ELECTROSLAG REMELTING: A PROCESS OVERVIEW

ELEKTROPRETALJEVANJE POD ŽLINDRO – PREGLED PROCESA

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The electroslag remelting process (ESR) is important because it provides better control of the solidification microstructure and chemical homogeneity; it also enables greater cleanliness and better mechanical properties. The manufactured high-alloyed steels and other alloys with a controlled chemical composition are used in aerospace, in thermal- and nuclear-power plants, in chemical engineering, for military equipment, special tools, etc. An overview and the basics of the ESR process are presented in this paper.

Keywords: electroslag remelting, solidified microstructure, chemical homogeneity, clean steel

Postopek elektropretaljevanja kvalitetnih jekel pod žlindro (EPŽ) ima velik pomen zaradi sposobnosti nadzora strjevalne strukture in kemijske homogenosti saj postopek omogoča doseganje večje čistosti jekla in boljše mehanske lastnosti. Tako izdelana visokolegirana jekla, in zlitine z garantirano kemijsko sestavo in lastnostmi, se namensko uporabljajo v letalstvu, termoelektrarnah in jedrskih elektrarnah, v kemični industriji, v medicini, za vojaško opremo, za specialna orodja, itd. V prispevku so opisane osnove tehnologije pretaljevanja zlitin pod žlindro.

Ključne besede: elektropretaljevanje pod žlindro, strjevalna struktura, kemijska homogenost, čisto jeklo

1 INTRODUCTION

Nowadays, steelmaking technology enables the production of high-purity steel melts. However, during ingot casting the reoxidation of the melt occurs, thus increasing the inclusion content. Segregations on the macro and micro scales are also characteristic for ingot casting. These cause anisotropy in the mechanical properties of the steel. The ESR process almost completely removes the macro-segregation phenomenon in heavy steel ingots, thus ensuring a more homogeneous chemical composition and a finer microstructure with fewer and more evenly distributed non-metallic inclusions than in cast ingots.[1] The influence of ESR on remelted steel is shown in **Figure 1.**[2] This is why the ESR process is essential for heavy steel ingots that are used for the manufacturing of large generator and turbine shafts.[3]

The ESR process is suitable for high-quality materials such as:

- steel ball bearings, steel rollers, tool steels, wear-resistant steels for low and high working temperatures, high-speed steels for high performance,
- highly alloyed stainless steels, corrosion- and acid-resistant steels and steels for high-temperature applications,
- steels for aviation and aerospace technology, for medical, pharmaceutical and chemical industries,
- Ni superalloys, Ti and Zr alloys for aerospace, medical and chemical industry, components,
- off-shore, power and aerospace engineering, reactor comp.

ESR is a continuous process, where during the remelting of the consumable electrode, refining and solidification of the steel occur simultaneously. Cast, rolled or forged ingots can be used as a consumable electrode.

The ESR process is based on an electrical current running via an electrode through the molten slag and ingot. Due to the high electrical resistance of the slag, the slag heats up and melts. The consumable electrode is immersed in the liquid slag where the slag heat gradually melts the tip of the electrode. Liquefied steel is dripping

	Worse	Same	Better	Much better
Quality of ingot				
Surface				
Porosity, density				
Yield of metal				
Chemical composition				
Basic elements				
Hydrogen				
Oxygen				
Sulfur				
Oligoelements				
Degree of purity				
Microscopic				
Macroscopic				
Structure of ingot				
Block segregation				
Crystal segregation				
Mechanical properties				
Hardness				
Tensile strength				
Toughness				
Isotropy				

Figure 1: Effect of ESR on the properties of remelted steels[2]
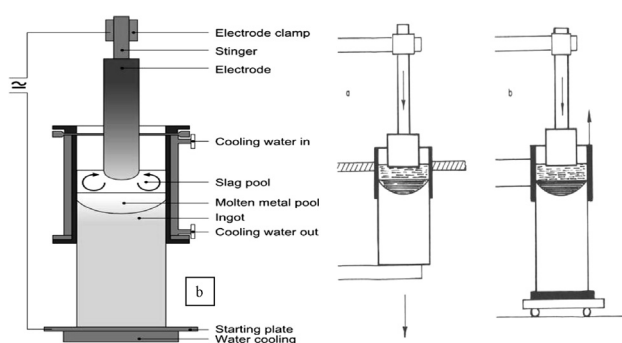**Slika 1:** Vpliv ESR na lastnosti pretaljenih jekel[2]

Figure 2: Schematic representation of the ESR unit: a) retracting ingot, b) rising mould[5,6]
Slika 2: Shematski prikaz ESR naprave: a) navzdol vlečen ingot, b) dvigajoča kokila[5,6]

from the electrode tip and is refined when passing through the liquid slag, with oxides and sulphur being bound in the slag. After passing through the slag, the steel cools down and solidifies again into a remelted ingot.[3,4] The whole remelting process takes place in a water-cooled copper mould, which allows the remelted ingot to solidify quickly and very uniformly.

