Results of the tool steel H13, which has been remelted with new generation ESR-REF (Electro Slag Remelting with Rotating Electrode Function) unit,

designed by SMS group GmbH/GER

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ABSTRACT

SMS group responds to the constantly increasing demands of the tool manufacturing industry continual innovations. The challenge was to choosing of the right innovation method for the development of the new generation of the ESR furnace, especially with the demand to reduce the melt pool depthless, to repress the carbide formation by accurate ingot crystallization during ESR process.

Furthermore, the methods defines a specific objective for the implementation

SMS group presents in this paper the innovation method ESR unit with rotating electrode function and implementation of this method for remelting of the tool steel grade H13 on the basis of the same principles of the conventional ESR process with rigid electrode.

To find out the influence of a rotating electrode during the ESR process, SMS Mevac GmbH redesigned the atmospheric rigid mold ESR unit at the IME Institute for Process Metallurgy and Metal Recycling at RWTH Aachen University: its vertically oscillating function has been changed to a rotating and vertically oscillating function.

This paper presents the results regarding the thinner slag skin, the molten metal pool formation for better crystallization accuracy, and the cleanliness of ESR ingots, which have been remelted with rotating electrodes.

1. INTRODUCTION

The increasingly stringent requirements for the quality of special alloys have led to the need for new technologies that can be assigned into the ESR process. These can be summarized for the ESR process as follow; reducing the melting pool depth, increasing of the droplets number and increase the reaction surface in the liquid slag by creating of smaller droplets due to forced horizontal centrifugal force. The droplets fall through the slag pool and shape a liquid metal pool in which the metal crystallizes with an orientated structure in a water-cooled copper crucible.

In order to investigate these ideas and to quantify the influence of a rotating electrode during the ESR process, the atmospheric rigid ESR unit at the IME Institute for Process Metallurgy and Metal Recycling at RWTH Aachen was successful re-designed by SMS group GmbH from rigid electrode to rotating and vertically oscillating functions.

This paper presents the results of the remelted tool steel, H13 / X40CrMoV5-1 / 1.2344 when a rotating electrode is used during the ESR process. The electrodes were remelted with the same parameters; 0 rpm, 20 rpm and 50 rpm (rotation per minute), to solidify a flat molten metal pool for better crystallization accuracy with the additional target to enhance the number of droplets to improve the cleanliness of ESR ingots without crystallization errors and segregation.

2. FUNDAMENTALS

Electroslag remelting process (ESR) is a metallurgical refining process designed to improve the cleanliness of the alloy, optimize crystallization and remove segregation by inserting the electrode into the liquid slag in the water-cooled copper crucible. The alternative current (AC) flows from the electrode through the slag and ESR ingot to the crucible copper plate. The electrical energy is converted into joule heat by the resistance of the slag, which heats up [1-3]. The top of the electrode in the liquid slag begins to melt and creates a metal droplet that drips through the slag due to its relative density differences. The refined molten metal begins to crystallize from the mould wall to the mould center (**Figure 1**).

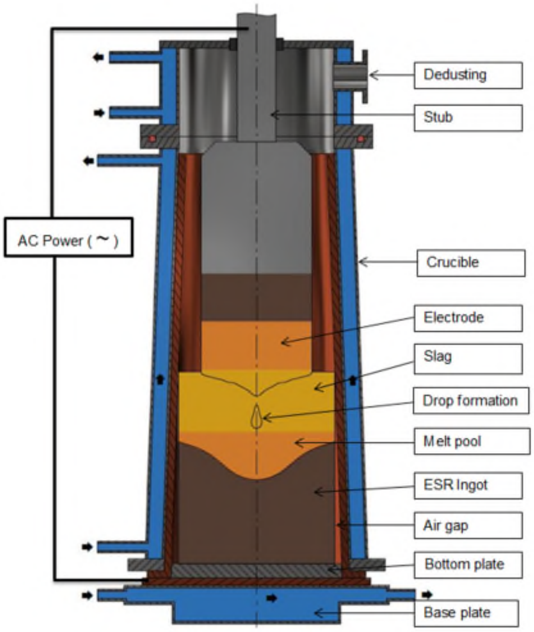


Figure 1: Schematic of electro slag remelting

An optimal ESR process requires a slag composition that should be compatible with the liquidus temperature of the steel grade. Slag plays an important role in the ESR process; its functions are[4];

• Resolution and absorption of impurities
• Impurities separation
• Sheathing of the ESR ingot with thin slag skin from bottom to the top

ESR process mainly are defined within the ternary slag components; calcium fluoride, Calcium oxide and alumina system. This identifies a range of slags with different content of the components liquidus temperatures in the range 1350-1500°C (**figure 2**), which makes them suitable for melting a wide range of alloys including steels and superalloys, i.e. the main subjects for ESR[3].

