The Newest Gereration of the ESR (Electro Slag Remelting) Unit with Rotating Electrode Function Desigend by SMS Mevac GmbH

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Abstract

One of the key parameter of the ESR process is the melt pool formation respectively accurate crystallisation speed with thin slag thickness (like the skin of the snake) on the surface of the remelted ESR ingot by defined melt rate.

These fundamental parameters detemine the mechanical and technological characteristics of the the "isotropic" materials for industrial products of supreme requirements.

The rotating electrode opens up the possibility of reduction of the melt pool volume during ESR process.

To examine the results of the rotating electrode during the ESR process, the atmospheric static mold ESR unit at the IME Institute for Process Metallurgy and Metal Recycling at RWTH Aachen University was redesigned by SMS Mevac GmbH from the vertically-oscillating function to a rotating and vertically-oscillating function.

1. Introduction

Tertiary metallurgy units produce economically, reliable and cost-effective of the "isotropic" materials for industrial applications of highest demands. These materials will be applied especially by industries such as air-and aerospace, power and energy, automotive as well as oil and gas. The core units of the tertiary metallurgy are **VIM** (Vacuum Induction Melting), **ESR** (Electro Slag Remelting) and **VAR** (Vacuum Arc Remelting) units.

1.1 VIM (Vacuum Induction Melting) unit is employed in the production of ultra-clean metals, speciality steels, superalloys and NF metals.

The key components of the unit include a melting chamber equipped for melting under vacuum with integrated MF-power supply, the charging equipment, a casting chamber and a launder exchange chamber. All the chambers are connected to the vacuum pump system.

Features and benefits of the VIM unit

- Evaporation of undesired trace elements
- Melting in an oxygen-free atmosphere avoids the oxidation of elements with strong oxygen affinity
- Massive degassing of crude materials
- Attainment of very close analysis tolerances (PPM range)
- Removal of dissolved gases (O,N,H)
- Precise setting of the melting temperature and excellent homogeneity of the melt
- Casting of electrodes for remelting and semis for further processing

1.2 ESR (Electro Slag Remelting) unit involves the gradual and controlled melting of the lower end of a self-consuming ingot through a layer of molten slag. As the process continues, a purified ingot is built up in a water cooled mold. Being electrically conductive, the molten slag acts as a resistance heating element when high current is passed between the electrode and the mold.

1.3 Remelting takes place under inert gas (Ar, N2). The plant consists of two melting stations arranged at 90°. The remelting process is computer-controlled and takes place fully automatically.

Features and benefits of the ESR units:

No increase in hydrogen content and no core segregation
Controlled nitrogen contents, lowest sulfur contents and minimized non-metallic inclusions

- Excellent material properties
- Low melting loss caused by elements with affinity for oxygen
- Ingot diameters from 300 to 1,600 mm
- Ingot weights from 2.0 to 160 t

1.4 **VAR** (Vacuum Arc Remelting) unit involves the gradual and controlled melting of the lower end of a self-consuming ingot by electric arcing.

As the process continues, a purified ingot is built up in a water-cooled mold. The process takes place under vacuum. This ensures that the electric arc is stable at all times and oxidation of the remelt material is avoided. At the same time, volatile, non-metallic matter is removed and non-metallic inclusions are separated by flotation and solidify at the upper surface of the ingot.

Undesired elements with low evaporation temperature, such as Pb, Sb, Sn, are also removed. The VAR units are likewise designed with two melting stations arranged at 90°. The process is also computer controlled. Remelting takes place fully automatically.

Features and benefits of the VAR unit:

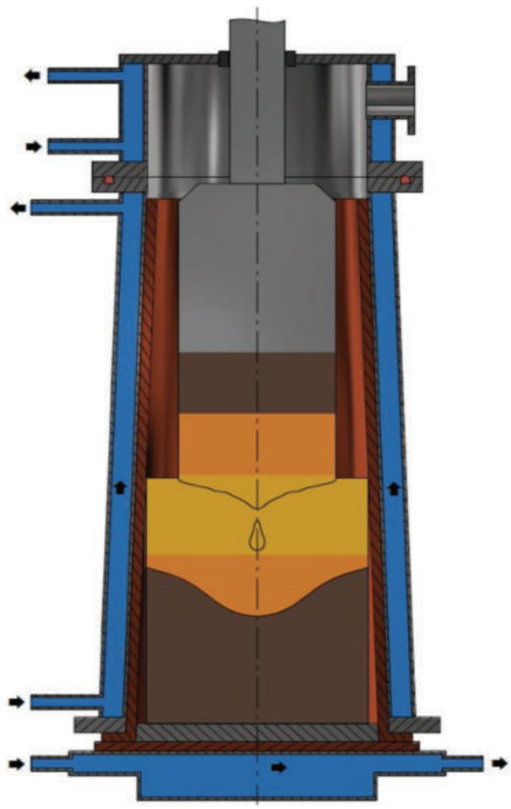
- Ultra-low gas contents and reduction of tramp elements
- Low degree of core micro segregation and low susceptibility to freckle formation
- High analysis accuracy
- Ingot diameters from 300 to 1,000 mm
- Ingot weights from 1.0 to 30 t