The mould with the slag pool is moving upwards as the new ingot is formed. The design of the mould can be in the form of fixed long moulds or collar-type moulds. The use of collar-type moulds with movable moulds or a movable base plate, gives the possibility of producing ingots of any required length (**Figure 2**).[5,6] Furthermore, the ESR enables the production of ingots with the desired shape, i.e., round, square, rectangular.

In Slovenia, among other steelmaking processes, ESR technology is used in the Metal Ravne steelworks.

2 ATMOSPHERE CONTROL

Due to the ever-increasing demands for material properties, different variations of the ESR process were developed to ensure these demands.[6–8]

IESR (electroslag remelting under a protective atmosphere of inert gas at atmospheric pressure) is a variation of the ESR where an inert gas (argon) protects the slag and metal from oxidation and the absorption of nitrogen and hydrogen from the air. The oxidation of the electrode is almost entirely avoided, thus providing better cleanliness of the ingot. However, due to the absence of oxygen in the furnace atmosphere, desulphurization is not optimal.

PESR (electroslag remelting under increased pressure) is a variation of the ESR with an increased pressure of nitrogen and the melt solidifies under pressure. In this way a large amount of nitrogen can be introduced into the steel melt. The pressure depends on the alloy composition and the desired nitrogen content in the remelted ingot.

VAC-ESR (electroslag remelting under vacuum) is a variation of the ESR that provides vacuum degassing of

the melt. Dissolved gases such as hydrogen and nitrogen are removed, and the remelted metal is protected from oxidation. The process is suitable for the remelting of superalloys and titanium alloys.

3 PROCESS PARAMETERS

The heat required to run the ESR process is generated by the Joule effect in the slag bath. The electrical characteristics, heat balance and electrode/ingot diameter, influence the quality of the remelted ingot.[7,9] An energy input of between 1000 kwh/t and 1500 kwh/t of steel is usually required for ESR. The slag bath is considered to be a variable resistor, whose resistance is determined by the electrode distance, the effective slag resistivity and by the electrical current path. The usual slag depth is of the order of 100 mm.

The shape of the liquid pool is influenced by the heat input in the process.[10,11] The greater the distance between the consumable electrode and the remelted ingot, the smoother the heat distribution in the slag. When determining the electrode distance, it is important to take into consideration that a shorter current path means a higher current with concentrated heat generation under the electrode tip and an undesirable deepening of the metal pool. On the other hand, a longer current path demands a high voltage, which causes more even heat generation and a flatter, more favourable pool profile. ESR operating voltages are usually in the region of 40 V or less.

A choice of AC versus DC circuit ESR[9] is possible. For ingots of 20 cm in diameter or more, single phase AC gives optimum refinement and melt rate. The DC-ESR requires a lower melt rate for metal refinement. However, when the metal refinement is not the main criterion, the DC-ESR provides the highest melting rates per unit of power consumption. The present practice is to utilize a single-phase AC power supply and low electrode/ingot diameter ratio (0.4 to 0.7).[11] Typically, a frequency of 50 Hz or 60 Hz is used in AC operation. However, for the largest ingots, where reactivity becomes more important, it is better to use low-frequency power (5-10 Hz) for improved efficiency.

Optimum melting rates and energy inputs depend on the ingot diameter. A. S. Ballantyne and A. Mitchell[12] considered the optimum conditions for the maximum permissible melt rate at the lowest possible power with the Equation (1):

Melt rate = constant × power × fill ratio (area) ×
$$× \text{ mould area / electrode distance} \qquad (1)$$

Many operators considered melt rate as proportional to the ingot diameter, which is obtained at a melt rate of the order of 0.004 kg/min/mm.[7] The relationships between the melt rate, current and voltage for a 240-mm diameter ingot are shown in **Figure 3**. For a given
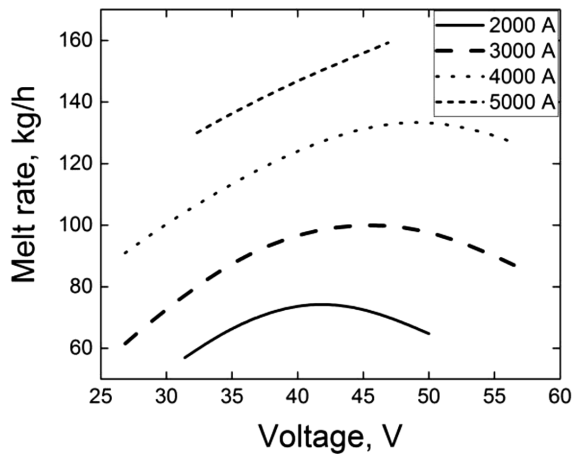
Figure 3: Effect of current and voltage on melt rates[7]
Slika 3: Vpliv toka in napetosti na hitrost taljenja[7]

current and ingot size there is an optional voltage that corresponds to a maximum melt rate.[7]

