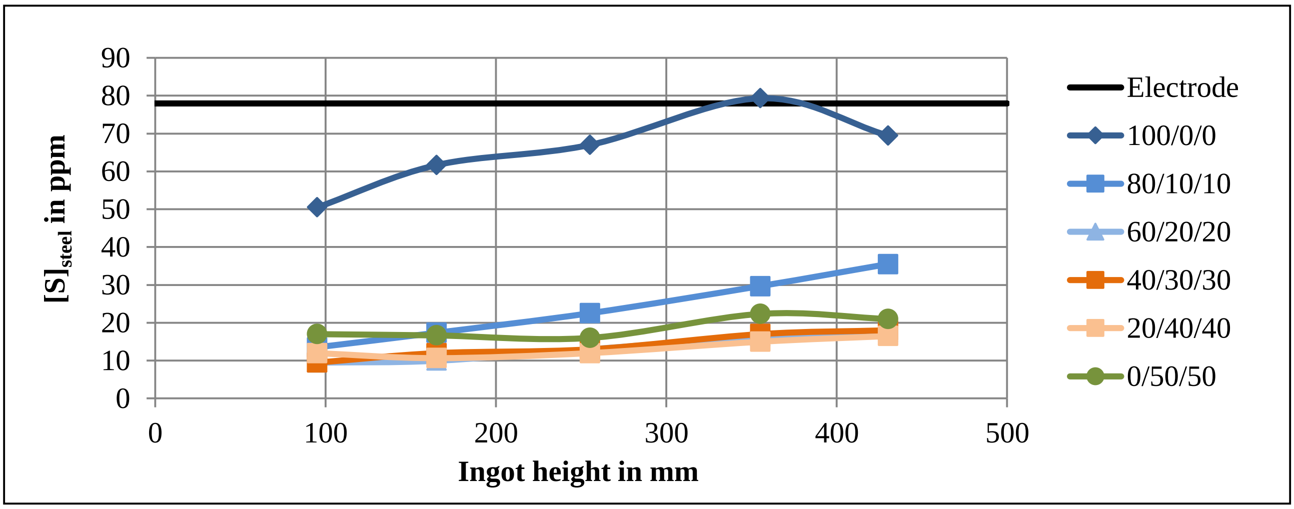

Figure 10: Development of sulphur contents in the remelted ingots for various slag systems

A characteristic image of the resulting bainitic microstructure after remelting is given in Figure 11 (right), showing the positions and sizes of non-metallic inclusions investigated by light microscopy. By using this method, information about the number, size and the total area of inclusions were gained. As demonstrated in Figure 11 (left) large inclusions were successfully removed, whereas the amount of small inclusions was partially increased after remelting. Especially the ingots remelted by slags consisting of approximately 40/30/30 and 20/40/40 showed a high cleanliness level.