1.5 ESR-RE The latest generation of ESR allows the operation with rotating electrode. The volume of the melt pool is the main influencing parameter in both ESR and VAR processes determining the accuracy of crystallization speed and melt rate.

2. Fundamentals

The electroslag remelting (ESR) process is as a metallurgical method of refining metals making use of molten slag. The electrical power is converted into heat by the resistance of the slag which consequently heats up. The required heat is generated by the alternating current (AC) which flows from the electrode ram to the stub electrode through the slag, ESR ingot, finally to the copper plate [1-3].

Thereby the slag temperature rises above the melting temperature of the electrode alloy, the tip of the electrode melts and the film of molten metal crates into droplets,



being refined by contact with the liquid slag, before falling through the slag and collecting in a melt pool in the water-cooled copper crucible (**Fig. 1**).

Figure 1: Schematic of electro slag remelting

The crystallisation of the molten metal in correspondence with the melt rate is an important feature of the ESR process. It depends on power level, cooling rate of the cooper crucible, slag composition, the immersion depth of the electrode in the liquid slag respectively the thickness of the slag skin.
The thickness of the solid slag skin and the interface between the ingot and mould is demonstrated in **figure 2**[5].

Also the slag composition is very significant for the ESR process, it influences the [4];

- dissolution and absorption of impurities
- precipitation and growth of new impurities during solidification of the ingot
- encasing of the ESR ingot with thin slag skin

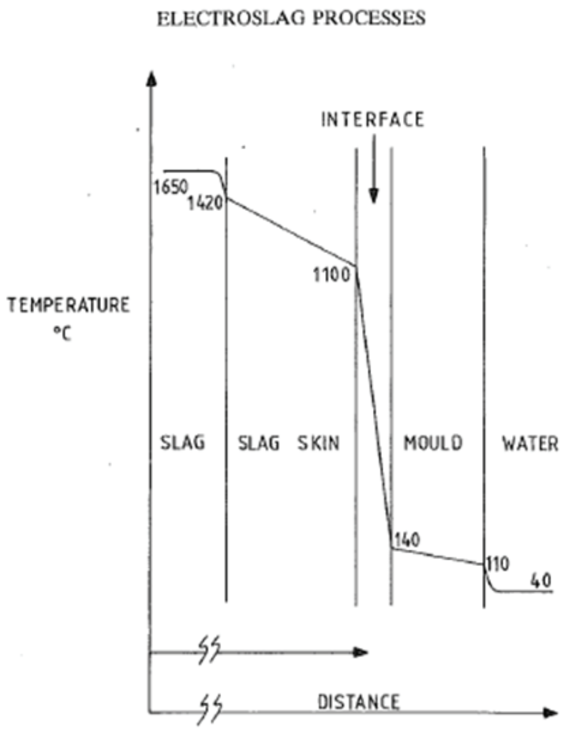


Figure 2: Temperature gradients in slag mould interface [5].

3. Electro Slag Remelting with a rotating electrode (ESR-RE)

Numerous publications of ESR studies deal with rotating electrode, and rotating crucible[6-11].
The differences of the two ESR processes with; (a) static electrode and (b) with rotating electrode are illustrated in figure 3[6].

The ESR process with a rigid electrode just moves down depending on the melt rate. The liquid slag creates metal droplets on the touching surface of the electrode top. The droplets sink by gravitational forces through the slag pool and crystallize the liquid metal pool to a "V-Form" in the water-cooled copper crucible.