The ESR process can be controlled by a computer: from melt initiation, through power build-up, steady melt rate period, reduced melt rate period to maintain pool profile, hot-tapping sequences and melting termination.[13]

4 SLAG

The slag plays an important role in the ESR process; it generates Joule heat for the melting of the electrode, refines the liquid metal through the absorption of non-metallic inclusions, desulphurization, protects the metal from contamination, provides lubrication for the copper mould/solidifying steel shell interface, and controls the horizontal heat transfer between solidifying metal and mould.

Slags for ESR are usually based on calcium fluoride (CaF_2), lime (CaO) and alumina (Al_2O_3). Silica (SiO_2), magnesia (MgO) and titania (TiO_2) may be present, depending on the alloy to be remelted and refined. The CaF_2 content increases the solubility of basic components in the slag (CaO and MgO) and thus increases the effective sulphide capacity of the slag.[7] In order to perform its intended functions, the slag must have some well-defined properties, which are:

- its melting point must be lower than that of the metal to be remelted,
- it must be electrically efficient,
- its composition must ensure the desired chemical reactions,
- it must have suitable viscosity at the remelting temperature.

As presented in **Table 1** the concentrations of calcium fluoride may vary from 0 % to 100 % of mass fractions.[7] The remaining slag constituents are mostly used for decreasing the basicity.

The slag chemical composition is changed during the ESR process, due to the formation of volatile fluoride,

the precipitation of high-melting-point phases and the reaction in the ESR process.[14] The changes in composition affect the slag's metallurgical properties and eventually affect the quality of the final product. The quantity of consumed slag steel depends on the remelted ingot diameter.[6]

Table 1: Composition of some ESR slags, in mass fractions (w/%)[7]
Tabela 1: Sestava nekaterih ESR žlinder, v masnih odstotkih (w/%)[7]

CaF_2	CaO	MgO	Al_2O_3	SiO_2	Comments
100					Electrically inefficient, use where oxides are not permissible
70	30				Difficult starting, high conductivity, use where Al not allowed, risk of H_2 pick-up
70	20		10		Good all-round slags, medium resistivity
70	15	0	15		
50	20		30		Good all-round slag, higher resistivity
70			30		Some risk of Al pick-up, good for avoidance of H_2 pick-up, higher resistivity
40	30		30		Good general-purpose slags
60	20		20		
80		10	10		Moderate resistivity, relatively inert
60	10	10	10	10	Low melting point, "long" slag
	50		50		Difficult starting, efficient electrically

Many of the slags used in ESR can be described with the ternary fluorspar-lime-alumina system.[7] The phase diagram shown in **Figure 4** has been extensively investigated and defined by K. Mills.[15] The main feature is an eutectic corresponding to compositions with roughly
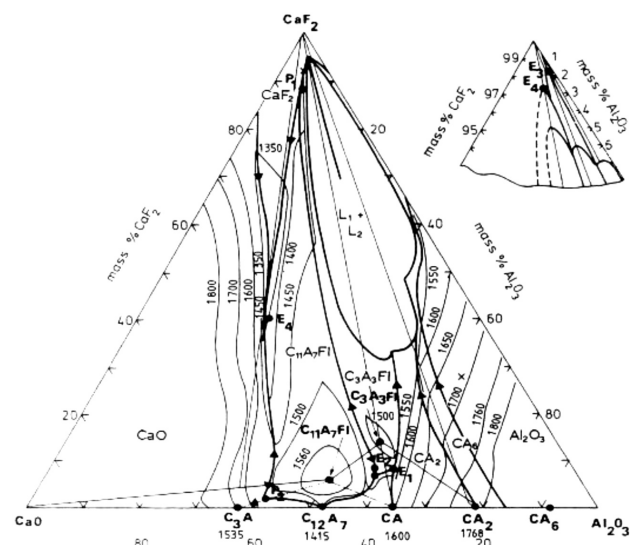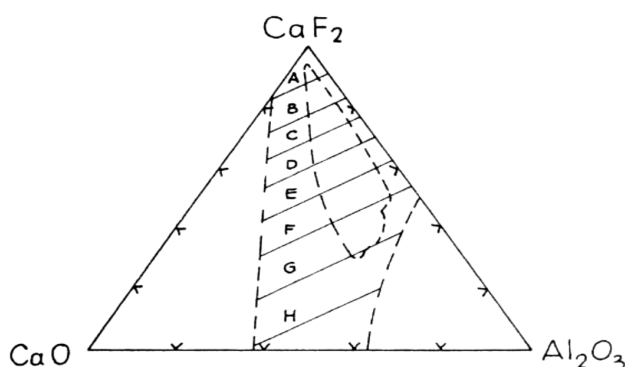