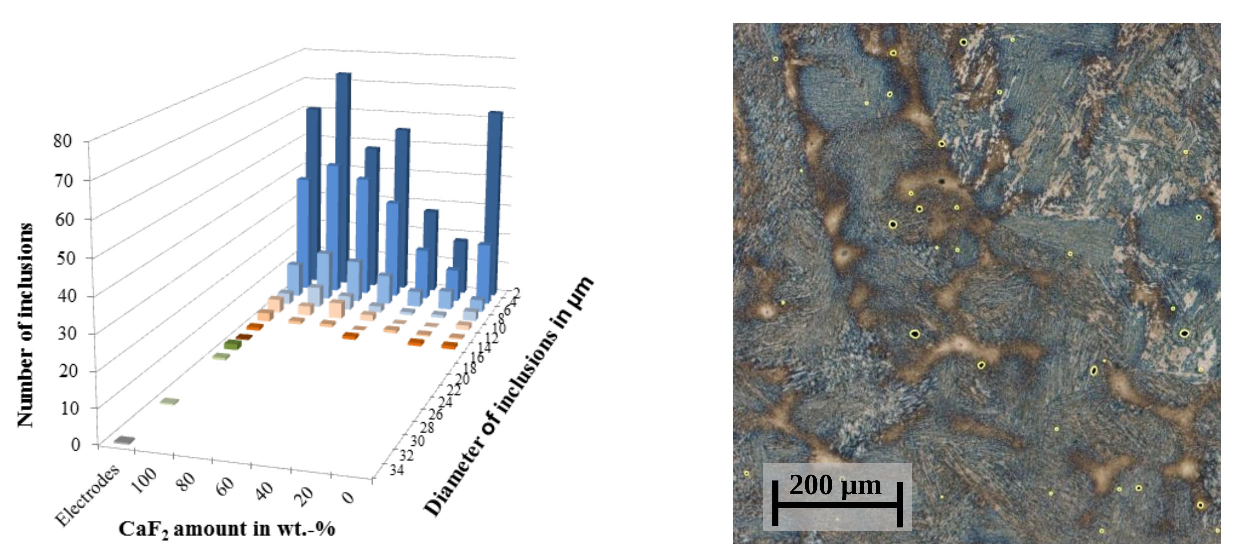

Figure 11: Distribution of NMIs (left) and obtained microstructure after remelting (right)

With regard to the total area of non-metallic inclusions, the utilization of all slags led to a significant decrease. This clearly confirms the general refining potential of the ESR process however, the total number of inclusions increased when operating under slags containing more than 80 wt.-% of CaF$_2$. Simultaneously, the total area of inclusions is higher when remelting is performed using high fluorine slags (see Figure 12).

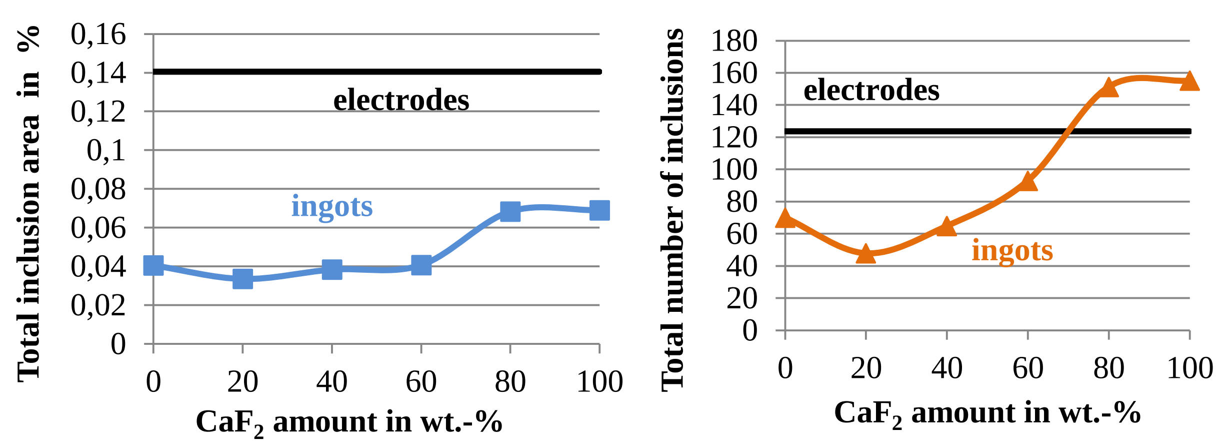

Figure 12: Total area (left) and total number (right) of NMIs after remelting depending on slag composition

Conclusions

In the present study the influence of various fluorine contents on the behavior of electrical parameters, on the distribution of alloying elements and on the refining ability with regard to non-metallic inclusions and dissolved impurities were investigated. Although the amount of Al_2O_3 was varied significantly, higher aluminum contents in the steel were not detected when Al_2O_3 contents in the slag were increased. Besides that, the aluminum pick-up, accompanied by a silicon loss did not result in lower oxygen values or a change of oxygen contents over the ingot height, despite the stronger deoxidation ability of aluminum. Contrary to expectations, lower total oxygen values were achieved by the utilization of high oxide slags. Additionally, the desulphurization capacity was increased with rising amounts of oxides in the slag which is mainly due to the content of CaO and the formation of CaS.

Compared to the electrode material, the cleanliness level was improved in all remelted ingots. It is striking, that the usage of high oxide slags results in a decrease of the total area as well as of the total number of non-metallic inclusions. On the other hand, remelting under high fluorine slags led to a decrease of NMI area but their total number was increased, which demonstrates the formation of new, smaller and equally distributed inclusions.

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