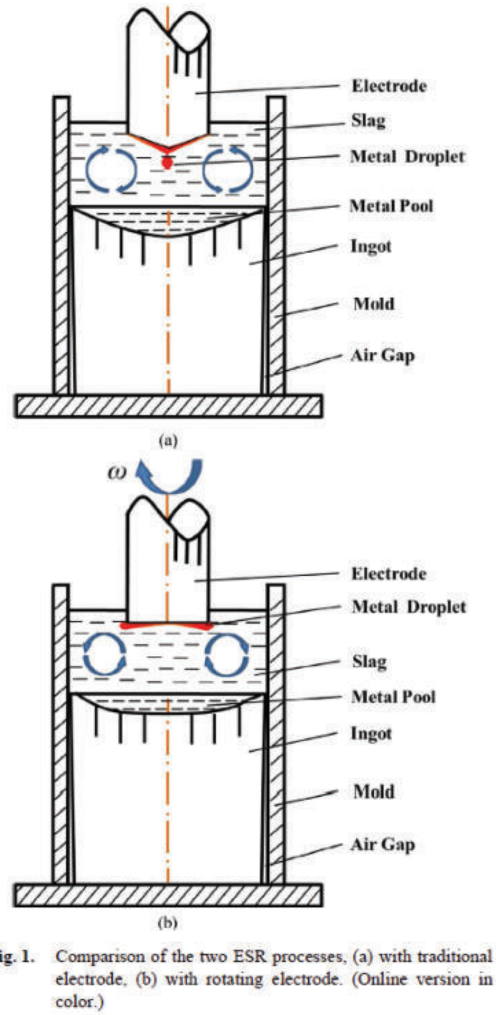


Figure 3: ESR processes with (a) rigid electrode and (b) rotating electrode [6]

The ESR process with a rotating electrode function has an electrode that rotates around its own vertical axis. The droplets from the touching surface of the electrode top in the liquid slag move by centrifugal force also horizontally. Thereby the number of the droplets increases with smaller sizes, sink through the liquid slag pool by gravitational forces and crystallize to a flat "U-Form" metal pool in in the water-cooled copper crucible.

The figure 4 presents a comparison of the metal droplets shape in the liquid slag pool and crystallisation profile of the melt pool in the water cooled crucible with a rigid electrode and a rotating electrode during ESR process.

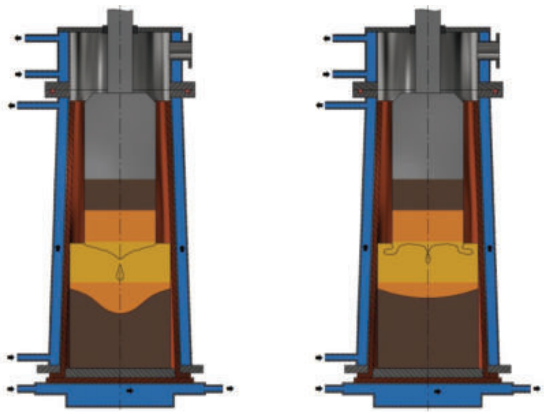


Figure 4: Shape of the melt droplets and pool profile with rigid (a) and rotating (b) electrode during ESR processes.

4. Experimental procedure

4.1. Experimental equipment

SMS Mevac redesigned the existing atmospheric ESR furnace at the IME Institute for Process Metallurgy and Metal Recycling, RWTH Aachen from a rigid electrode function to a rotating electrode function.

A new developed liquid gallium current collector device transmits power from a static ram onto a rotating electrode ram as shown in figure 5.

The variable-speed motor operates between 0 and 50 rpm and it can be up-scaled to 250 rpm. The rotating speed can be adjusted during the ESR process without interruption.

Table 1 shows the main technical parameters of the redesigned ESR unit.

Main technical data of the Electro-Slag-Remelting unit from IME Institute for Process Metallurgy and Metal Recycling, RWTH Aachen University	
Max. Power level	450 kW
Max. Current level	6 kA
Max. Voltage level	80 V
Frequenz	50 Hz
Max. Electrode dimension	Ø 110mm x 1400mm
Max. Mould dimension	Ø 160mm x 800mm
Operation mode	Atmospheric
Installted electrode rotating speed level#1	0-50 rpm
Optional designed electrode rotating speed level#2	0-250 rpm