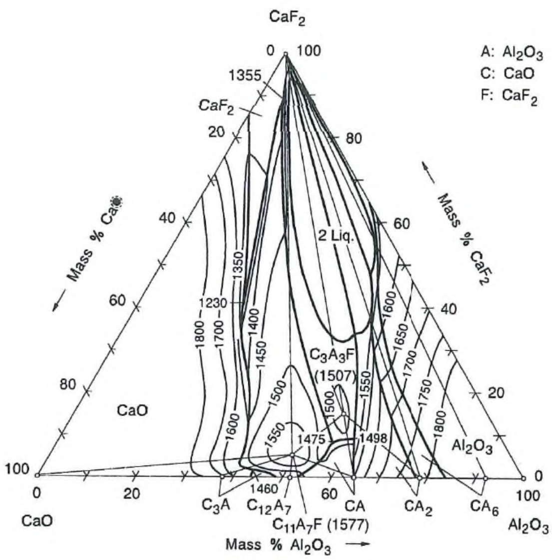


Figure 2: Liquidus surface in the Al_2O_3-CaF_2-CaO system after Chatterjee, Zhmoidin[6] (sealed samples). For liquidus relation in numerous sub-systems, see also Chatterjee, Zhmoidin[7], Smirov et al[8] and Zhmoidin, Chatterjee [9].

The binary calcium fluoride and aluminum oxide (70% fluoride, 30% alumina, **figure 3**) are used with the experiments grade H13 / X40CrMoV5-1 / 1.2344 to desulphurise the heats and to show the melt pool formation with additional adding of iron sulphide in a defined times (**figure 9&10**).

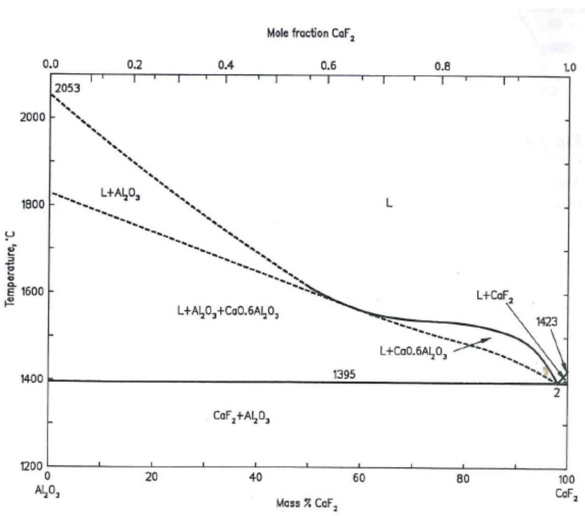


Figure 3:Al_2O_3-CaF_2:Pseudo-binary system in a sealed cell after Chatter Catterjee, Zhmoidin[6] and Povolotski et al[10] and Ries, Schwerdtfeger[11]. The thermodynamics of the system and calculated phase diagram were reported by Zaitsev et al[12]

The special design and programming philosophy of the ESR control systems from the ESR furnace design companies is reaching the process properties limits, e.g. : The melt rate respectively the feeding speed in combination with the power level and the immersive depth control of the electrode in the liquid slag act on the formation of melting pool and slag skin.

The requirements for improvements in the mechanical and technological properties of special steels and superalloys are increasing, which, combined with the high cost of a remelted metal, requires new technical innovations in the current ESR furnace design. The challenge is to melt the ESR ingots cost-effectively and error-free and keep the melting pool flat. In order to meet this challenge, SMS group GmbH has re-designed the existing rigid mould ESR furnace at the Institute IME of the University RWTH Aachen into an ESR furnace with rotating electrode ram.

This development based on the electrode, which rotates around its vertical axis and oscillates up and down.

3. ELECTROSLAG REMELTING WITH ROTATING ELECTRODE

There are specialist literatures available that describe various ESR studies with [13-18]:

• rotating electrode and
• rotating crucible

The important differences between the two ESR processes with; (a) rigid electrode and b) with rotating electrode are shown in **figure 4**[13].

The standard ESR process with a rigid electrode simply moves downwards according to the remelting speed rate. The metal droplets are removed from the touching surface of the electrode tip in the liquid slag. These sink through gravitational forces through the slag and produce the "V-shape" of the liquid metal pool as they crystallize in the water-cooled copper crucible.

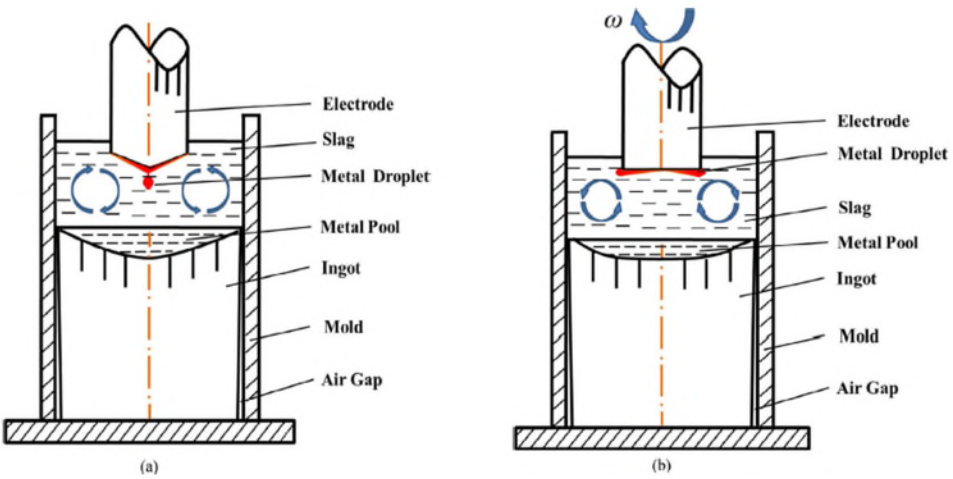


Figure 4: ESR processes with (a) rigid electrode and (b) rotating electrode [13]

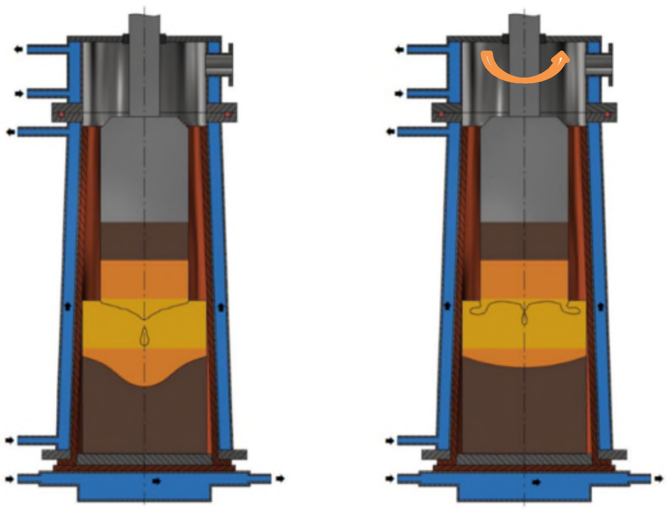
The ESR process with a rotating electrode, as the name states, has an electrode that rotates around its own vertical axis. The rotation radially implements a centrifugal force that moves the metal droplets horizontally from the touching surface of the electrode tip in the liquid slag.

The tip of the electrode retains a flat shape as the smaller droplets are on the side. The droplets sink through the liquid slag due to gravitational forces and metal pool form in a shallow "U-shape" in the water-cooled copper crucible.

In comparison to the two remelting processes, the following explanation can be given (**figure 5)**:

A centrifugal force is pushed in the radial direction and moves the metal droplets horizontally over the touching surface of the electrode top during the ESR process with a rotating electrode. It creates a flat shape above the electrode tip by increasing the number of smaller droplets compared to the remelting process with a rigid electrode.

Figure 4 shows the formation of the metal droplets in the liquid slag and the solidification shape of the melt pool in the water-cooled crucible during the ESR process with a rigid electrode and a rotating electrode.



a) **b)**

Figure 5: Detachment of the melt droplets and pool shape solidification with rigid (a) and rotating (b) remelting processes.

4. EXPERIMENTAL EQUIPMENT

SMS group has redesigned the existing atmospheric ESR furnace at the IME Institute for Process Metallurgy and Metal Recycling, RWTH Aachen, from a rigid electrode ram to a rotating electrode ram with a new designed and developed current collector system based on liquid gallium. This system transfers power from a rigid ram to a rotating electrode ram, as shown in **figure 6**. The speed motor is designed for operation between 0 and 50 rpm, the speed can be fixed or dynamically adjusted during the ESR process. It has also a design option to spped up to 250 rpm. The main technical parameters of the ESR furnace are shown in **Table 1**.

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

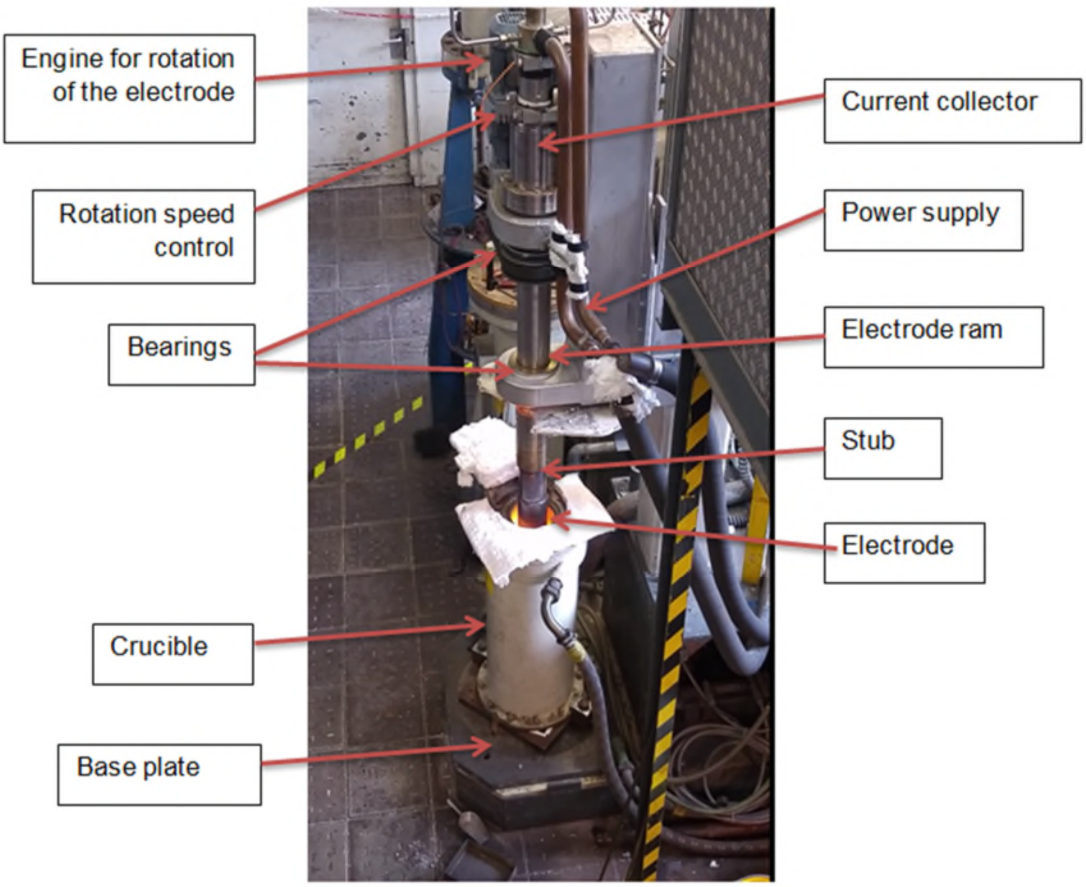


Figure 6: Redesigned ESR furnace at Institute IME/RTH Aachen

5. EXPERIMENTS

Six electrodes of toll steel grade H13 / X40CrMoV5-1 / 1.2344 were remelted in atmospheric static mould according to table 2 to determine the influence of a rotating electrode during the ESR process. The ramming speed was automatically measured, controlled and recorded. A speed monitoring system based on an inductive proximity sensor is used to check the speed monitoring of the electrode ram. The chemical composition of the pre-melted ESR slag consist of 70% CaF2 and 30% Al2O3 and was preheated up to 650°C.

6.1 EXPERIMENTS TOOL STEEL H13 / X40CRMOV5-1 / 1.2344

The six electrodes of the grade H13 / X40CrMoV5-1 / 1.2344 were remelted and the same ESR recipe. That means

1. Cold start, 2. Ramped up to the steady state phase and 3. End of the remelting process without hottopping and with the same ESR parameters, e.g. power level, slag composition, melt rate, feeding speed and filling ratio, etc. (**Figure 7&8**). For the visualizing of the melt pool profiles in the different phases iron sulphide (FeS) is charged manually in a defined time intervals into the liquid slag.

6.1.1 THE ESR REMELTING GRAPH OF THE HEAT 1 AND HEAT 2

The characteristic of the main remelting parameters graphs of the melt 1 and melt 2 is shown in **figures 7 and 8.**

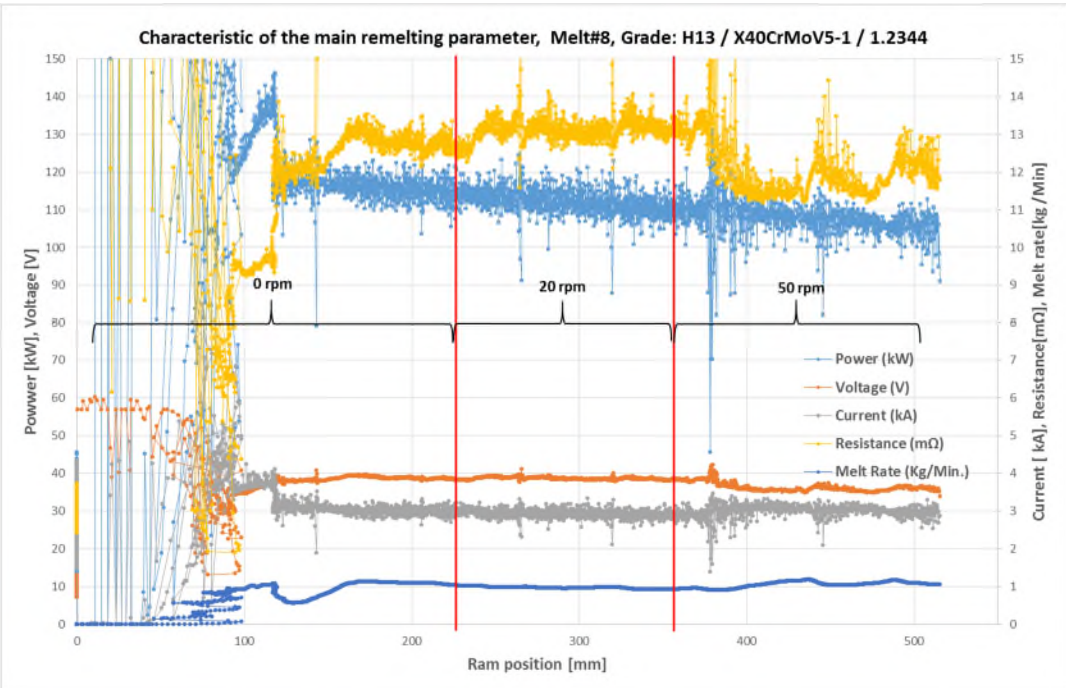


Figure 7: Characteristic of the main remelting parameter, Melt 1, Grade:H13/X40CrMoV5-1 /1.2344

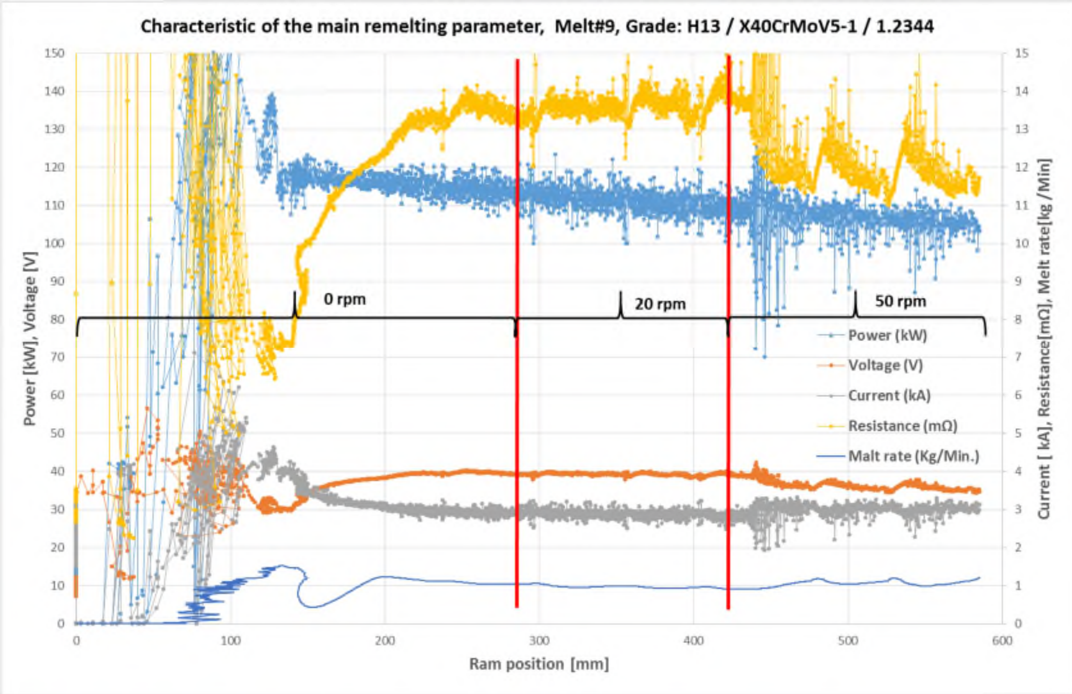


Figure 8: Characteristic of the main remelting parameter, Melt 2, Grade:H13/X40CrMoV5-1 /1.2344

6.1.2 MELT PROFILES OF THE HEAT 1 & 2

The ESR ingots of melts 1 and 2 were remelted with the same remelting recipe and parameters to verify and compare the results. This means that the first third of the electrode length was melted with a non-rotating (0 rpm) electrode or a rigid electrode. The second third of the electrode was remelted at 20 rpm and the last third at 50 rpm.

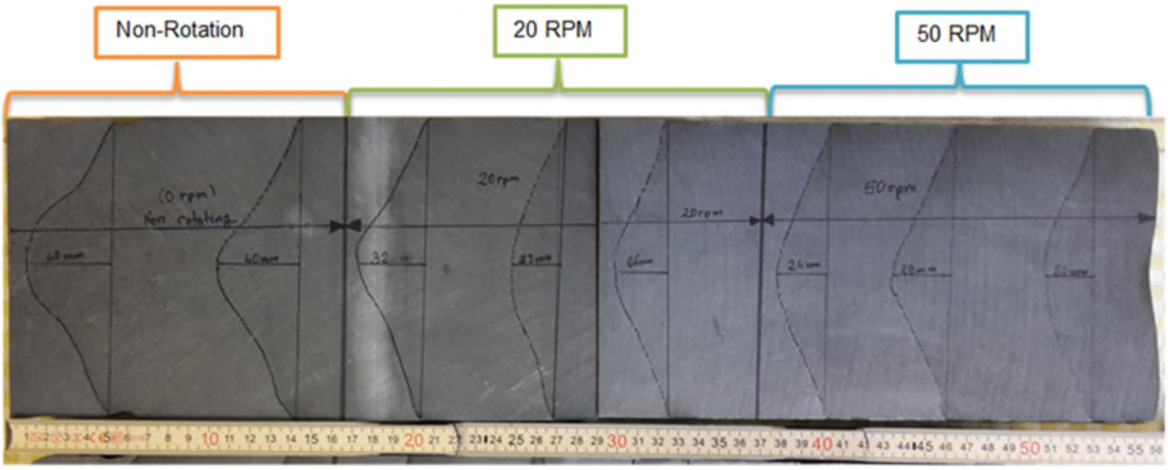


Figure 9: Melt pool profiles depending on the electrode rotation speed, heat 1.

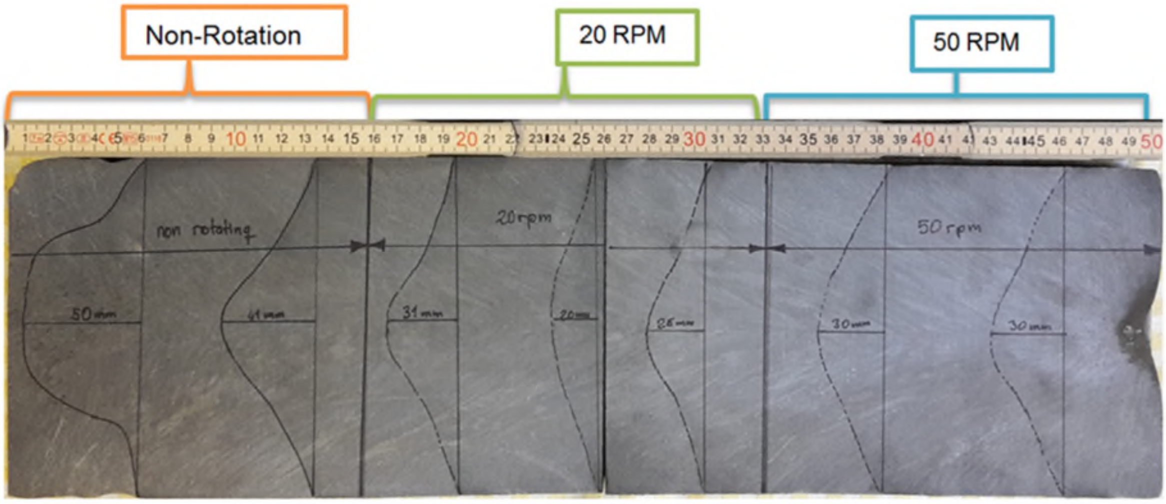


Figure 10: Melt pool profiles depending on the electrode rotation speed, heat 2.

6.1.3 MELT POOL DIMENSION AND REDUCTION OF THE HEAT 1 & 2:

It can be demonstrated, that rotating the electrode during the ESR process reduces the melt pool of the tool steel grade H13 in comparison with the nonrotating part as well (table 5):

Rotation per minute (rpm) / ω (r/min)	Heat 1			Heat 2		
	Pool depth	Melt pool reduction		Pool depth	Melt pool reduction	
0 rpm	50 mm			43 mm		
20 rpm	20 mm	-30 mm	-190%	23 mm	-20 mm	-148%
50 rpm	30 mm	-20 mm	-93%	29 mm	-14 mm	-97%

Table 2: Rotation speed and melt pool dimension or reduction heat 1 & 2

6.1.4 INTERPRETATION OF THE RESULTS HEAT 1&2

Heat 1: At a rotational speed of 20 revolutions per minutes, the melt pool shrinks from 50 mm to 20 mm, which in the second third of the ESR ingot is -30 mm or -190% compared to the non-rotating part. In the last third of the ESR ingot at 50 revolutions per minute, the melt pool depth decreased from 50 mm to 30 mm, which means -20 mm or 93% reduction.

Heat 2: At a rotational speed of 20 revolutions per minutes, the melt pool shrinks from 43 mm to 23 mm, which in the second third of the ESR ingot is -20 mm or -148% compared to the non-rotating part. In the last third of the ESR ingot at 50 revolutions per minute, the melt pool depth decreased from 50 mm to 29 mm, which means -14 mm or 97% reduction.

The melt pool further increasing in the last third of the ESR ingots were grounded on the massive change of the rotation speed, from 20 rpm to 50 rpm in a very short time, (fraction of the seconds), the electrode speed control system could not regulate the immersion of the electrode in the slag with such a high variation.

6.1.5 EXAMINATION OF THE MICROSTRUCTURE ACCORDING TO SEP 1614,

All the samples have been investigated in the industrial laborites at the company DEW in Germany and completely samples have a fine, well-dissolving structure with weak edges from the edge to the core dendritic structure. The intensity of the carbide network from the edge to the core has been investigated. At the edge and transition are carbide network residues with fine primary carbides and the grain size corresponds to DIN EN ISO 643 (**Figure 11**).

Figure 11: Examination of the microstructure

6.1.6 ELEMENT DISTRIBUTION AND SEGREGATION OF C, CR, V AND MO

The ESR ingots number 3, 4, 5 and 6 were forged from 160mm to 92mm diameter and spread over the entire length - each at a distance of 200 mm - six discs. These have been halved for element distribution images and examined in the longitudinal direction.

The backscatter electron images (CP) represent the lattice orientation of the grains by channeling the channeling effect. Most CP images show a fine-grained structure and there are not noticeable element distribution and segregation of the elements C, Cr, V and Mo.

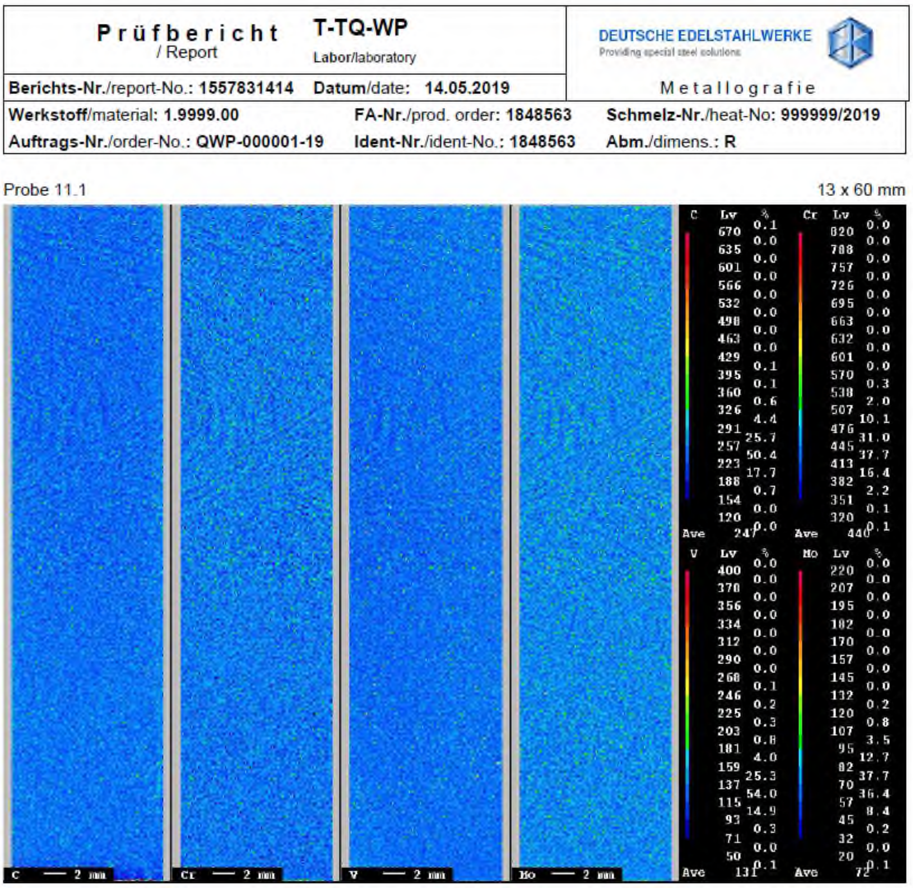


Figure 12: Element distribution and segregation C, Cr, V and

Table 3: Experimental schemes H13 / X40CrMoV5-1 / 1.2344								
No	Grade	Slag	Average power	Average current	Average voltage	Average melt rate	Rotation per minute (ω)	Approx. electrode length
1	H13 / X40CrMoV5-1 / 1.2344	70%CaF2+ 30%Al2O3	105 kW	3,01 kA	35,08 V	1,01 kg/Min.	0 rpm	from 30 mm to 350mm
							20 rpm	from 351mm to 750mm
							50 rpm	from 751mm to 1050mm
2	H13 / X40CrMoV5-1 / 1.2344	70%CaF2+ 30%Al2O3	112 kW	3,03 kA	34,63 V	0,97 kg/Min.	0 rpm	from 30 mm to 350mm
							20 rpm	from 351mm to 750mm
							50 rpm	from 751mm to 1050mm
3	H13 / X40CrMoV5-1 / 1.2344	70%CaF2+ 30%Al2O3	110 kW	3,12 kA	33,79 V	1,14 kg/Min.	0 rpm	from 0 mm to 1050mm
4	H13 / X40CrMoV5-1 / 1.2344	70%CaF2+ 30%Al2O3	104 kW	3,03 kA	32,87 V	1,20 kg/Min.	20 rpm	from 0 mm to 1050mm
5	H13 / X40CrMoV5-1 / 1.2344	70%CaF2+ 30%Al2O3	104 kW	3,21 kA	32,39 V	1,32 kg/Min.	50 rpm	from 0 mm to 1050mm
6	H13 / X40CrMoV5-1 / 1.2344	70%CaF2+ 30%Al2O3	108 kW	3,20 kA	32,87 V	1,18 kg/Min.	0 rpm	from 30 mm to 350mm
							20 rpm	from 351mm to 750mm
							50 rpm	from 751mm to 1050mm
Analysis: C: 0,4%, Si: 1,0%, Mn: 0,4%, P:<0,03%, S:<0,03%, Mo: 1,4%, V: 1,0%,								

Table 3: Experimental schemes of the tool steel H13 / X40CrMoV5-1 / 1.2344 with key ESR remelting parameter

6. CONCLUSION AND OUTLOOK TOOL STEEL, H13 / X40CRMOV5-1 / 1.2344

1. The atmospheric rigid form ESR unit at the IME Institute for Process Metallurgy and Metal Recycling at RWTH Aachen University has been redesigned by SMS Mevac GmbH to include a rotating electrode function with vertical function.

2. It can be generally pointed out that the rotation of the electrode during the ESR process significantly reduces the depth of the meltwater.

3. The slag skin thickness on the surface of the ESR ingots was less than 1 mm when the rotating electrode was used at speeds of 20 revolutions and 50 revolutions.

4. The maximum reduction in meltwater depth was achieved at 20 rpm; from 50 mm to 20 mm, i.e. 30 mm or -190% melt pool reduction.

5. The depth reduction of the melt pool is lower with 50 revolutions of 50 revolutions min, in the last third of the ESR ingot from 23 mm to 29 mm. However, the rotational speed of 50 revolutions also reduced the melting pool from 43 mm to 29 mm, i.e. 114 mm or -97% reduction of the melting pool compared to the non-rotating first third.

6. The average power level (from start to finish) is 110kW without rotation and reduced from 50 revolutions to 104 kW at 20 revolutions and 50 revolutions. This is 6kW or 5% less power when a rotating electrode is used for ESR remelting.

7. The specific melt rate increase:

   with 20 rpm to 5.3%, from 1.14kg/min to 1.20kg/min and
   with 50 rpm to 15.8%, from 1.14kg/min to 1.32kg/min. compared to the non-rotating ESR electrode meltdown.

In the end, the rotating electrode ESR remelting resulted in lower energy consumption and higher melting rates when the electrode is melted with a rotating ESR electrode.

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