Figure 4: Phase diagram of the CaF_2-Al_2O_3-CaO system according to K. Mills[15]
Slika 4: Fazni diagram sistema CaF_2-Al_2O_3-CaO po K. Millsu[15]

Table 2: Phase diagram of the CaF_2-Al_2O_3-CaO system and the physical properties of slag at 1600 °C, according to K. Mills[19]
Tabela 2: Fazni diagram sistema CaF_2-Al_2O_3-CaO in fizikalne lastnosti žlindre pri 1600 °C, po K. Millsu[19]

Contour	Electrical conductivity κ (Ω^{-1} cm^{-1})	Viscosity η (10^{-1} Ns m^{-1})	Density ρ (g cm^{-3})	Surface tension σ_s (mN m^{-1})	Total normal emissivity ε_{TN}
A	6	0.15	2.47	285	
B	5	0.2	2.48	300	0.96
C	4	0.25	2.49	310	
D	3.5	0.3	2.5	320	0.9
E	3	0.4	2.55	335	
F	2.5	0.6	2.6	350	0.85
G	2	0.8	2.7	400	
H	1	1.0	2.8	450	0.81

equal proportions of lime and alumina. This identifies the slags with liquidus temperatures in the range 1350–1500 °C, which make them suitable for melting of a wide range of alloys, including steels and super alloys. In the case of slag with 70 % fluoride and 30 % alumina the lime is excluded as much as possible in order to prevent hydrogen pick-up, while there are no problems with the presence of the two liquids. The binary lime-alumina system on the other hand, has only a limited range of slags with suitable melting characteristics, while the binary calcium fluoride-lime system is used in cases

Figure 5: Microstructure of ESR slag
Slika 5: Mikrostruktura ESR žlindre

where a high degree of desulphurization is required. However, its disadvantage is having a low resistivity. High lime contents also increase the risk of moisture retention or hydrogen pick-up.

According to the tendency to reduce CaF_2 in slags, the investigations of the slag S 2015 (Wacker Cheime) with 30 % CaF_2 were performed. The results also showed that tested slags with 4.7 % CaF_2 can be satisfactorily applied in the ESR-process of UTOP Mo6 steel.[16]

A certain amount of SiO_2 addition into the ESR slag in the case of the drawing-ingot-type ESR process is important for improving the lubrication performance, controlling silicon and aluminium content in the liquid steel and modifying oxide-type inclusions.[17] Furthermore, the addition of SiO_2 suppresses the crystallization temperature of CaF_2-Al_2O_3-CaO slags. Furthermore, the MgO and SiO_2 in fluoride-containing slags affect the slag's surface tension.[18]

Although CaF_2 is a crucial component in any ESR slag and it greatly decreases the melting temperature of the slag systems, it is insoluble in oxide phases. An example of an ESR slag microstructure is shown in **Figure 5**, where the lighter dendrite-like phase is a stable CaO-Al_2O_3 phase, the darker phase is fluorspar, and the small white dots the undissolved magnesia particles. The fluorspar phase contains only calcium and fluoride and is not dissolved in other microstructural constituents.
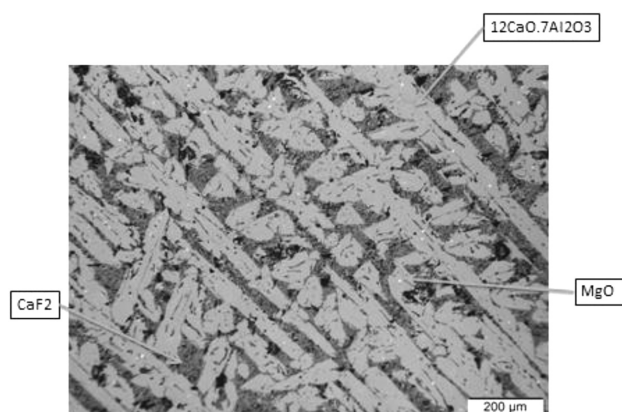
Slag properties, such as electrical conductivity, thermal conductivity, density, viscosity and surface tension play an important role in effective melting and metal refining. K. Mills[19] has produced a table of the physical properties of slags for practical purposes (**Table 2**). Slag resistivity affects the operating characteristics and economics of ESR. Alumina increases the resistivity of the slag and promotes good heat generation, thus enabling a reduction of the slag bulk content, which also reduces the heat loss due to the reduced area of contact between the slag and the mould wall.

