Parameters determining Solidification Structure and Process Efficiency of ESR Superalloys

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Abstract

The influence of selected slag properties and process variables on the solidification structure of the final ingot during electroslag remelting (ESR) is currently under investigation at IME, RWTH Aachen University. Special attention was given to the formation of the slag skin which affects the heat transfer to the water-cooled copper mould. Since a lot of electroslag-remelted alloys are prone to segregation, a rapid heat extraction from the melt is desired to minimize the local solidification time and hence the extent of segregation effects in the final ingot. Additionally, process efficiency must always be considered in order to define appropriate slag compositions and process parameters.

Twelve 110 mm electrodes of the nickelbase-superalloy 718 were remelted in a 400 kW-lab scale ESR furnace using different mixtures of slags within the system CaF_2-CaO-Al_2O_3. To exclusively investigate the influence of one single physical property, the mixtures were blended in such a way, that significant differences in viscosity, the liquidus temperature or the solidification path were existent with only the smallest possible variation of other properties at the same time. As electrode material, one of the most produced superalloys, alloy 718 was utilized. Furthermore, parameters like melt rate and height of the bulk slag were varied in particular.

To assess the influence of the aforementioned parameters on the solidification of the slag and the metal, different characterization techniques were applied. The slag skin thickness was measured and compared to the secondary dendrite arm spacing of the produced ingots determined by optical microscopy. Subsequently, the local solidification time was calculated and correlated to the niobium content of the dendrites and interdendritic phases, analyzed via SEM-EDX. Depth and shape of the liquid metal pool were compared to melt rate as well as to the microstructure. Finally, the degree of process efficiency was determined with regard to power input, height of the slag bath and the electrical conductivity of the slag.

Excerpts of this extended abstract were published at the 1st International Conference on Ingot Casting, Rolling and Forging. [1]

1 Introduction

The so called triple-melt process, consisting of vacuum induction melting, electroslag remelting and vacuum arc remelting, represents an indispensable production route for nearly all modern high-performance materials like Ni-based superalloys. Thereby, the electroslag remelting process permits the minimization or avoidance of potential material and solidification defects. The high level of cleanliness, an accurate chemical composition and the reduction of segregation effects allows the usability of the remelted material for highly stressed components, such as turbine blades, discs and wheels in the aerospace industry. Since the limiting criteria for manufacturing ingots with increasing diameters or melt rates is the sensitivity of superalloys for segregation, it is of interest to increase the cooling rate during solidification and consequently to reduce the local solidification time (LST).

2 Fundamentals

In the ESR process, a consumable electrode is continuously melted in a water cooled cooper mould while being inserted into a liquid slag bath. On the electrode tip, a thin film of liquid metal is present where metal droplets are formed and detached. Due to the density difference between the remelted material and the utilized slag system, the metal droplets are sinking through the slag and are collected in a liquid metal pool before solidifying as the remelted ingot (cf. Figure 1, left). The heat input for primary melting the slag and afterwards for remelting the electrode is inserted by applying a voltage between electrode and ingot. The comparatively high electrical resistance of the liquid slag results in a nearly full transformation of the introduced electrical energy into heat in the slag bath.