Table 1: Main technical data of the atmospheric ESR furnace

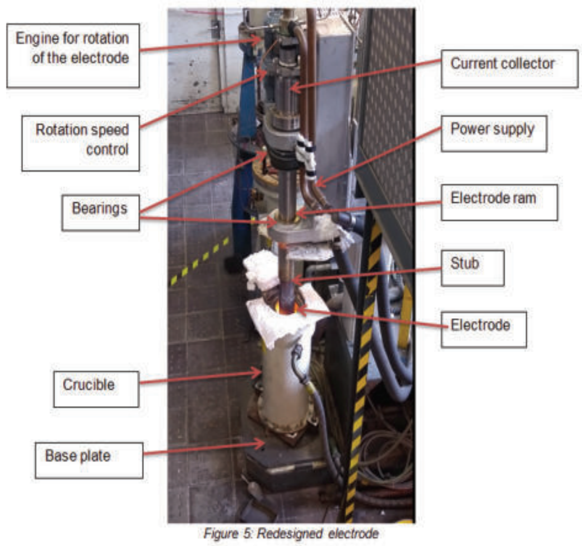


Figure 5: ESR-RE furnace at Institute IME/RWTH Aachen

5. Results and Discussion

After five initial function tests melts with rotating electrode, a number of experimental trials were executed with structural steel, S235JR / ST37-2 and tool steel, H13 / X40CrMoV5-1 / 1.2344. An inductive proximity sensor was used for measuring the rotational speed. A control system continuously recorded the speed of the ram. The premelted electroflux consisted of 70% CaF2 and 30% Al2O3 and was preheated up to 650°C before it was added manually into the crucible.

5.1. Experiments with structural steel, S235JR / ST37-2

The ESR process basically consists 3 phases: 1. Phase: The starting phase, 2. Phase: steady state phase and 3. Phase: the hottopping phase.

Two bars of structural steel were remelted as follows:

The process started with cold start and afterwards approx. 350mm (one third of the electrode length) were remelted without rotation. Then the electrode rotation speed started at 20rpm for the second third of the electrode length and finally the rotation speed was ramped up to 50 rpm in the last third of the electrode until 1050mm. The remelting process was finished without hottopping (**table 2**).

No	Grade	Slag	Average power	Average current	Average voltage	Average melt rate	Rotation per minute / ω (r/min)	Approx. electrode length
6	S235JR / ST37-2 structural steel	70%CaF2+ 30%Al2O3	110 kW	2,97 kA	35,77 V	0,91 kg/Min.	0 rpm	from 30 mm to 350mm
							20 rpm	from 351mm to 750mm
							50 rpm	from 751mm to 1050mm
7	S235JR / ST37-2 structural steel	70%CaF2+ 30%Al2O3	103 kW	3,02 kA	34,81 V	0,92 kg/Min.	0 rpm	from 30 mm to 350mm
							20 rpm	from 351mm to 750mm
							50 rpm	from 751mm to 1050mm
Analysis: C: max.0,17%, Si: max.0,30%, Mn: max.1,40%, P: max.0,045%, S: max.0,045%, N: max. 0,009%								

Table 2: Experimental schemes of the structural steel S235JR / ST37-2

5.2. Decreasing of the melt pool depth depending on the rotation speed

It was observed that the melt pool depth decreased exponentially with the increase of the electrode rotational speed (figure 6 and 7).

Heat 6: At 20 rpm electrode rotation speed, the melt pool depth decreased from 58 mm to 18 mm by 40 mm, i.e. 222% reduction of melt pool depth in the second third of the ESR ingot and at 50 rpm from 58 mm to 8 mm by 50 mm or 625% reduction in the last third of the ESR ingot in comparison with the first third of ESR ingot on non-rotating operation, Fig. 6).
Heat 7: At 20 rpm electrode rotation speed, the melt pool depth decreased from 57 mm to 18 mm by 39 mm, i.e. 217% reduction of melt pool depth in the second third of the ESR ingot and at 50 rpm from 57 mm to 9 mm by 48 mm or 533% reduction in the last third of the ESR ingot in comparison with the first third of ESR ingot on non-rotating operation, Fig. 7).