L. A. Kamenski et al.[20] refer to "long" and "short" slags when discussing slag viscosity. Long slags remain fluid over a wide range of temperatures and are likely to give thin slag skins and therefore good ingot surfaces. Short slags rapidly become viscous on cooling and are likely to give thick slag skins and poor ingot surfaces. High calcium fluoride contents promote short slags, whereas silica and magnesia favour long slags.

The slag plays an important role in ESR, from the control-of-inclusions point of view.[21] The chemical and physical properties of slag also have a great effect on the removal of inclusions.

5 THERMODYNAMICS

In the case of ESR of steel in an air atmosphere, chemical reactions take place and change the chemical composition of the as-cast ingot.[22] The levels of some

elements, such as Co, Ni, Cr, Mo, W, C remain unchanged after remelting. However, the content of Si, O, and S can be changed from 10 % to 80 %, while the content of Al and Ti can vary depending on the melting conditions (decrease or increase). Therefore, some measures need to be taken to prevent the losses of elements. This can be achieved by using special ESR variations as discussed before. Another way is control of the slag composition and regular additions to the slag, which is desirable due to steady melting conditions. The oxidation of the elements can be prevented by deoxidation of the slag during the melting process by additions of aluminium.

The oxygen potential of the slag determines the chemistry of the ESR process.[7] It affects the non-metallic inclusions and sulphur removal. Oxygen reacts with some elements in the metal and suppresses hydrogen pick up. In the slag oxygen is mostly bound as FeO, MnO and SiO_2. To estimate the oxygen content in the steel it is necessary to find the relationship between FeO in the slag and oxygen in the remelted ingot.[22,23] However, due to the very low solubility of FeO in CaF_2 slags, its activity is extremely high. The oxygen content can be estimated by thermodynamic analyses of the reactions between active components and oxygen. Silicon and manganese are elements that can react with the oxygen present in the steel and from the slag.[23,24] When silicon is the strongest deoxidizer, the oxygen content of the steel is determined by the Si content.[23] At constant temperature and Si content in the steel, the oxygen content of the metal is higher at higher activity of the SiO_2 in the slag, or by lowering the basicity of the slag.

Aluminium losses in the remelted ingot are small, especially at high alumina content in the slag. On the other hand, the presence of Al_2O_3 in the slag reduces the oxidation of silicon. The reaction between the silicon in the electrode and Al_2O_3 in the slag also controls the oxidation of aluminium in the remelted ingot.[25] Thus, Al

content in the remelted ingot depends on the content of Al_2O_3 in the slag and the content of silicon in the electrode, temperature and chemical composition of the steel.[7,25] The content of Al in the remelted ingot decreases when CaF_2-Al_2O_3-CaO slags with increased SiO_2 content are used. When aluminium is used for deoxidation, up to 15 % of added Al is transferred to the molten steel. The content of titanium in the remelted steel will depend on the content of Al and Ti in the consumable electrode, the content of Al_2O_3 and TiO_2 in the slag and the oxygen potential in the gas phase above the slag (**Figure 6**).[26] The equilibrium between the Al and Ti content in the electrode at different TiO_2 contents is presented in **Figure 6**.

For the content of Al in electrode, the titanium loss can be minimized by the addition of TiO_2 to the slag. At high contents of Al, aluminium reduces TiO_2 in the slag and also regulates the ratio of Ti:TiO_2.

In the early stages of ESR development, the removal of sulphur was considered as one of the major objectives. The rate of desulphurization increases with the basicity of the slag. Sulphur transfer takes place mainly at two interfaces, according to the following two reactions:[23]

Slag/metal reaction: $[S] + (O^{2-}) = (S_{2-}) + [O]$ (2)

Gas/slag reaction: $(S^{2-}) + 3/2 \{O_2\} = \{SO_2\} + (O^2)$ (3)
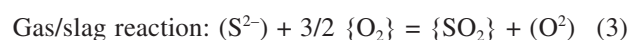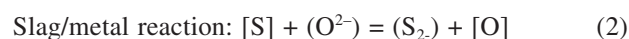
A thermodynamic analysis of the reactions shows that the desulphurisation is related to the concentration of O^{2-} ions in the slag, the partial pressure of oxygen in the gas phase and the chemical composition of the steel.[27] The transfer of sulphur from the metal to the slag is promoted by the high slag basicity and low concentration of oxygen in the metal. On the other hand, the sulphur transfer from slag to gas is promoted by a high partial pressure of oxygen in the atmosphere and the low basicity of the slag. The ability of the slag to take sulphur is defined in terms of its sulphur capacity. The sulphur capacity for the fluorspar-lime-alumina system increases as the CaF_2 content is increased and by increasing the amount of lime to the saturation point.[28]

In the case of ESR under inert gas, the sulphur remains in the slag and builds up there as the process continues. In such cases the sulphur capacity is the ruling factor, and the slag bulk must be adjusted in order to continue its desulphurising action to the end of the process, i.e., the slag/metal ratio assumes greater importance.[7]

6 SOLIDIFICATION AND STRUCTURE

The solidification structure of an ESR ingot is a function of the local solidification time and the temperature gradient at the liquid/solid interface.[4,7] To achieve a directed dendrite primary structure, a relatively high temperature gradient at the solidification front must be maintained during the entire remelting period.
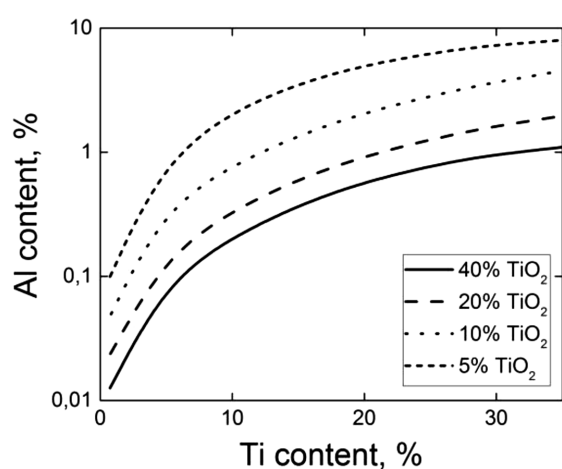

Figure 6: Effect of Al:Ti ratio in the electrode on TiO_2 content in the slag[26]
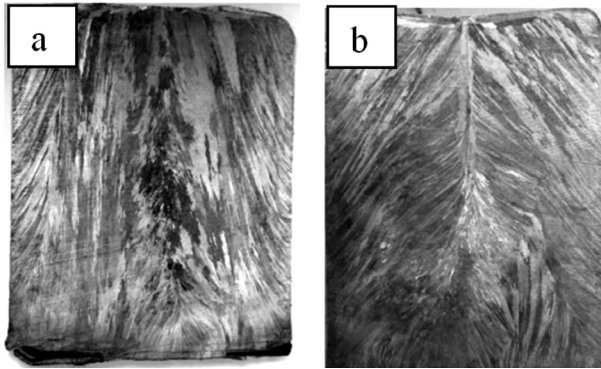**Slika 6:** Vpliv odvisnosti Al:Ti v elektrodi na vsebnost TiO_2 v žlindri[26]

Figure 7: The ingot grain growth at a melting rate of: a) 0.9 kg/min and b) 1.2 kg/min[32]
Slika 7: Rast zrna v ingotu pri hitrostih taljenja: a) 0,9 kg/min in b) 1,2 kg/min[34]

Macrostructure of the ESR ingots is different from the macrostructure of conventionally cast ingots due to the different heat transfer and heat removal. The growth direction of the dendrites is a function of the metal pool during solidification. Thus, the gradient of dendrites with respect to the ingot axis increases with melting rate. In extreme cases the growth of directed dendrites can come to a stop. The ingot core then solidifies non-directionally in equiaxed grains, which leads to segregation and micro shrinkage. Even in the case of directional dendritic solidification, the micro segregation increases with the dendrite arm spacing. A solidification structure with dendrites parallel to the ingot axis yields optimal results. However, this is not always possible. A good ingot surface requires a minimum energy input and accordingly a minimum melting rate.

Increasing the melting rate increases the difference between the gradient of the solidus and liquidus isotherms and leads to increased pool depth.[29] Hence, grains grow in radial direction instead of vertical direction. **Figure 7** shows the direction of the grain growth dependent on the melting rate, which affects the pool depth.
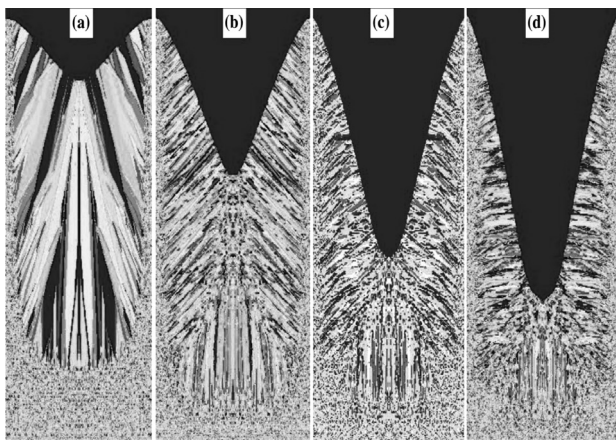

Figure 8: The predicted grain structure of ESR ingot[30] for different melting rates; a) 136 kg/h, b) 271 kg/h, c) 407 kg/h and d) 542 kg/h
Slika 8: Napovedana zrnatost ESR-ingota[30] pri različnih hitrostih taljenja: a) 136 kg/h, b) 271 kg/h, c) 407 kg/h in d) 542 kg/h

Figure 8 presents the predicted grain structures for different melting rates up to 600 kg/h.[30] Increasing the melting rate causes a finer grain structure and changes the growth direction of the columnar structure from the axial to radial growth and deeper liquid pool at very high melting rates. Increasing the molten slag temperature also results in a coarser columnar grain structure and a reduced thickness of the refined equiaxed grain layer, both at the surface and the bottom of the ESR ingot.

In spite of directional dendritic solidification, defects such as tree-ring patterns, freckles and white spots can occur in a remolten ingot.[4,7,31] Macro-segregation and porosity structures in the middle of the ingot are very uncommon for ESR ingots.

A major attribute of ESR is its ability to produce material with reduced micro-segregation. This is linked with the local solidification time and dendrite-arm spacing.[7] ESR material normally freezes in a columnar manner, which gives less micro-segregation than equiaxed structures. The greater the temperature gradient, the smaller is the distance between the dendritic arm spacing and the lower is the chemical heterogeneity in the micro areas. In ESR, temperature gradients are greater than for conventional casting. Therefore, the secondary dendrite-arm spacing will be smaller in ESR than in conventional
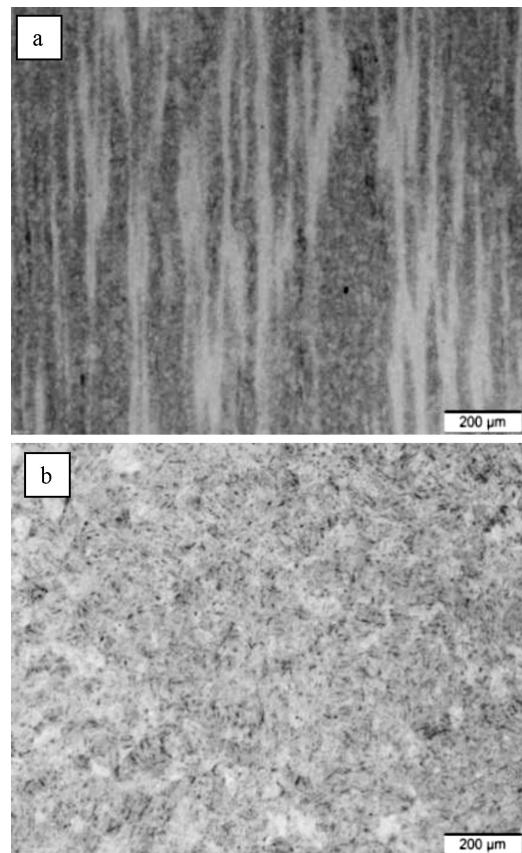

Figure 9: Segregations in the hot-work tool steel: a) consumable electrode, b) remelted ingot
Slika 9: Izceje v orodnem jeklu za delo v vročem: a) elektroda pred pretaljevanjem, b) pretaljen ingot
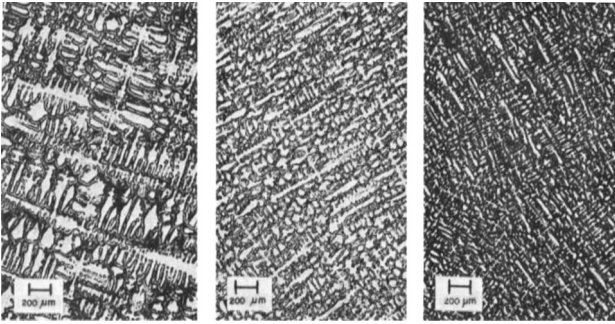
Figure 10: Microstructures of ingots of ESR nickel alloy 718, with dendrite-arm spacing at different cooling rates: a) slower cooling, b) faster cooling and c) fastest cooling[32]
Slika 10: Mikrostruktura EPŽ ingota nikljeve zlitine 718 in razdalj med dendritnimi vejami: a) počasnejše ohlajanje, b) hitrejše ohlajanje in c) najhitrejše ohlajanje [32]

ingots. The effect of decreasing the segregation effect is shown in **Figure 9**, where a comparison of microstructures before (**Figure 9a**) and after (**Figure 9b**) ESR processing was made for a hot-work tool steel. The microstructure in both cases is tempered martensite. The difference in segregation bands is obvious. While the segregations are evident in the consumable electrode (**Figure 9a**) they are almost completely eliminated in the remelted ingot (**Figure 9b**).

Figure 10 shows the effect of local solidification time on the dendrite spacing.[32] The dendrite-arm spacing is decreased as the cooling rate is increased.

Besides a more homogeneous composition and compact solidification structure, the removal of non-metallic inclusions is an important characteristic of ESR.[33] Normally, inclusions easily initiate micro-voids and
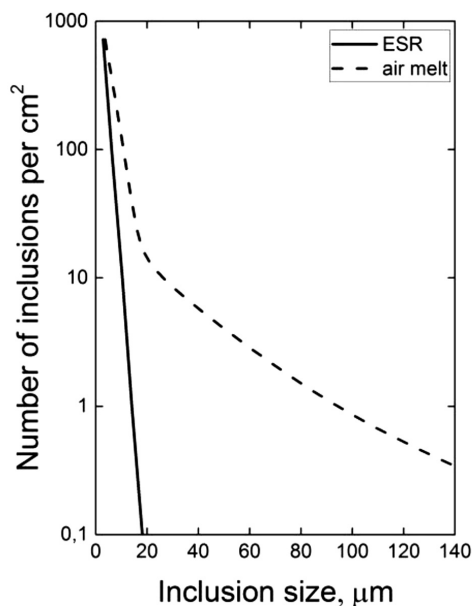
cracks at the inclusion/steel interface, which can be the origin of fatigue fracture or other defects. Also, ESR steel is not an exception.[34] Many factors influence the formation of non-metallic inclusions in ESR steel, including furnace atmosphere, content of inclusions in the consumable electrode, slag amount and its composition, power input, melting rate, filling ratio, etc. Most non-metallic inclusions occur due to the reactions between oxygen and elements such as manganese, silicon and aluminium.[35] Deoxidization of the slag during electroslag remelting[36] has an important influence on the non-metallic inclusions formation in the ESR ingot. The results of the experimental work show that the lowest number of inclusions is attained in ESR with the lowest viscosity and the highest interfacial tension.[37] However, the absence of large inclusions is typical for ESR, as shown in **Figure 11**.[38]

The removal of non-metallic inclusions during ESR takes place at the tip of the electrode, where mainly absorption and dissolution of non-metallic inclusions in the slag take place.[6,39] As the electrode tip is heated towards its melting point, the inclusions in the electrode are re-dissolved before the metal melts. Any other inclusions, such as larger exogenous inclusions in the electrode, are not dissolved in the solid metal and will be exposed to the slag when the electrode tip becomes molten. If the slag composition is suitable, the temperature is high enough and the dwell time is long enough the non-metallic inclusions will dissolve in the slag.[40] However, at this point there may be further reactions due to the difference in equilibrium constants, as well as the possibility of the flotation of large inclusions. The metal at this point is free from non-metallic inclusions, but may have in solution elements that produce inclusions by reaction during the freezing time (sulphur removal reaction).[41,42] The removal efficiency of inclusions increases with the reduced melting speed.[43]

The research work of Y.-W. Dong et al.[44] was focused on the impact of fluoride-containing slag and interactions at the slag-metal interface on the non-metallic inclusions in steel. Results indicate that a multi-component slag (CaF_2, CaO, Al_2O_3, SiO_2, MgO) has a better capacity for controlling the amount of inclusions. Most non-metallic inclusions for multi-component slag are MgO-Al_2O_3 inclusions, while mainly Al_2O_3 inclusions exist when using conventional 70 % CaF_2 – 30 % Al_2O_3 slag. Furthermore, the maximum inclusion size for multi-component slags was found to be smaller than for conventional binary slag.

Figure 11: Inclusion size and frequency for inclusions >2.5 μm in air-melted and ESR with 3 % Cr-Mo-V steels[38]
Slika 11: Velikost in število vključkov > 2,5 μm po ESR-pretaljevanju in pretaljevanju na zraku jekla 3 % Cr-Mo-V[38]

7 CONCLUSION

The main purpose of the remelting process is to control the non-metallic inclusions in the steel, remove segregations and shrinkage, and produce more homogenous ingots. The low speed of remelting, combined with the water-cooled mould, ensures a particularly homoge-

neous and balanced, stable solidification. The segregations within a remolten ingot are thus much lower (or even eliminated) compared to open cast continuous cast billets or conventional cast ingots. For this reason most segregation-sensitive steels are ESR processed for homogenisation.

The slag plays an important role in the ESR process, as it absorbs non-metallic inclusions, removes sulphur, influences the ingot surface and the melting rate as well as the overall economics of the process. That is why the chemical composition and physical properties of the chosen ESR slag is of paramount importance for a high-quality ESR ingot.

In order to further improve non-metallic inclusion reduction, specialised versions of the ESR process like IESR, PESR and VAC-ESR have been developed.

The application of the ESR process is appropriate for tool and high-speed steels as well as special stainless steels and special alloys intended for the most demanding applications.

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