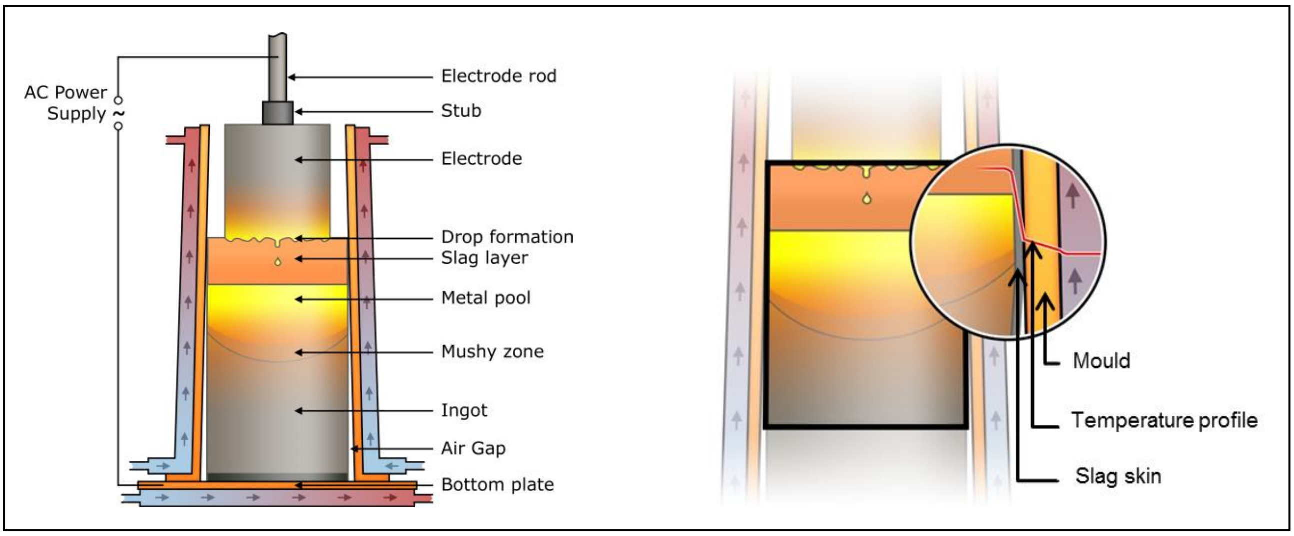

Figure 1: Schematic procedure (left) and detailed illustration of heat removal (right) in the ESR process [2]

As a consequence of the refining capacity of the utilized slag system, a significant improvement of cleanliness as well as the removal of detrimental elements could be achieved by electroslag remelting. Furthermore, the comparatively small volume of liquid metal as well as the high cooling rate results in a directional solidification structure with reduced micro- and macro-segregations. Due to the extensive water cooling of the mould, a solid slag skin forms between the ingot and the mould (cf. Figure 1, right). This layer affects the heat transfer and consequently the solidification conditions on the one hand and the surface quality on the other hand. Particularly the thickness of the slag skin was found to be an important factor influencing the heat transfer and consequently the local solidification time of the remelted material. [3-5] Furthermore, numerical computations and studies of the dendrite arm spacing indicate that a range of melt rates exists where the local solidification time is minimized. [5-7]

3 Experimental Procedure

The remelting of twelve electrodes (triple-melted, forged and heat treated in advance) with 110 mm diameter of alloy 718 was carried out in an open 400 kW electroslag remelting furnace under argon inertization. The mould diameter and consequently the ingot diameter were in the range between 145 and 160 mm. To investigate the influence of the power input and the height of the bulk slag, five trials with constant slag composition (mostly CaF_2, CaO and Al_2O_3) were carried out as illustrated in Table 1.

Table 1: ESR trials with different melting parameters and constant slag composition

Trial	E1	E2	E3	E4	E5
Average power input / kW	110	80	140	110	110
Amount of slag / kg	4.0	4.0	4.0	2.5	8.0
Height of the bulk slag / mm	90	90	85	52	174

To identify the effect of a single physical slag property on the formation of the slag skin and the solidification of the ingot, all further slag attributes have to be kept constant. Although, all physical slag properties are dependent on the ionic structure of the slag it was possible to blend various compositions with significant differences in viscosity, liquidus temperature or solidification path with only the smallest possible variation of other properties at the same time. The utilized mixtures are given in the ternary phase diagram of CaF_2-CaO-Al_2O_3 in Figure 2 which represents the common system for ESR slags. In these trials the average power input and the amount of slag were kept constant with 100 kW and 4 kg, respectively.

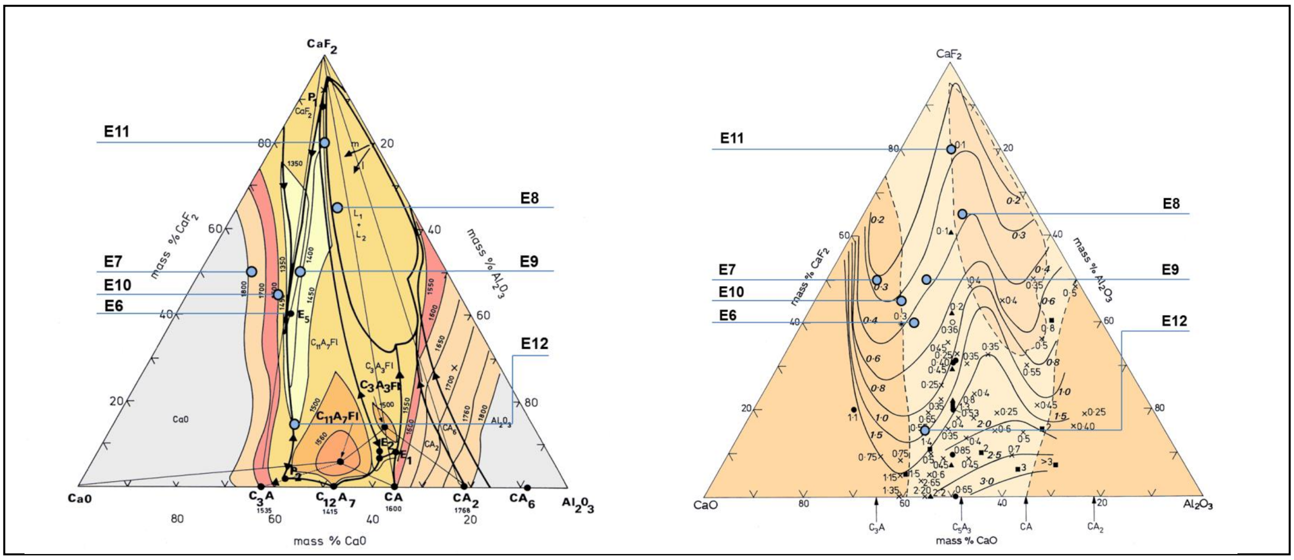

Figure 2: Utilized slag compositions in their ternary phase diagram [8] showing the liquidus temperature (left) and their viscosity (right)

To evaluate ideal conditions with regard to process efficiency an energy balance was established for the experimental series using a constant slag composition and variable process parameters (E1-E5) as well as for different slag compositions which differ greatly in their electrical resistivity (E11, E12). The calculation of the efficiency was carried out by comparing the applied melting power and the determined power loss caused by the cooling water. Due to the high fill ratio radiation losses were neglected.

3 Results and Discussion

The investigation of various slag skin fractions of the respective trials indicate that the slag skin thickness depends more on slag composition than on the selected process parameters. A thin slag skin would therefore be the result of a low liquidus temperature, low viscosity and a short solidification path of the appropriate slag system. In this case, the solidification path refers to the position of the slag composition in its ternary phase diagram and the distance to eutectic or peritectic points. Furthermore, selected SEM-BSE images of the slag skin demonstrate that at the slag-mould interface a high melting component of CaO and Al_2O_3 primarily solidifies. However, the ingot facing side of the slag skin shows a composition very close the composition of the bulk slag.

Depending on the different melt rates and slag skin thicknesses, a varying depth and shape of the liquid metal pool can be noticed. Referring to the trials E1-E5, where no significant change of the slag skin thickness was observed, a linear increase of the liquid metal pool depth with rising melt rate is found (cf. Figure 3, left), which agrees well with the results described by Patel et al. [9]

The metallographic analysis of the secondary dendrite arm spacing (SDAS) validate the expected improved heat removal at the ingot surface in contrast to the center. It is common knowledge that a small SDAS is the result of a comparatively low local solidification time (LST). [10] Comparing the SDAS and consequently the LST with the average slag skin thickness, a correlation could be found only for a part of the performed trials. Within these, the SDAS increases with rising slag skin thickness. However, the melt rate appears to be the more dominating factor with influence on the LST. For the conducted experiments, an overall decrease of the local solidification time with an increasing melt rate can be observed (cf. Figure 3, right). A possible explanation for that could be found with regard to the dependency of solidification front morphology and the determining parameters solidification front velocity (v) and thermal gradient (G). An increasing solidification front velocity which is caused by a high melt rate and a simultaneous rise of the temperature gradient due to the higher process temperature would therefor result in a reduced dendrite size.

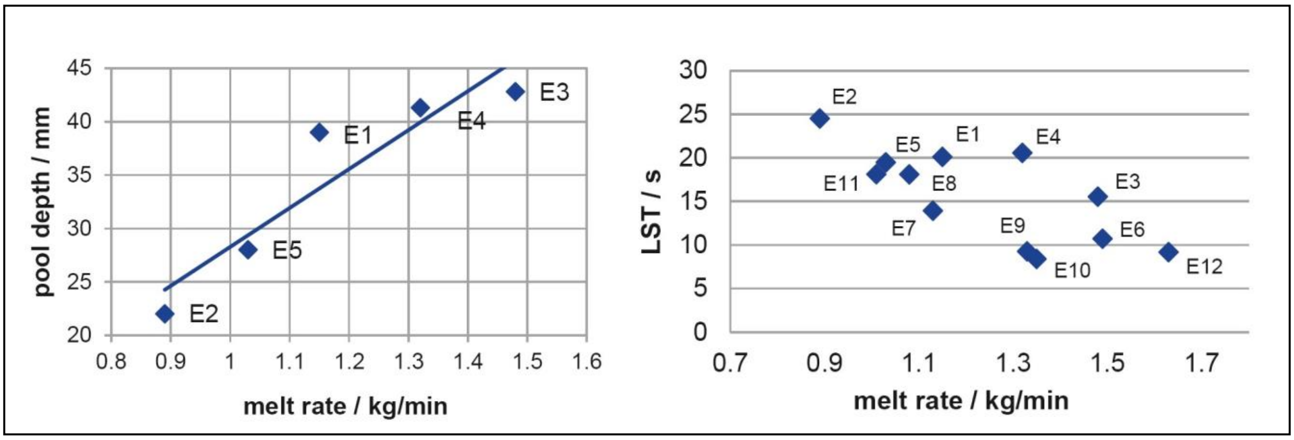

Figure 3: Correlation between melt rate and pool depth (left) and between melt rate and LST (right) during ESR

The performed line-scans across the dendritic and interdendritic areas and the resulting distribution of the various alloying elements correspond to the initial partition coefficients in alloy 718, determined by Aubertin et al. [11] Cr and Fe tend to crystallise in the dendrites, whereas Nb and Mo preferably segregate to the interdendritic liquid. Furthermore, the distribution of Nb, which shows the strongest tendency to segregation, only shows a slight increase of the segregation formation from the ingot surface to its center. Additionally, a decrease of microsegregation can be observed with increasing melt rate and local solidification time, notably in the ingot centre.

Due to the small equipment size the occurring heat losses and subsequently the efficiency are comparatively low. In general, the melting rate rises with increasing power supply and decreasing height of the slag bath. A distinct effect on process efficiency could be detected by the amount and height of the slag bath. As the height of the slag bath decreases from 174 to 52 mm, the amount of energy which is directly transferred to the mould is reduced from 90.6 to 82 %. Additionally, an increase of the electrical resistance of the slag system also results in an improvement of the efficiency.

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