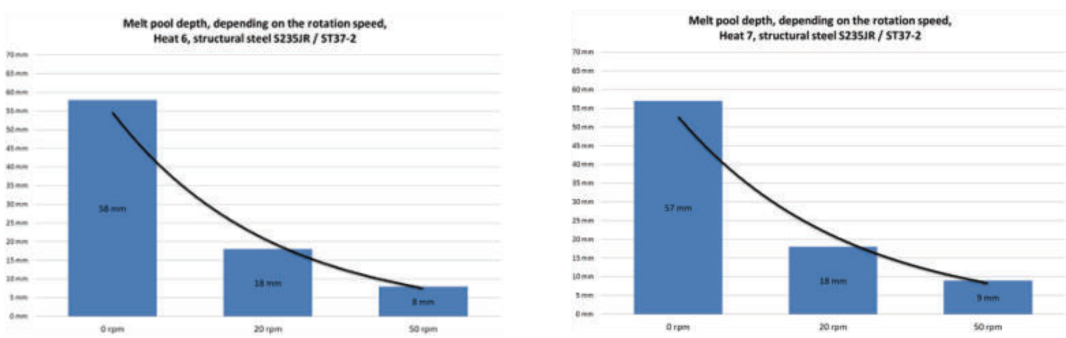


Figure 6 und 7: Melt pool depth, depending on the rotation speed, heat 6&7

5.3. The ESR remelting graph of the heat 6 and heat 7

The typical ESR remelting parameters of the heat 6 and heat 7 presents the **figure 8 and 9.**

