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The influence of the mould cooling temperature on the surface appearance and the internal quality of ESR ingots

M Kubin[1], B Ofner[1], H Holzgruber[1], R Schneider[2], D Enzenhofer[2], A Filzwieser[3], S Konetschnik[3]

[1] INTECO special melting technologies GmbH, Bruck/Mur, Austria
[2] University of Applied Science Upper Austria, Wels, Austria
[3] METTOP GmbH, Leoben, Austria

E-Mail: michael.kubin@inteco.at

Abstract. One of the main benefits of the ESR process is to obtain an ingot surface which is smooth and allows a subsequent forging operation without any surface dressing. The main influencing factor on surface quality is the precise controlling of the process such as melt rate and electrode immersion depth. However, the relatively strong cooling effect of water as a cooling medium can result in the solidification of the meniscus of the liquid steel on the boundary liquid steel and slag which is most likely the origin of surface defects. The usage of different cooling media like ionic liquids, a salt solution which can be heated up to 250°C operating temperature might diminish the meniscus solidification phenomenon. This paper shows the first results of the usage of an ionic liquid as a mould cooling medium. In doing so, 210mm diameter ESR ingots were produced with the laboratory scale ESR furnace at the university of applied science using an ionic liquid cooling device developed by the company METTOP. For each trial melt different inlet and outlet temperatures of the ionic liquid were chosen and the impact on the surface appearance and internal quality were analyzed. Furthermore the influence on the energy balance is also briefly highlighted. Ultimately, an effect of the usage of ionic liquids as a cooling medium could be determined and these results will be described in detail within the scope of this paper.

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Introduction

Surface quality of as cast ESR ingots is an important precondition in order to further process the ESR ingot in the forging shop without any prior surface dressing. One main key point of a smooth surface appearance, especially for large sized ESR ingots (diameter > 1.600mm), is the precise controlling of the ESR process [1]. However, also the temperature gradient between the mould wall and the ingot has an influence on the appearance of the ingot surface and on the origin of surface defects. The usage of water as a mould coolant in the ESR leads to a very strong cooling effect respectively a very steep temperature gradient which can result in the solidification of the meniscus of the liquid steel on the boundary liquid steel and slag. The overflow of the already solidified meniscus with liquid metal due to local turbulences or an increase of the liquid metal level results in surface defects such as “groves”, “tears” or “metal fins” [2]. The usage of different cooling media like ionic liquids a salt solution which can be heated up to 250°C operating temperature, on the above mentioned temperature gradient and can diminish the meniscus solidification phenomenon.

It has been observed that good surface quality is associated with the presence of a finite depth (few centimetres) of liquid-metal contact on the slag skin [3] also known as “liquid head” or “standing height”. To achieve these requirements, the melting point of the slag must be higher than that of the metal [4]. In most common industrial practice, the problem with poor surface has been dealt with increasing the power input (and so the melt rate), by using the highest stable fill ratio and the lowest electrode immersion depth. Kharicha et al. [5] proposed the hypothesis that the current flowing through the slag/mould and the ingot/mould interfaces is the key factor to explain the empirical correlations gathered by industry on the quality of the ingot surface. It was shown that the final ingot surface quality is controlled by the heat balance at the slag skin. Increasing the power decreases the skin thickness by acting on the heat flux in the slag/ingot side of the skin. Another way consists in acting on the heat flux in mould side by decreasing the amount of heat removed by the coolant liquid. It was indeed suggested by industry that running the process with warmed mould may encourage the formation of smooth skin [6].

Furthermore, the ESR process is a very energy intensive process. According to Mitchell [7] good average power efficiency during the ESR-operation lies in the order of about 1300 kWh/t. The consumed energy cannot be further used as the temperature of the cooling water at the mould outlet reaches only a maximum of approx. 50°C. When using ionic liquids the mould outlet temperature can be increased and the energy extracted from the ESR process can be further used.

These above mentioned considerations were the initial starting point in executing several trial melts at a laboratory ESR furnace to examine the impact on the quality of an ESR ingot as well as on the energy balance when using ionic liquids for the mould cooling.

1. Remelting trials with the laboratory scale ESR furnace

To evaluate the above mentioned influence of the temperature of the mould cooling medium, test trails were performed with the laboratory ESR plant at the University of Applied Science Upper Austria. The test ingots with a diameter of 210 mm were produced by remelting 151,5 mm dia. electrodes using a standard ESR slag (Wacker 2015). The flow rate of the ionic liquid was steadily adjusted during the test melts in order to obtain higher temperatures at the mould outlet (see Table 1). For the first three trials the standard cooling water system was used. For the trails using the ionic liquids an intermediate cooling circuit for the ionic cooling solution was interconnected between the mould and the standard cooling water system. This cooling module including the necessary controlling device was provided by METTOP GmbH.

Table 1. Summary of the cooling parameters used for the executed test trials

Test No.		**Mould inlet temperature**	**Mould outlet temperature**
V082	Pre- test with water cooling	30°C	40°C
V083	Standard test with water cooling	30°C	40°C
V084	Repetition Standard test with water cooling	30°C	40°C
V085	Trail melt with ionic liquid	60°C	110°C
V086	Trail melt with ionic liquid	60°C	150°C
V087	Trail melt with ionic liquid	60°C	195°C

For evaluation of the pool profile shape and depth ferro-phosphor and iron sulphide were added just before the hot topping process. All test ingots were evaluated in terms of surface quality, geometrical form and depth of the pool, solidification structure (secondary dendrite arm spacing) and the respective heat transfer balance.

Table 2. Summary of the remelting parameters used for the executed test trials

Test No.	**Power [kW]**	**Steady state melt rate [kg/h]**	**Current [A]**	**Immersion depth of electrode [mm]**
V082	105	-	4.000	approx. 20
V083	110	105,7	4.000	approx. 20
V084	105	101,6	4.000	approx. 20
V085	108	105,3	4.000	approx. 20
V086	105	102,0	4.000	approx. 20
V087	110	105,5	4.000	approx . 20

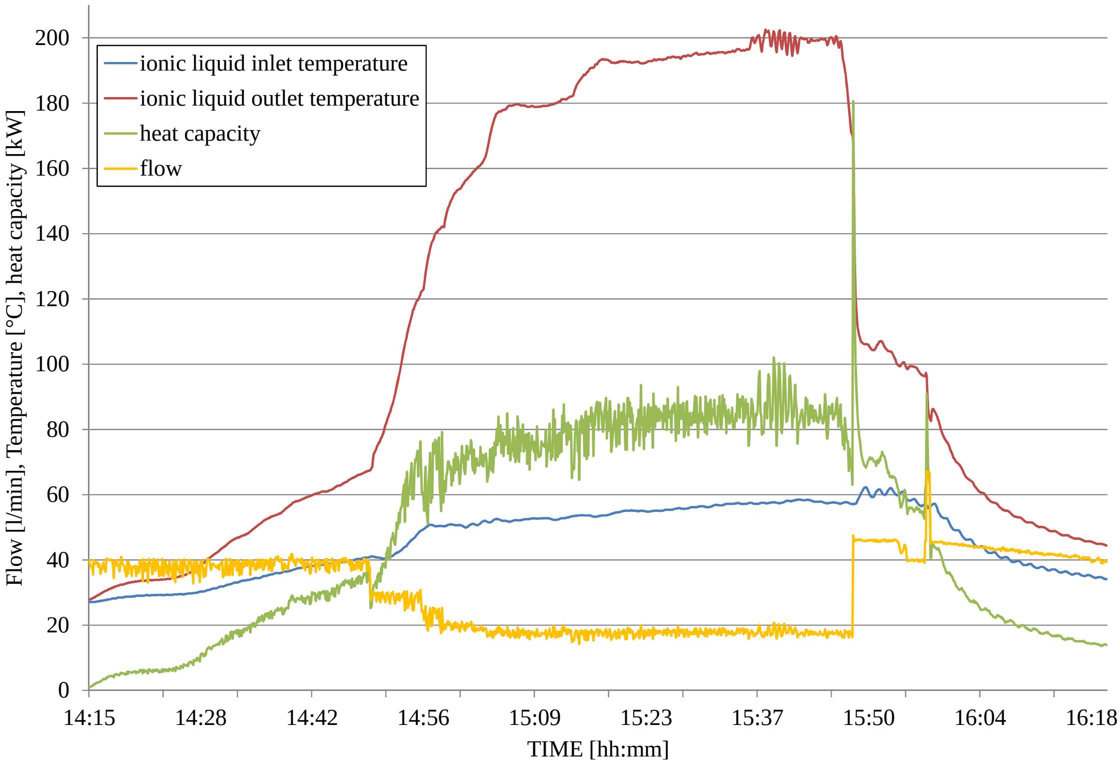

Figure 1: Cooling circuit parameters of test V087. A temperature difference between mould inlet and outlet of 135°C could be obtained

In **Figure 1** a typical trend of the cooling parameters is shown. For the test V087 the highest temperature difference between inlet and outlet was adjusted.

2. Quality of produced lab-scale ESR ingots

2.1. Surface quality

A comparison of the achievable surface quality of the trial ingots can be seen in **Figure 2.** As can be seen there is a clear relationship between the temperature of the mould cooling medium and the surface appearance of the ESR ingot. A significant improvement of the surface quality could be determined. Whilst during the test implemented with the conventional cooling method the surface was free of deeper notches but contains irregular depressions. With the implementation of the intermediate cooling circuit and the associated increase of the cooling temperature, the surface quality improved steadily. According to [8] the precondition for achieving a good ingot surface quality is a sufficient overheating of the slag bath. It can be assumed that the higher cooling temperature influences the overheating of the slag bath in a favorable manner so that the effects on the surface quality become quite significant.

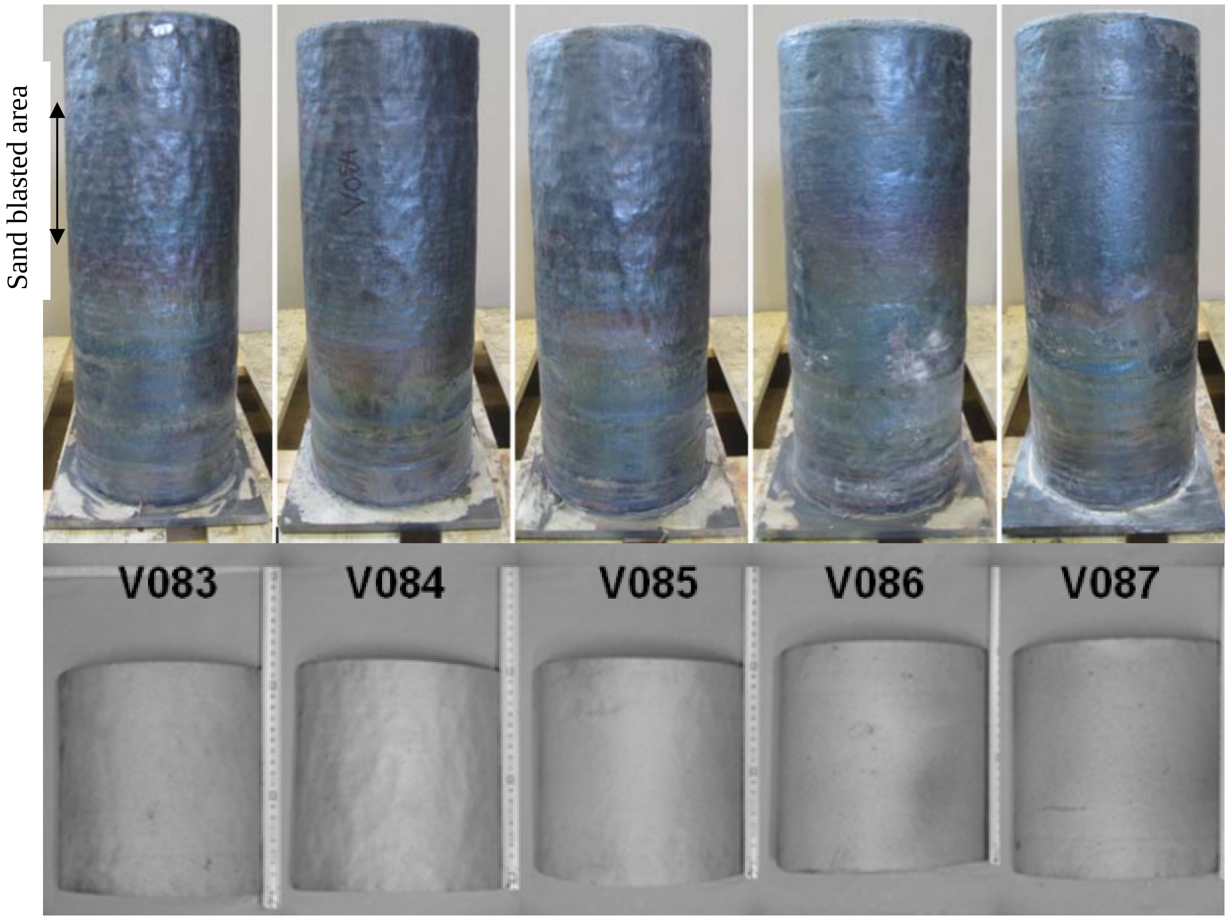

Figure 2: Comparison of the surface appearance (above: entire ESR ingot, below: sandblasted surface)

2.2. Internal quality

For evaluating the internal quality the pool profile formation (shape and depth of the liquid metal pool) and the secondary dendrite arm spacing were examined. If an ESR ingot is built up at a certain melting rate in the case of ingots with a sufficient length, steady state conditions in terms of thermal conditions are obtained. This means that the melting profile remains approximately steady during this time and with the "ingot building velocity" in the direction of the ingot axis the melt pool moves upwards. The pool profile deepens with the increase of the melting rate [8]. The evaluation of the Baumann print shows a slight increase of the melting pool depth during the test respectively with the rise of the mould cooling liquid outlet temperature as can be seen in **Figure 3**. The shallowest metal pool was achieved at the trail ingots with water cooling with approximately 46 mm. The deepest pool depth was observed at the melt V087 with approximately 59 mm. However it could be explained that the increase in the temperature promotes the overheating of the melt pool and reduces the heat transfer from the ingot to the mould. In addition to the evaluation with the Baumann print, the pool profiles were also investigated with the etching by the Oberhoffer method and the results showed the same tendency. Moreover it can be stated that there is a tendency that the pool profile becomes a more "C-shaped" form with increasing temperature instead of the usual "V-shaped form" in the ESR process. This C-shaped form of the pool profile has certain advantages regarding the formation of macrosegregations [9].

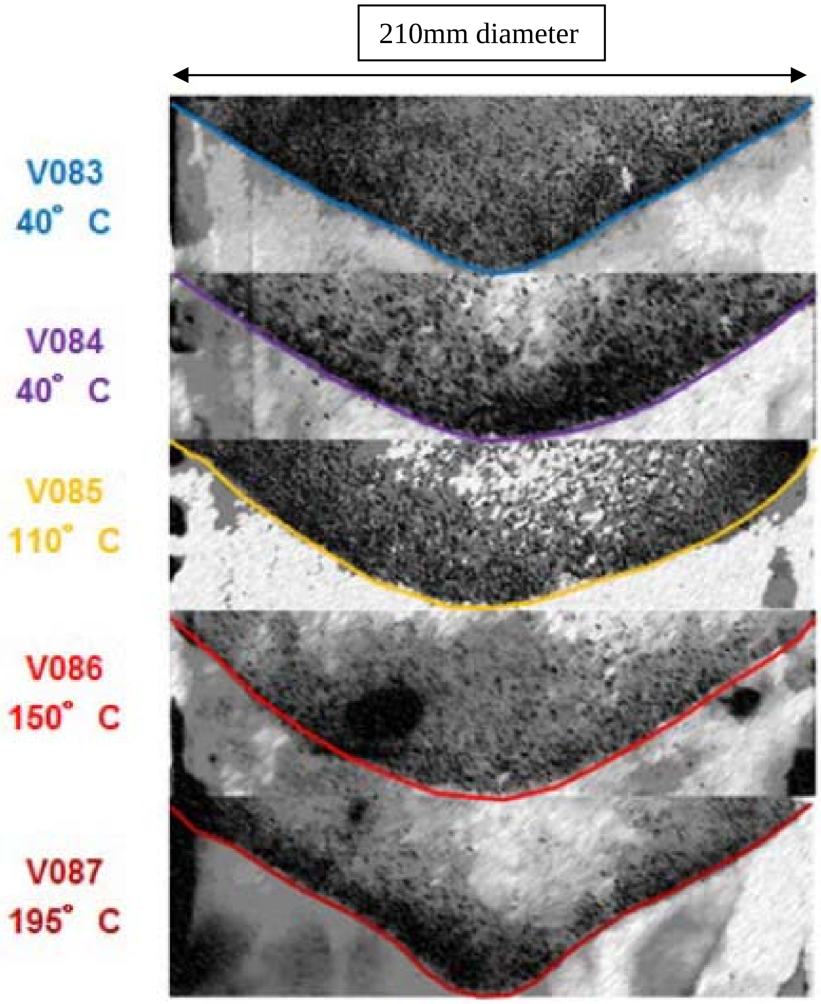

Figure 3: Comparison of the pool shape and depth of the trial ingots

Among the most important parameters of the solidification process affecting the structure and properties of the ingots are the rate of cooling of the metal in the two-phase region and the temperature gradient ahead of the solidification front [10, 11]. With increasing distance from the surface, the rate of cooling of the metal in the two phase zone falls continuously. This reduction along the radius of the ingot is evidently the reason for the increase of the secondary dendrite arm spacing [12]. An appropriate way to evaluate the solidification structure is the analysis of the secondary dendrite arm spacing. Desired microstructures are characterized by short distances between the dendrite arms. During the tests the dendrite arm spacing between the single experiments showed a slight increase of these distances with the rise of the mould cooling liquid outlet temperature (see **Figure 4**). This effect was more significantly detected in the middle of the ingot. This can be explained with the before mentioned effect that the energy remaining in the ingot rose with the increase of the cooling liquid outlet temperature due to the lowered cooling intensity. A higher mould outlet temperature induces a higher rest energy which leads to a lower temperature gradient in the solidification front resulting in higher dendrite arm spacing.

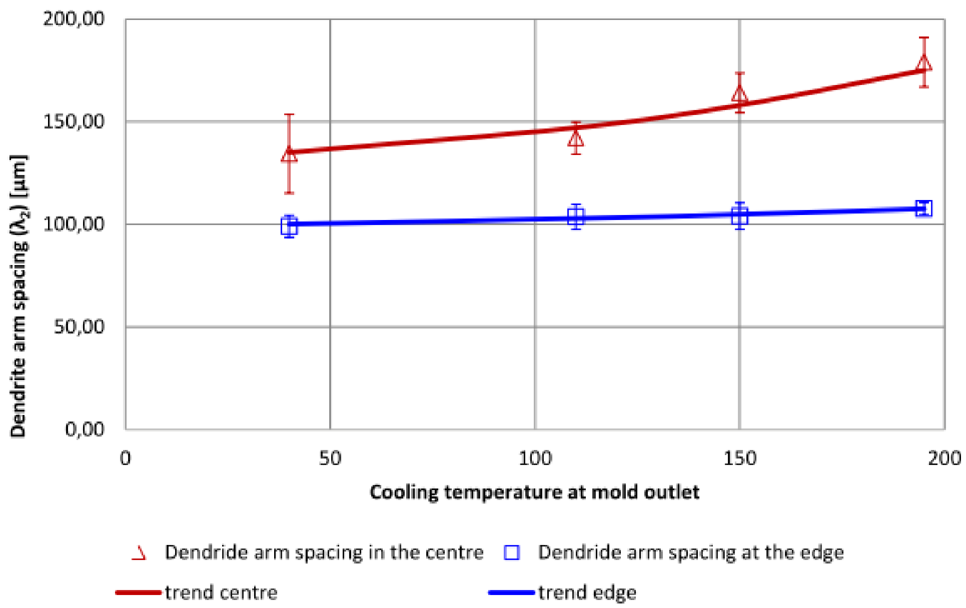

Figure 4: Secondary dendrite arm spacing as a function of the cooling temperature

2.3. Heat balance

According to [7] good average power efficiency during the ESR-operation is in the order of approximately 1300 kWh/t. Concerning these test trials the average power consumption was determined with 1292 kWh/t with a standard deviation of 16 kWh/t. This indicates that the tests all together were implemented on the one hand with very constant parameters and on the other hand in a quite efficient way. With regard to the energy distribution between the cooling energy dispensed to the bottom plate and the mould and the rest energy in the ingot, as can be seen in **Figure 5**, a slight decrease of the cooling energy during the test is recognisable. On the contrary the energy remaining in the ingot got nearly in the same way higher, so that ultimately no significant chance of the whole energy consumption could be noticed.

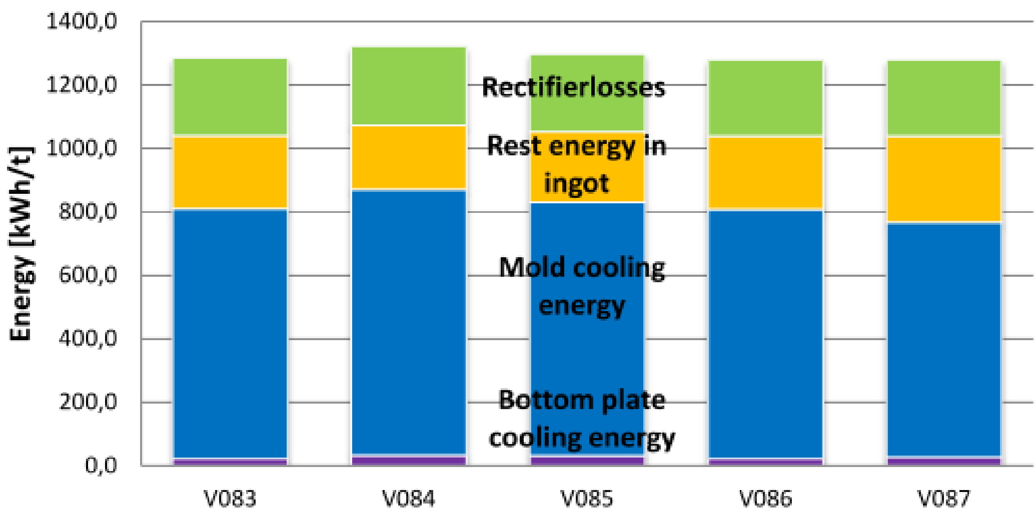

Figure 5: Energy distribution between bottom base plate, mould, ingot and rectifier losses

3. Summary, Conclusion and Outlook

The evaluation of the tests demonstrated that the impact of the temperature increase of the cooling media of the mould on the properties to be investigated was apparent. The most significant effects were monitored in terms of the surface quality. Whilst during the tests implemented with water as cooling media the surfaces were in a quite good condition but contained a lot of irregular depressions. With the implementation of the ionic liquid for the cooling and the resulting temperature increase, the depressions got significant fewer so that in the end in case of the last test the surface was smooth all over the entire ingot.
In the case of the melt pool depth, a dependence of the pool profile could be investigated. Higher temperatures lead to slightly deeper pool depth but also a tendency to a more “C-shape” pool profile could be recognized. Concerning the microstructure a statement in respect to the dendrite arm spacing with the cooling temperature could be given. Whereas at the areas closer to the surface of the ingots only a very small increase of the dendrite arm spacing was observed, in the areas in the centre they increased with the rise of the cooling temperature.
Concerning the energy balance it has to be said that the energy needed for the cooling of the mold decreased slightly and in response the remaining rest energy in the ingot increased almost in the same way. This is due to a storing effect of the energy in the ingot and the ionic cooling circuit.

Even though this series of tests displayed a definite answer, to deepen this knowledge a few more tests should be carried out. One aspect could be to decrease the range of the temperature of the ionic cooling liquid between the inlet and outlet of the mold and investigate how this affects the whole process. Also the potential of a possible energy recuperation due to the high temperature of the cooling media at the mould outlet shall be further investigate.

References

[1] Kubin M, Scheriau A, Knabl M, Holzgruber H, and Kawakami H 2013 *Proc. of LMPC* (Austin: J. Willey Pub)
[2] Hoyle G 1979 *Proc. of 6th Vacuum Metallurgy Conference*, p. 624
[3] Cameron, J.; Etienne, M.; Mitchell, A. Metallugical Transactions vol. 1 issue 7 July 1970. P. 1839-1844 “Some electrical characteristics of a DC electroslag unit
[4] Bell, M. Mitchell, A. “Some observations on the surface quality of electroslag ingot” Journal of the Iron and Steel Institute, Vol, 209, Part 8, (Aug., 1971), 658-670
[5] Kharicha A., Karimi Sibaki E., Wu M., Ludwig A.: Liquid Metal Processing & Casting Conf. 2013 (LMPC 2013) Sept. 22-25, Austin, Texas (2013) pp. 95-99. “Contribution of the mould current to the ingot surface quality in the electroslag process”
DOI: 10.1002/9781118830857 .ch13
[6] Melberg, P.O., Proc. 4th Int. Symp. On ESR Processes, ISIJ, Tokyo, 1973, p. 13-25. “Temperature distributions in slag and metal during electroslag remelting of ball-bearing steel”
[7] Mitchell A, and Smailer R M 1979 *International Reviews* **5** p. 231
[8] Holzgruber W 1975 *Radex Rundschau* **3** p. 409
[9] K O Yu 1986 *Journals of Metals* **38** 1 p. 46
[10] Kou S, Poirier D, and Flemmings M C 1977 Proc. *of Electric Furnace Conference* **35**, p.221
[11] Thielmann R, and Kreyenberg J 1985 *Proc. of 8 th ICVM Special melting/refining and metallurgical coating under vacuum or controlled atmosphere*, p. 1130
[12] Bordin I P, Goryainov V A Koshman V S, Zaitseva L A, and Tsapaeva L L 1985 *Steel in the USSR* **15** p. 533