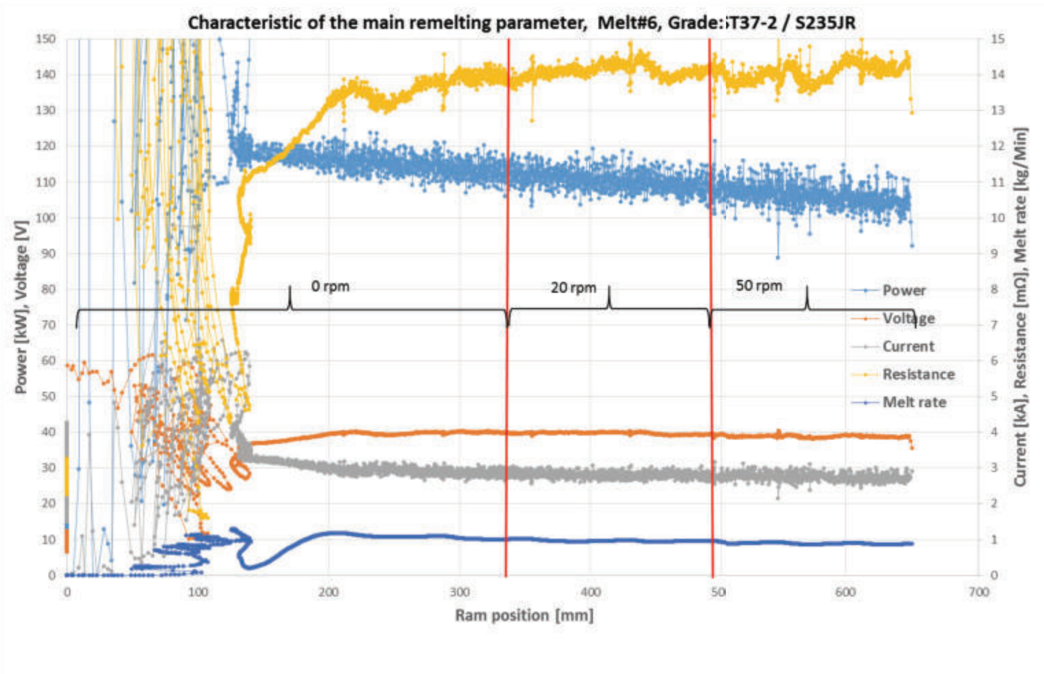


Figure 8: Typical ESR remelting parameter, heat6, grade: S235JR / ST37-2

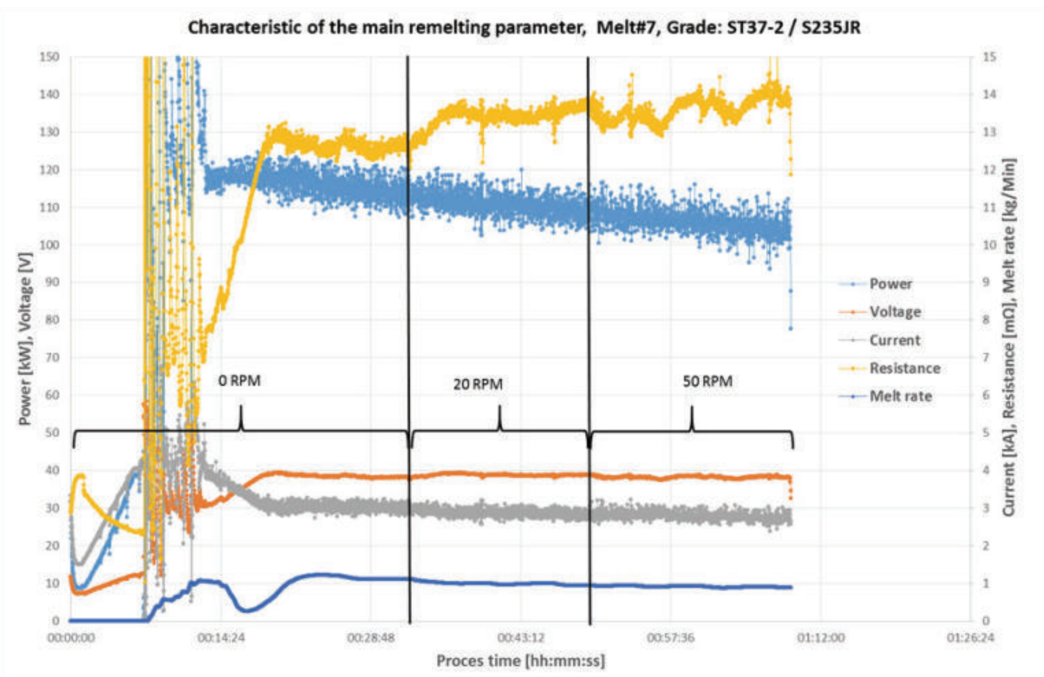


Figure 9: Typical ESR remelting parameter, heat 7, Grade: S235JR / ST37-2

5.4. Melt profile formation of the heat 6 and 7

The same ESR procedure is used with the heat 6 and 7 to compare und confirm the results. That means, the first third of the electrode length remelted with nonrotating electrode. The second third of the electrode remelted with 20 rpm and the last third with 50 rpm.

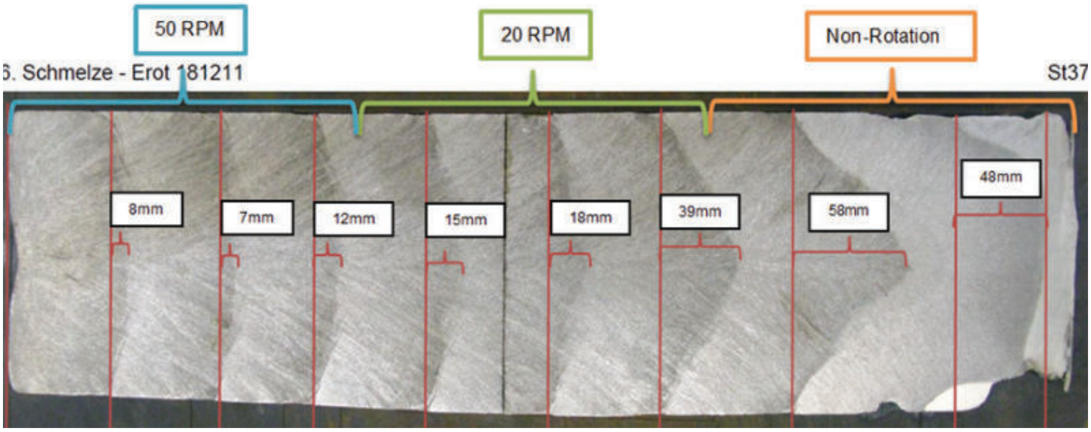


Figure 10: Melt pool profiles depending on the electrode rotation speed heat 6.

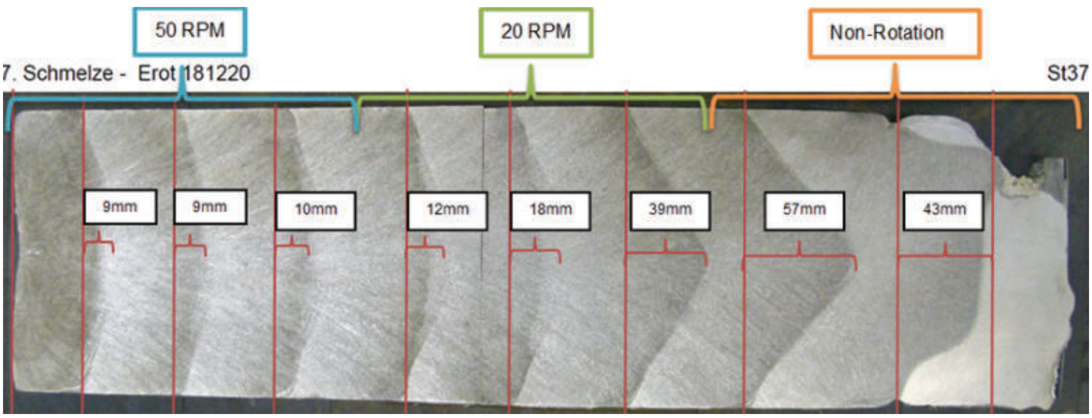


Figure 11: Melt pool profiles depending on the electrode rotation speed heat 7.

5.5. Melt pool decreasing dimension of the heat 6 & 7

There is no doubt, that the rotation of the electrode reduces the specific melt pool depth in comparison with a nonrotating electrode as follows (**table 3** and **figure 10&11**):

Rotation per minute (rpm) / ω (r/min)	Heat 6			Heat 7		
	Pool depth	Melt pool reduction		Pool depth	Melt pool reduction	
0 rpm	58 mm			57 mm		
20 rpm	18 mm	-40 mm	-222%	18 mm	-39 mm	-217%
50 rpm	8 mm	-50 mm	-625%	9 mm	-48 mm	-533%

Table 3: Rotation speed and melt pool dimension or reduction heat 6&7

6. Conclusion and outlook

1. SMS Mevac GmbH redesigned the atmospheric static mould ESR unit at the IME Institute for Process Metallurgy and Metal Recycling at RWTH Aachen University to an ESR unit with rotating electrode and with integrated vertically-oscillating function.

2. Two different steel grades, structural steel S235JR / ST37-2 and tool steel and H13 / X40CrMoV5-1 / 1.2344, have been remelted to study the influence of a rotating electrode during the ESR process.

3. It should be generally noted that rotation of the electrode during the ESR process substantially reduces the melt pool depth.

4. The rotating of the electrode creates slag thickness less than 1mm on the surface of the ESR ingots.

5. Significant melt pool decreasing (more than 500%) has been achieved by increasing the electrode rotation during ESR remelting of structural steel S235JR / ST37-2.

6. The melt pool reduction has been also reached with the tool steel and H13 / X40CrMoV5-1 / 1.2344.

7. References

[1] Plöckinger, E.: "Electroslag Remelting – a Modern Tool in Metallurgy", The twenty-third hatfield memorial lecture, 1972

[2] Hoyle, G. – "Electroslag Processes – Principles and Practice", Applied Science Publishers LTD, London & New York, 1983

[3] B. E. Paton and L. B. Medovar: Steel Transl., 2008, 38, 1028.

[4] A. Michel and S. Joshi, The thermal characteristics of the electroslag process, Met. Trans., 4 (March 1973) p. 631.

[5] Alec Mitchel, Ingot forum Pittsburgh 2005

[6] Chumanov, I. V. and Chumanov, V. I.: "Technology for electroslag remelting with rotation of the consumable electrode", Metallurgist Vol. 45, No. 3-4, 2001, p. 125 ff

[7] Chumanov, V. I. and Chumanov, I. V.: "Increasing the efficiency of the electroslag process and improving the metal quality by rotating a consumable electrode: Part 1", Russian Metallurgy (Metally), Vol. 2010, No. 6, 2010, p. 499 ff.

[8] Wang, Q. et al.: "Effect of Rotating Electrode on Magnetohydrodynamic Flow and Heat Transfer in Electroslag Remelting Process", ISIJ International, Vol. 54, No. 9, 2010, p. 2408 ff.

[9] Chang, L. et al.: "Effects of relative motion between consumable electrodes and mould on solidification structure of electroslag ingots during electroslag remelting process", Ironmaking and Steelmaking, Vol. 41, No. 8, 2014, p. 611 ff.

[10] Chang, L et al.: "Effects of Mould Rotation on Element Segregation and Compact Density of Electroslag Ingots during Electroslag Remelting Process", High Temperature Materials Processing, Vol. 34, No. 4, 2015, p. 469 ff.

[11] Chumanov, V. I. and Chumanov, I. V.: "Speed Control of Remelting in the Electroslag
Process by Changing the Rotation Speed Consumable Electrode", 2016 2nd International
Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM)