State of the art of electroslag refining and challenges in the control of ingot cleanness

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ABSTRACT

Electroslag remelting (ESR) today and shortly will still be the main process for producing high-quality ingots by suppressing segregation, not just refining chemical composition from impurities. The article analyses state-of-the-art with a focus on ESR with consumable electrodes and recent technology with liquid metal supply (ESR LM) in view of their refining abilities and development trends, taking into consideration that the size of the ingots required by industry grows and the composition of new materials withstanding increasingly higher mechanical and temperature loads sophisticates. The yield of suitable metal in large ingots produced by conventional casting is low due to problems of element segregation by height and cross-section. For example, conventional ingots for nuclear power plant rotors today reach nearly 700 t in weight. Attempts to directly replace such giant ingots with big-diameter ESR ingots weighing approximately 400 tons were also unsuccessful because of growing segregation. Modern ESR equipment and technologies produce 200-250 tons of ingots of satisfactory quality, reaching 2,5 m in diameter, implementing the change of consumable electrodes during remelting to increase ingot length. Another way to mitigate segregation is to enlarge the smaller diameter ESR ingot by a 500-800 mm coaxial layer to the desirable diameter by ESR in the current-supplying mould (CSM). Modelling and experiments prove that refining from impurities and nonmetallic inclusions at ESR most effectively occurs at the slag bath and liquid metal pool interface because the ESR LM has provided the same desulphurisation. ESR's special refining capabilities in CSM come from the much longer time of liquid melt residence shown at titanium purification from hard-melting nitride inclusions that are unremovable in VAR and EBM. Implementation of ESR technologies in CSM, especially with liquid metal supply, is prospective to produce heavy enlarged and hollow forging ingots with prevented development of segregation due to dividing cross-section and reducing overheat of solidifying metal.

INTRODUCTION

Electroslag remelting is currently the leading process for producing high-alloyed steels and alloy ingots used in critical industries. This position is due to its unique ability to refine both the chemical composition through slag treatment and the structure of the ingot by suppressing segregation, achieved through the constant renewal of the liquid metal bath of small depth.

Since B. Medovar and B. Paton made the first ingot in 1952 (Paton, Medovar and Latash, 1958; Electroslag Technology,1991), areas of application of Electroslag remelting were widened and partially changed due to rethinking its role and importance. The development of ladle refining, and later the widespread use of additional degassing at vacuum treatment of steel, have led to a widespread reduction in the application of ESR furnaces for nearly two decades at the end of the last century.

The primary objectives now are to improve ESR metal's homogeneity and cleanness for producing sophisticated steel and alloy grades, reduce production costs, and increase the competitiveness of the ESR. Today's trends include increasing the ESR ingot weight, improving automation and efficiency of equipment, and recent interest in new specified slag systems intended for certain steel and alloy grades. Improvements in ESR technology and new innovative technical solutions for ESR equipment are crucial for product competitiveness, given that the demand for high-quality steels and alloys is expected to continue to rise in the coming years.

Heavy mechanical engineering has significantly progressed in recent years. Specifically, there has been an impressive intensification in the power of certain machines, industrial vessels, and aggregates. This expansion in the power of a single unit has been accompanied by an equally impressive rise in the size of their components and parts and the temperature and pressure in production processes where these machines are in use.

One of the biggest consumers of heavy metal parts is the power sector. Renewables (wind and photovoltaic power) become major electric power supply sources worldwide, but their output fluctuates daylong, destabilising the power system. That means that fossil fuel energy now and nuclear energy in the future are necessary to compensate power systems to deal with fluctuations in renewable output and customer demand. As a result, the manufacturing of big-size steel ingots and forgings from them will grow. The same tendency is in nuclear energy, the petrochemical industry, metallurgy, etc. For example, advanced ultra-supercritical steam turbine rotors operating at temperatures exceeding 700°C and pressure surpassing 30 MPa require clean steels and alloys with dense, stable, homogenous structures.

What makes ESR unique is its ability to combine remelting and gradual solidification of a continuously renewed liquid metal pool in a single process. This results in the formation of ingots that are much more chemically homogeneous and have a surface ready to be deformed due to a thin slag skin. Naturally, the constant complication requirements to products evoke new ESR technologies and equipment, which have undergone several advancements to keep up with the industry's ever-increasing demands. Therefore, the article aims to analyse the state-of-the-art electroslag remelting and identify trends for further development and improvement of technologies and equipment.

A SHORT LOOK AT THE HISTORY OF ELECTROSLAG REMELTING TECHNOLOGIES AND EQUIPMENT DEVELOPMENT

The priority in the electroslag remelting invention in its modern state (Fig.1 a) with the use of alternating current of industrial frequency belongs to Borys Medovar (1916-2000) and Borys Paton (1918-2021). To eliminate misunderstandings that sometimes arise, we emphasise that in the "Kellogg process", invented a decade earlier in the USA by H. Hopkins, direct current was used as it was mistakenly assumed that the current flow through the slag was in the form of a soft arc (Hopkins, 1940), and the purpose of direct current usage was to minimise arc instability.

The first pilot furnace for melting 500 kg round ingots (type R-909) was built in 1956-1957 under Borys Medovar's leadership (Fig.1 b).

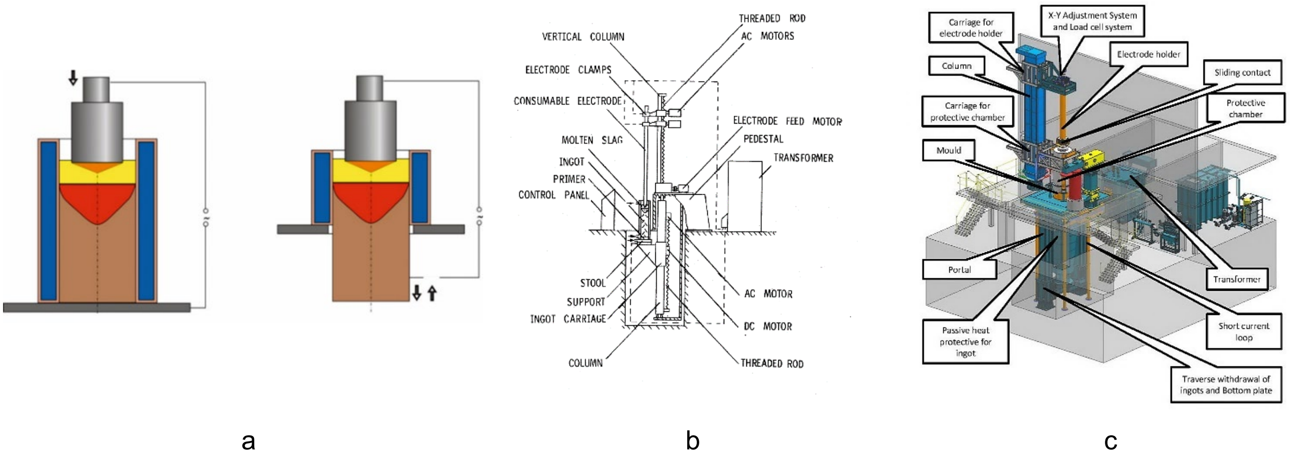


FIG 1 – The most common diagrams (a) of ESR remelting in a stationary mould (left) and short collar mould (right), the layout of the first furnace R-909 (b) of modern ESR process, and today's ESR plant structure (c).

The world's first electroslag furnace was put into industrial operation in 1958 at the Dniprospetsstal electrometallurgical plant in Zaporizhzhia, Ukraine. During the seventy years of electroslag remelting, engineers from many countries have invented, worked out, tested, or commercialised in the industry several drastic improvements of the original electroslag remelting of the consumable electrode and new types of related technologies.

Among them, the most widespread ESR technologies have become:

- Inert Gas Electroslag Remelting (IESR) — single phase one consumable electrode remelting at atmospheric pressure in a closed chamber filled with protective inert gas (argon) is today's benchmark process. Change of the consumable electrodes is used to reduce the height of the furnace (Jarczyk and Franz, 2012; Arh, Podgornik and Burja, 2016);

- Pressure Electroslag Remelting (PESR) — single phase one consumable electrode remelting in a closed chamber filled with nitrogen for melting steels with an excess nitrogen content (Stein and Menzel, 2014; Ritzenhoff et al., 2013);

- Three-phase electroslag remelting, using three parallel electrodes connected to a three-phase line or six electrodes arranged as three bifilar pairs, is still in use in China (Liu et al., 2021) for stainless and other steel remelting. Despite difficulties in providing reliable protection atmosphere and uneven melting of electrodes in bifilar pairs, it is a very good decision due to even electrical load.

The following options of ESR with a consumable electrode in the copper water-cooled mould are less general but have a certain potential in areas of their use:

- Electroslag Remelting Under Vacuum (VAC-ESR or VSR-Vacuum Electroslag Remelting) is designed for deep degassing during remelting of superalloys and titanium alloys, the efficiency of which was not high enough due to the barrier effect of the slag layer or gas evacuation and because of evaporation of slag components (Radwitz, Scholz and Friedrich, 2013);

- Arc Slag Remelting (ASR) is an energy-saving process of obtaining high-nitrogen steels and titanium and its alloys by remelting a consumable electrode due to an electric arc between it and the surface of the liquid slag bath (Medovar, 1997; Paton et al., 2004).

The recent technologies using the short collar current-supplying (synonym - current conductive) mould (Fig. 2a) still be of interest:

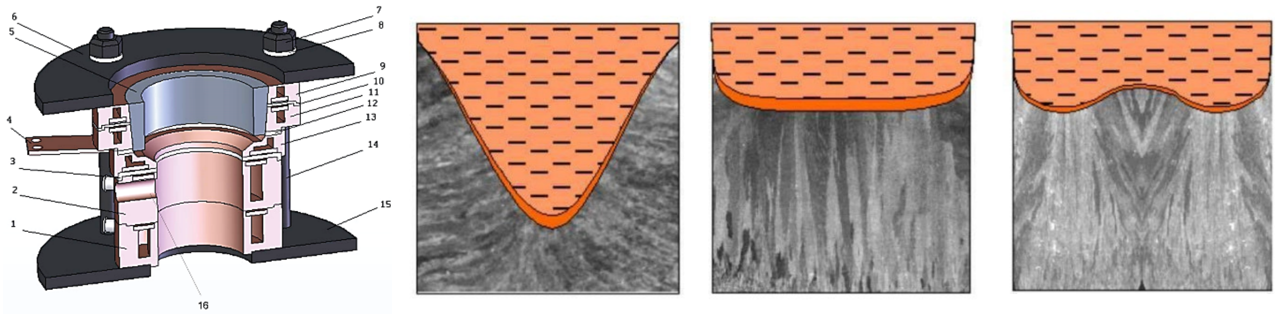
- Electroslag Rapid Remelting Process (ESRR) for high-productive manufacturing of high-alloyed steels and superalloys by remelting a single large-diameter electrode (3-10 times larger than the ingot) in a T-shaped mould connected with a power source to increase process productivity (Alghisi, Milano and Pazienza, 2005; Karimi-Sibaki et al., 2018);

- Electroslag Remelting with Two Circuits (ESR TC) for gradual formation of the homogenous ingot from segregation-prone steels and superalloys (Medovar, 2005) due to breaking the rigid dependence between the speed of electrode melting and ingot formation to control of heat input and temperature of slag and metal baths to form shallow liquid metal bath, which is difficult to achieve in a standard ESR (Fig. 2 b).

Extra opportunities are provided by electroslag processes using a current-supplying mould (Medovar et al., 2016; Paton et al.,2007; Medovar et al., 2018) without consumable electrodes:

- Electroslag Surfacing by and recycling of discrete materials (fines, powder, shavings, etc.) in a current supplying mould for the production or renewal of a working layer of rolling mill rolls, rotors of electric motors, stamps of high-speed and tool steels, tungsten carbides, etc. (Kuskov et al., 2018);

- Electroslag Refining using Liquid Metal (ESR LM) and Electroslag Surfacing by Liquid Metal – ESS LM (Fig.2 b) for the production of highly homogeneous ingots of solid cross-section, hollow ingots, and composites with coaxial or horizontal arrangement of layers from steels and alloys prone to segregation ((Medovar et al., 2018; Medovar et al., 2020).



a b

FIG 2 – Current supplying mold structure (a – 1, 2 – forming section; 3, 12, 8, 10, 12 – electric insulation; 7 – nut; 4 – current supplying bus; 5 – protective graphite ring; 6 – upper flange; 9, 12 – current supplying section; 13 – dividing section; 14 – stud; 15 – lower flange;16 – metal level sensor) and liquid metal pool shape (b) at different ESR methods: from left to right - standard ESR, ESR TC, ESR with liquid metal (Medovar, L. et al., 2005)

This article compares the two most different technologies—classical ESR with consumable electrodes and ESR with liquid metal—to better understand and highlight their abilities to refine a metal's chemical composition and structure.

ELECTROSLAG TECHNOLOGIES' ABILITY TO REFINE THE CHEMICAL COMPOSITION OF METALS

Along with the term "Electroslag remelting", another name for this technology in English-language sources is "Electroslag refining". The latter retained the context associated with one of the first purposes of the process - remelting ingots or rolled products rejected due to the high content of impurities, primarily sulphur and nonmetallic inclusions (NMI). ESR technologies are limited in refining agent addition during the process, first, because of the lack of ability to control resulting changes in both slag and metal phases.

Refining from impurities and NMI during ESR is ensured by the use of fluoride and fluoride-oxide slags (system of CaF_2–Al_2O_3–CaO–(SiO_2, MgO)), which were initially selected from the experience of electro-slag welding. Pure calcium fluoride was the first slag for the ESR to maximise the refining effect from oxide, sulphide, and nitrides. CaF_2 is still used today for remelting the most critical alloys (including titanium alloys) despite its high price, low conductivity (which makes an inversely proportional effect on energy consumption at ESR), and some technological limitations.

From the point of view of refining, the main impurity and alloying elements involved in the electroslag remelting of steels and nickel-based alloys can be divided into four main groups (Tab.1):

TAB 1 – Elements classification on their behaviour in the ESR slag-metal system for Fe- and Ni-based alloys

Process components	**Elements present in metal, absent in initial slag and able to react with slag**	**Elements present in both phases, able to transfer from one to another via exchange and redox reactions**	**Elements present in slag, absent in metal due to extra low solubility and acting in slag-metal reactions**	**Trace elements present in steel, absent in slag and do not react with slag**
Consumable electrode	Fe, Mn, C, Cr, Ti, Mo, V, W, B	O, N, S, H, Al, Si		P, Ni, Cu, Sn, Pb, Zn, Sb
Slag: CaF_2–Al_2O_3–CaO–(SiO_2, MgO)		S^{2-}, O^{2-},N^{4-}, $3Al^{3+}$, Si^{4+}	F-, Ca^{2+}, Mg^{2+}, Na^+, K^+	
Reactions (compounds are coming into slag or forms NMI)	$X[Me]+Y\{O^{2-}\} = \{Me_xO_y\}$ $\{Me_xO_y\}+\{O^{2-}\}=Me_xO_{y+1}\}$		$[Me] + \{S2^-\} = \{3MeS\}$ $[Me] + \{N2^-\} = \{MeN\}$	No
Ingot	Fe↓, Mn↓,C↓, B↓, Cr↓, Ti↓, V↓, Mo↔, W↔,	S↓↓, N↔ O↑↓, Al↑↓, Si↑↓- Depending on concentrations	NMI of CaS, CaO, MgO, MgS and their complexes with other oxides and nitrides	P, Ni, Cu, Sn, Pb, Zn, Sb etc: all ↔
In process slag	FeO↑↑, MnO↑↑, MnS↑ ↑, B_20_3↑, BN↑, Cr_20_3↑, TiO_2↑, TiN, V_20_5↑, $Mo0_3$↔ , WO_3 ↔	CaS↑↑ Al_20_3↑↑↓, SiO_2↑↑↓↓, MgS↑, MgO↑ Depending on concentrations		No

1) Elements that are contained in the metal and are absent in the initial slag but can react with its components, which can pass from the metal to the slag and vice versa as a result of displacement or redox reactions, mainly forming oxides, sulphides, nitrides, or carbides. These are manganese, iron, carbon, chromium, vanadium, molybdenum, and other alloying elements, the oxidation of which violates the specified chemical composition, structure, and steel properties. The same situation

applies to titanium and boron, in which oxide addition in slag is made to prevent their enhanced oxidation, trying to shift the equilibrium in favour of metal.

2) Elements are contained in the slag and participate in slag-metal reactions but are not in the metal due to their vanishingly low solubility. These are fluorine, calcium, magnesium, alkali, and alkaline earth metals. The oxides of the last group of elements ensure the removal of sulphur and change the composition of the initial nonmetallic oxide-type inclusions from a consumable electrode.

3) Elements are present in both phases, which can transfer from one phase to another via an exchange in redox reactions. These are, first of all, sulphur, oxygen, and nitrogen, the removal of which from the metal composition is one of the tasks of the process, the realisation degree of which depends on their initial concentration (at high initial content in the metal the refining occurs and vice versa). In addition to impurities, aluminium and silicon play a substantial role in the refining processes, competing in redox reactions involving oxygen being an active steel deoxidiser and, simultaneously, are contained as oxides in the initial ESR slag in significant quantities.

4) Trace elements are present in the steel in low concentrations and are not existent in and interact with an initial slag. These are phosphorus, nickel, copper, lead, tin, and others. Accordingly, metal refining from these elements in the ESR process using slag is practically impossible.

The following refining actions occur at the remelting with slags of CaF_2- Al_2O_3–CaO–(SiO_2, MgO) system that is typical for steels and nickel-base alloys:

- - chemical interactions between the slag and metal (redox reactions, i.e. sulphides, oxides, nitrides formations/removal), which happen at all interfaces between slag and metal (Figure 3), and NMI removal to slag accompanied by change in their chemical composition and new inclusions formation occurring by:
- - NMI interaction with slag on all interfaces resulting in their composition change or complex particle formation;
- - elements from NMI dissolve in a metal (thermal dissolution with no contact with slag) and re-precipitate at a temperature reducing while cooling and solidification form new particles in the metal, i.e., saturated by liquates near the growing solidification front (Burja et al., 2018; Persson et al., 2020).

The efficiency of NMI removal from metal depends on their properties (size, density, solid or liquid states, and their surface tension with metal and slag) and the shapes and intensity of macro- and microflows in a metal pool. Depending on the combination of these factors, the nonmetallic inclusions can be either assimilated by the slag surface, captured by the solidification front or still be circulating until the metal's last portions solidify.

Many years of ESR refining practice have proven a drastic reduction in the size and number of NMI and their type and composition changes. Endogenous particles of oxides, nitrides, sulphides, and oxysulphides mostly represent NMI in ESR metals. However, exogenous inclusions from the lining of the steel-teeming ladle or tundish still occur (often, they differ by a high magnesium or silicon content depending on the lining type and casting powder). The size of inclusions found in laboratory-scale trials is usually between 1-5 µm but more commonly ≤2 µm. However, larger inclusions are often present in industrial-size ingots, especially when larger sample areas are analysed (Persson et al., 2021). The high thermal inertia of ESR and steady remelting conditions make it possible to organise microalloying the metal from slag. Still, control of results is post-melted, which is impossible to correct. The most used recently is boron-bearing additions to slag to keep stable boron content in the ESR ingot.

THE CONTRIBUTION OF SLAG-METAL INTERACTION SURFACES IN REFINING AT ELECTROSLAG TECHNOLOGIES

The issue about the main place of metal refining at electroslag remelting was disputable for years. To answer the question of the contribution of different interaction surfaces, we made two ingots using two different technologies in comparable conditions. In our comparative experiments, we use the same T-shape current supplying mould (Fig. 1a) and produce two ingots from the same chemistry metal by standard ESR and by electroslag refining by liquid metal pouring (ESR LM). The same current supplying mould (180 mm in dia), steel grade St45 and ANF29 slag (layer height of 200 mm) were used at the ESR and ESR LM to ensure comparable conditions. Process productivity was 120-160 kg/h (speed of ingot withdrawal — 15-17 mm/min). A comparison of the interaction surfaces was made for a 160 kg/h feed rate, which is typical for the stationary stage. The size and number of drops were measured and counted on a 160 mm electrode after its tip was rapidly frozen. The specific power consumption at ESR averaged 1350 kWh/ton of ingot (due to the necessity to melt a solid electrode), while at ESR LM - 900 kWh/ton at the same productivity level (Stovpchenko et al., 2020).

We compared cross-sections of contact surfaces and measured sulphur content before and after both technologies. In the standard ESR process, slag-metal interaction occurs on three contact surfaces (Fig. 3).

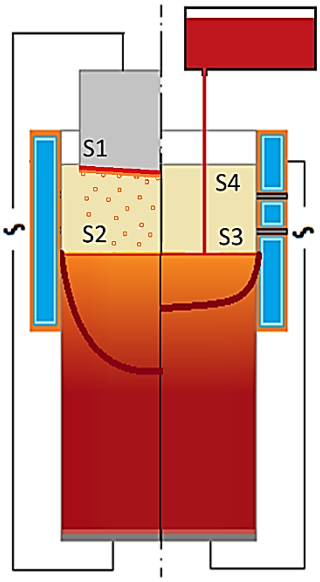
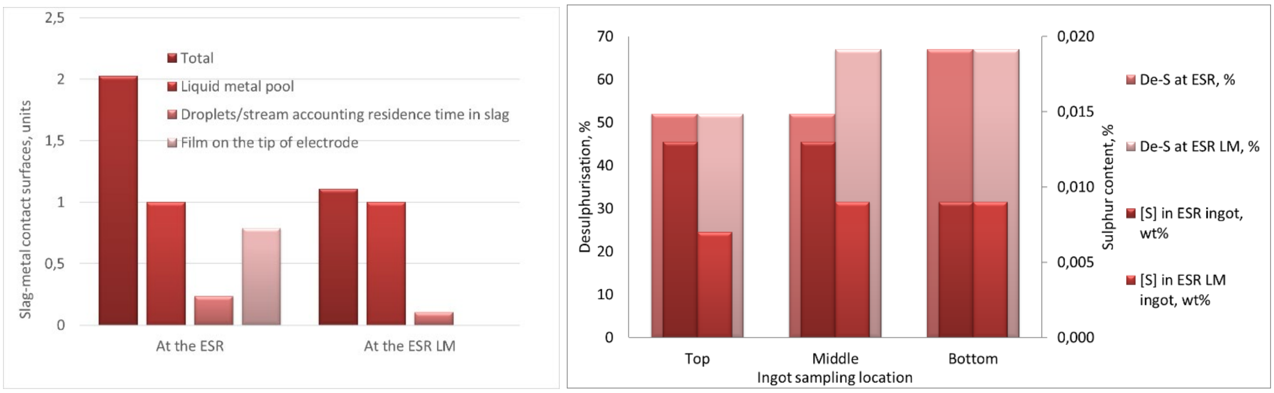


FIG 3 – The slag-metal interaction surfaces S1–S4 (description in text) at the ESR with a consumable electrode, left part, and ESR with liquid metal, right part (Stovpchenko, G. et al. 2020)

The first surface (S1) belongs to the liquid metal film at the tip of the melting consumable electrode contacting with slag. The second area (S2) is the surface of the drops of liquid metal rain inside a slag layer. The third area (S3) is the interface between the liquid slag bath and metal pool - the same for both ESR processes with and without electrodes. The S4 is the analogue of S2, which refers to the square area of a liquid metal stream in the ESR LM process that works without consumable electrodes. A formal comparison of the values of slag-metal contact surfaces of a standard ESR with a consumable electrode and an ESR LM without an electrode supply was performed.

According to the characteristic filling ratio, the molten metal film surface (S1) on the electrode tip is 0.5 to 0.7 of the ingot surface (Figure 4 a).



a b

FIG 4 – Geometrically defined values of slag-metal contact surfaces (a) and the sulphur content and degree of desulphurisation (b) in ESR and ESR LM ingots at comparable conditions (Stovpchenko, G. et al. 2020)

In our direct experiment, the total interface of the metal and slag phases in ESR was twice as large as that in ESR LM. Specifically, it was 2.03 in ESR and 1.12 in ESR LM. The main difference was due to the electrode surface, which was 0.79 in our experiment (due to the T-shape mould used).

The size of drops is directly related to the diameter of an electrode and can range from 1 to 10 mm found by direct experiments (Campbell, 1970) and numerical simulations (Kharicha, Ludwig and Wu, 2011; Wang et al., 2016; Dong, YW. et al.,2016; Liu et al., 2022). The largest drops have an equivalent diameter of 10 to 15 mm, and the smallest drops measure 1 to 4 mm. Due to the small size and short residence time in the slag of the drops, the part of their surface constitutes 0.23 of the liquid metal pool. During the ESR LM process, the liquid metal stream (S4) has permanent contact with the slag bath and can be broken into smaller drops. For the sake of simplicity, we can ignore the drop formation and express the interaction surface as a cylinder having a stream diameter (up to 20 mm – 0,11 of the surface of the metal bath) and a length that matches the mass of the metal at the same productivity as a standard ESR process.

Direct comparison of sulphur content before and after ESR and ESR LM (Figure 4b) shows the same value of desulphurisation (Stovpchenko et al., 2020), proving that the contact surface between a slag bath and metal pool is the most effective interface in refining (first of all from sulphide and oxysulfide nonmetallic inclusions).

It is worth highlighting that despite the absence of film at the tip of the electrode and another type of metal transfer through the slag (a stream instead of drops), the refining ability of the ESR-LM is the same. The reason is that, due to the lower density of nonmetallic inclusions, they move towards the slag under the influence of the Archimedes force, and, in addition, the value of surface tension at a flat interface between slag and metal bath is less than at near-spherical shape surface for metal droplets in slag. In the film at the tip of the electrodes, the conditions for NMI removal are even worse because the Archimedes force counteracts their movement to the slag bath (Fig. 5).

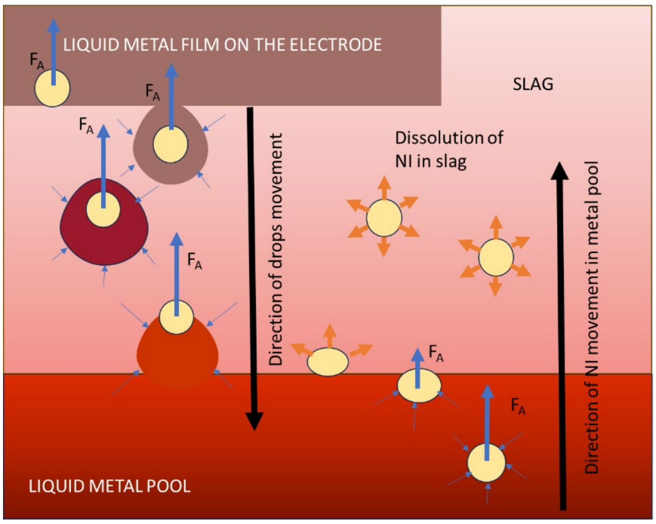


FIG 5 – Simplified scheme illustrating NMI (light spheres) movement on the different slag-metal contact at standard ESR: F_A is Archimede force, thin arrows show elements exchange between metal drops and slags.

The physical reason is that nonmetallic inclusions move towards the slag under the influence of hydrostatic lift force (Archimedes' force - F_A) due to their lower density in comparison with liquid metal (three times and more difference). In addition, the value of surface tension at a flat interface between the slag bath and metal pool is less than at droplets having a near-spherical surface in slag. In a film at the tip of electrodes, the action of Archimedes' force on nonmetallic inclusions is directed opposite to the location of the slag bath. In the liquid drops, the inner friction forces make them turbulent inside, make more difficult for NMI to be assimilated by slag. For these reasons, the main refining action of NMI removal much more easily occurs on the contact surface of the slag and metal baths and not in a film on the tip of the electrode.

Performed simulation of liquid metal drops' movement in the slag also shows that already during the passage of metal drops having size 2-10 mm through a 200 mm layer of slag, they heat up to the temperature of the slag (modelling parameters and more detailed results are available in (Stovpchenko et al., 2020). Large droplets move faster than small ones due to their internal flows and turbulence, making Stokes' law-based predictions inaccurate. Classical ESR has smaller droplets that move more slowly and heat up more than the ESR LM being compared. Turbulent flows (inside bigger liquid drops (from 6 to 10 mm) deformed their shape from sphere to flatter spheroid and also can cause their splitting into smaller parts, increasing the contact surface between metal and slag (Krivtsun *et al.*, 2021).

The extrapolation of the established features of the movement of solid and liquid drops explains the better removal of liquid-state nonmetallic inclusions. At smaller sizes, the difference in movement speeds between solid and liquid particles tends to be zero due to smaller inner friction in liquids, but the separation of liquid inclusions from steel proceeds similarly. In contrast, the assimilation of liquid inclusions in slag goes much easier without diffusion restrictions. Moreover, at a residence of liquid metal drops in oxygen-bearing ionic slag with free O^{2-} anion, oxidation of active elements from a liquid metal and other reactions between it and slag components are unavoidable and forming nonmetallic inclusions can be removed from the liquid metal pool mainly.

Slag temperature also affects refining ability at the ESR because of its increasing enhanced dissolution of previously formed NMI and their assimilation due to lower viscosity and rate of chemical reactions between slag and metal, resulting in new NMI formation in the liquid metal drops and pool. The temperature of the slag bath at ESR with a consumable electrode is typically estimated to be 100-250 K higher than the liquidus temperature of the steel or alloy and of metal droplets overheat - 90-100 degrees C (Klyuev and Volkov, 1984). The conventional ESR process uses the resistive type of heating that requires high overheating of slag to ensure contact melting of an electrode immersed in a slag, but ESR LM is devoid of this shortcoming. Due to an induction heated furnace, the liquid metal overheating is minimised to keep metal liquid during the short period (seconds) to be poured into the current supplying mould.

A decrease in the temperature of the slag bath is also favourable due to reducing the evaporation of volatile fluorides, which, along with exchange reactions, causes changes in the chemical composition and properties of the slag. No less important is the slag bath temperature for ESR ingot formation. It is the most important factor defining ESR process productivity, flow conditions, and depth of the liquid metal pool, and creating a high gradient of temperature is crucial for the solidification pattern and structure of the formed ingot.

Comparing the standard ESR and ESR LM allows asserting that the physicochemical conditions of refining in the ESR LM are more favourable due to the less slag-metal contact at the droplet stage and the consumable electrode absence with liquid metal film on it. At these contact surfaces in the standard ESR, conditions for nonmetallic inclusion removal are less convenient, and high temperatures can cause oxidation of elements from the metal composition. There is no need for electrode melting, resulting in reduced slag heating and no overheat of metal that comes with preset temperature from induction heated furnace (temperature 70-95 degrees less than for drops at ESR), allowing the forming of a shallower liquid metal bath that is favourable for the solidification control of ingots from segregation-prone grades of steels and alloys, where ESR LM technology can be prospective. Moreover, no need to melt the electrodes reduces electricity consumption on the value of heat required for the solid-liquid phase transition.

Despite the attractiveness of ESR with the liquid metal, it has a specific niche. The standard ESR with consumable electrodes in protective gas is often the perfect decision, especially when strict gas protection is critical and stationary mould is preferable. The current supplying mould works with ingot withdrawing, which requires a more precise operation; thus, it is worth using the ESR with consumable electrodes when a very low melting rate and flat liquid metal pool are needed to reduce segregation or for hollow ingot manufacturing.

Summarising, all ESR technologies stand apart from the steelmaking primary and secondary refining methods: it is refining by high-temperature slag only; other possible refining actions are not effective because of no direct contact of gas phase or alloying additives with liquid metal, causing difficulties with vacuum treatment and alloying (microalloying) organisation and control. Despite the much higher temperature of the ESR process than any treatment in traditional steelmaking, single melts go hours and decent hours to receive a very dense dendrite structure with minimal segregation due to good conditions in water-cooled copper mould with the gradual renewal of liquid metal pool for metal solidification control and ingot structure refining.

Specific case - ESR of titanium as a way to dissolve titanium nitrides

It is often overlooked that the first ESR plant was constructed to manufacture titanium ingots. Being the first to attempt this was difficult and led to dangerous accidents, which prevented commercialisation for many years. High reactivity of titanium at liquidus temperatures, severe limitations on flux compositions, and only alkaline-earth and lanthanide-series fluorides are suitable for titanium ESR (Paton et al., 1999).

Nevertheless, the research made worldwide on lab and pilot scales. The produced commercial batches of titanium and titanium alloys prove that it can compete with other remelting technologies (such as VAR and EBCHM) for titanium manufacturing in terms of ingot quality and product efficiency and even have an advantage - titanium refining from nitride inclusions, which was shown experimentally at titanium sponge remelting using ESR TC technology in the current supplying mould. The problem with hard-alpha phase defects is that the melting temperatures of these nitrogen-rich inclusions are much higher than the melting temperature of titanium itself. As a result, the time for dissolution of large inclusions coming from titanium sponge is longer than the time of their hovering in melting bath at vacuum arc remelting (VAR) or electron beam melting (EBM) - standard now processes for titanium remelting.

ESR with active slags containing metallic calcium helps to accelerate the dissolution process (Fig.6), which value observed at level $2 \cdot 10^{-4}$ m/s (Paton et al., 1999) that is much faster than at VAR – $2.2 \cdot 10^{-6}$ m/s (Bewlay and Gigliotti, 1997) and EBM - 4.2×10^{-5} to 4.9×10^{-5} m/s (Xu *et al.*, 2022).

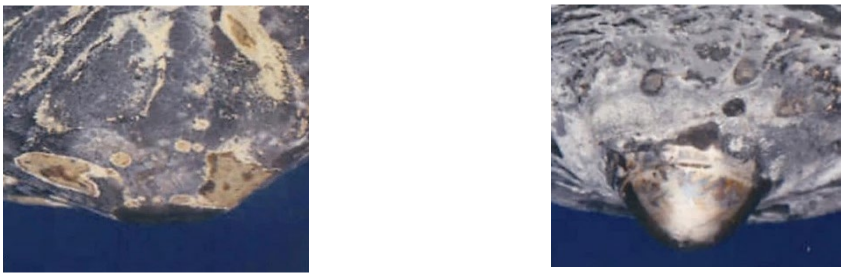


FIG 6 – The appearance of frozen after ESR tips of the consumable electrode with the films of nitrogen-rich phase-light spots (Paton, B. et al. 1999)

The successful experiments proved a perspective to include electroslag remelting of sponge as a consumable electrode or lump pieces for refining titanium from large-size nitride inclusions to achieve its uniform distribution in ingot volume before the final VAR. The ability to refine titanium from nitride inclusions gives opportunities for cost-effective commercial ingot production using ESR.

The results allow us to conclude that the slag layer at ESR works like refining media and heat buffer, helping to provide enough time for inclusions to remove being assimilated by the slag bath or to be dissolved fully or partially to be reborn in smaller sizes and even distribution. That is why ESR refines titanium from hard-to-melt titanium nitrides, and white spot defects are not characteristic of the ESR ingots.

ESR TECHNOLOGIES' ABILITY IN SOLIDIFICATION CONTROL FOR INGOT STRUCTURE REFINING

The industry has three primary technologies for receiving huge forge ingots - conventional casting, casting with electroslag hot topping, and electroslag remelting. It is well known that the bigger an ingot diameter is, the longer its solidification takes, resulting in an elevated degree of macrosegregation. The final portions of solidifying metal in conventionally cast ingot hold the highest concentration of elements displaced by the solidification front, shrinkage, and porosity. These parts are concentrated near the centre and top of the ingot. Therefore, huge forging ingots are designed with extra-hot top parts meant to be removed. Sometimes, the whole length of the central part is removed through trepanning. Naturally, this results in a low yield from ingot to ready forging, making sense for hollow ingot manufacturing. For ordinary people, it is difficult to imagine that for manufacturing backup roll or turbine rotors for nuclear power plants weighing 250-260 tons, the cast forging ingots of 700 tons are in use. At heavy hollow vessels and reactors (for nuclear and petrochemical industry) manufacturing by forging from huge cast solid ingots, the metal yield to ready part also does not exceed 25-35% (Medovar *et al.*, 2023).

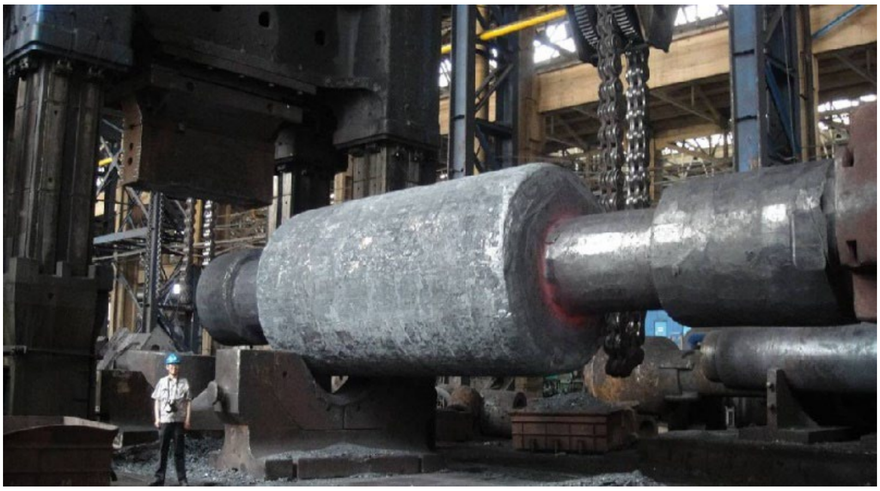


FIG 7 – Low-pressure rotor forging 408 t in weight maximal diameter 3650 mm forged from 715 tons conventional casted ingot of 30Cr2Ni4MoV (Courtesy of China First Heavy Industries)

Electroslag hot topping eliminates shrinkage, and increases yield but only partially weakens segregation as it does not change the residual melt composition saturated by impurities. Chemical composition purifying helps but does not fully resolve this problem. Even at very low concentrations of segregation-prone impurities, inner defects can arise like well visible A-segregation in 20 t slab ingot (1680x780mm) of 09Mn2SiV grade with sulphur content 0.004% (Fig. 8).

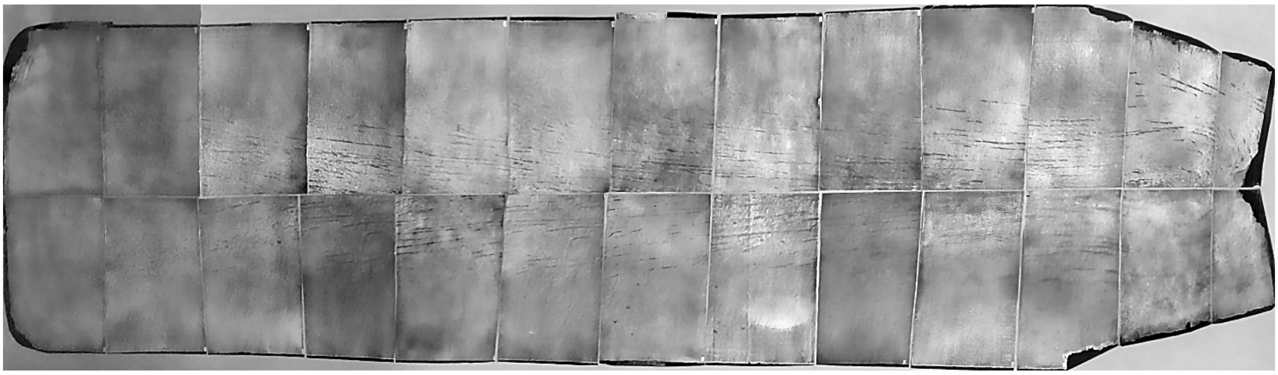


FIG 8 – Macrostructure of 20 t conventional cast slab ingot 780 mm side from 09Mn2SiV steel with sulphur content 0.004% and heavy A segregation in the central part (hot etching in 50% HCl)

The lines of A segregation form when solidification front stop - the point of columnar-to-equiaxed growth transition (CET) - a place where the heat sink is reduced, melt mixing flows low, and impurities accumulate - so the nonmetallic inclusions and excessive phases have enough time to grow and agglomerate. The mitigation of segregation is crucial in producing sound huge forging ingots, especially for sophisticated grades containing many alloying elements of varying physical properties and chemical activities in their composition.

The ESR rate of ingot formation is much lower than that of traditional metallurgy methods of pouring liquid metal into ingots or continuously cast billets. ESR deliberately significantly reduces the melting process productivity for the sake of solidification control for the high quality of an ingot, minimising the volume of the liquid metal pool, which helps prevent the segregation-caused redistribution of elements and formation of shrinkage defect.

The charge for the ESR is ingots or even forged or rolled billets after ladle treatment and vacuum degassing, which are pre-final products for most metallurgical applications. Naturally, the ESR with consumable electrodes is quite costly. However, the quality and yield of ESR ingot are significantly higher (85-95%) because the volume of metal that solidifies in one time is smaller, its composition is constantly renewed, and heat removal in a copper water-cooled mould is better than in an iron mould. Therefore, the efficiency rule is easy: the bigger the ingot size and alloy grade price, the more effective the use of ESR. The sulphur print of the ESR ingot of the same cross-section we planned to put aside, but it occurs white because for such a cross-section, due to progressive renewal of liquid metal, the pool provides a 100% dendrite structure with a density close to the theoretical value.

Today, the ESR heavy forging ingots reach 250 tons in weight and 2.6 m in diameter (Kubin et al., 2013; Bettoni, P. et al.,2014). Nevertheless, the attempts to directly replace giant cast ingots with ESR-made ingots weighing approximately 400 tons were unsuccessful because of growing segregation at increasing the ingot diameter to 3.5 m and, accordingly, the volume of simultaneously solidifying metal and depth of liquid metal pool.

The bigger the diameter of the ESR ingot, the deeper the liquid metal bath became, and the solidification conditions tend to approach those in a conventional ingot. The zone of equiaxed crystal appears, and as a result, segregation defects worsen.

The practice has shown that the ultimate diameter (mass) of the electroslag ingot, which retains quality advantages over the usual one (cast in iron mould), is different for steels and alloys of various degrees of alloying. Thus, for carbon and low-alloy steels, this ultimate diameter of ESR ingot is 2000-2600 mm (up to 250 tons), for high-alloy steels (stamping, corrosion-resistant, and high-speed steels) and alloys (including some superalloys) it is significantly less - near 1000 mm (usually it is to 20 t), and for grade Inconel 718, the critical diameter is just 500 mm (2,5-3 t). The last limitation is well known due to Prof. Alec Mitchel's calculation of Local Solidification Time (LST) showing that the critical point could be reached at an ESR ingot size of 1050 mm in dia (Fig. 9).

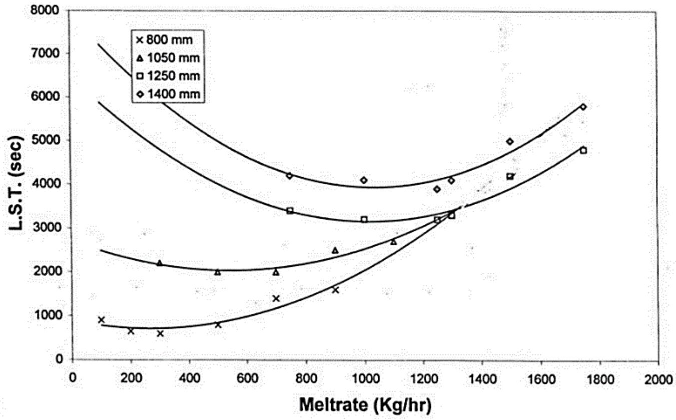


FIG 9 - LST versus ESR melt rate for different diameter ingots (Persson et al., 2021)

Detailed investigation (Persson et al., 2021) of NMI in ESR and PESR Remelted Martensitic Stainless Steel commercial ingots shows that as the ingot diameter increases and dendrite growth approaches the centre, the growth of inclusion number and size is near linear. Still, when the centre of the ingot solidifies in equiaxial mode, the increase in inclusion number and size is much higher. For the martensitic stainless steel grade 0.4Cr13MnSiV, the transition from dendritic to equiaxial solidification mode happens in the 800 to 1050 mm diameter ingot. It is also well-known that consumable electrode quality is critical for ESR ingot cleanness, and casting is the critical procedure causing NMI entraining, mostly reoxidation products (Campbell, 2023).

The reason is that at traditional ESR with one consumable electrode, the ingot is formed under direct dependence of the melting speed on the electric power (which cannot be less than a certain value to provide a smooth surface). The central supply and peripheral removal of heat lead to the formation of a deep metal bath of a conical shape, which solidification can be accompanied by segregation whose manifestation is the bigger, the larger the cross-section. Therefore, the problem of producing high-quality, huge-size ingots must be resolved using approaches other than increasing diameter. There are three ways to resolve this task with increasing ingot weight at keeping or increasing ingot diameter:

- increase the ESR ingot length;
- maximally reduce ESR technology productivity as was shown at ESR TC technology (Medovar et al., 2005, 2018) to keep shallow liquid metal bath and at ESR LM with an additional reduction of an overheat of slag and metal (Medovar et al., 2018, 2020);
- reduce the cross-section of solidifying metal by using an inner cooler - hollow ingot manufacturing or enlargement of smaller diameter and weight ingot into larger one. It is obvious that

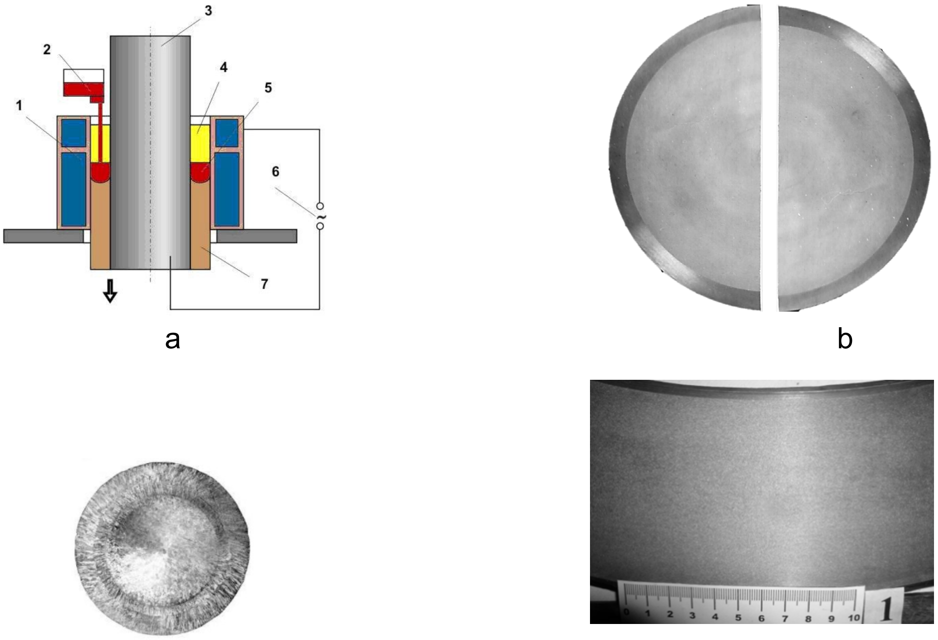
the reduction of a cross-section of an ingot diminishes the volume of simultaneously solidifying metal and weakens segregation (Medovar et al., 2011, 2016, 2023).

Colleagues from INTECO (Private communication, 2023) decided to use the first approach: to keep the already reached diameter of the ingot with satisfying quality and to increase its length and weight to 300 tons for a Confidential Customer in China. This equipment and technology implement the change of consumable electrodes during remelting, i.e. in fact, there is a kind of liquid phase welding of individual parts of a large ingot into a single whole, and an increase in the mass of the ingot is achieved through increased length. Such giant production takes weeks, and its handling is not easy.

We suppose the realisation of the last listed approach using technology with the current mould supply and producing huge weight ingots with central coolers as it is realised in hollow or enlarged ingots. Much smaller consumable electrodes (ESR TC technique) with less inherited segregation or liquid metal supply can be used for such ingot manufacturing. In the last case, we avoid the stage of consumable electrode casting/forging(rolling), where large-size NMI can be captured from the casting mixture or formed in the central part of the ingot when equiaxed dendrite growth occurs.

In traditional ESR, a depth of liquid metal bath approximates an ingot radius or more. However, at hollow or enlarged (by surfacing) ingots formation by ESR LM in current supplying mould, the liquid metal bath can be drastically reduced and reshaped, as shown in Figure 1 and proved by macrostructures in Fig. 10 a,b. The electroslag enlargement technology divides the cross-section of an electroslag ingot into coaxial layers, which are formed sequentially. Even better conditions to form the sound low-segregation ingot of heavy weight with fewer cross-sections of simultaneously solidifying metal are in ESR hollow ingot for large pipes and shell manufacturing.

The enlargement, in principle, is the same method as electroslag surfacing by liquid metal (ESS LM-Fig.10 a), successfully developed for surfacing a working layer of rolling mill rolls at NKMZ (Ukraine). The fusion zone is of high quality (Fig.10 b), even when dissimilar steels in the central ingot and the deposited layer are connected.



a b

c d

FIG – 10. ESR enlargement/surfacing/hollow ingot manufacturing principle (a): 1-current supplying mould; 2 – pouring furnace; 3 – ingot to enlarge/billet for surfacing/water-cooled inner mould; 4 – slag bath; 5 – liquid metal pool, 6 – power source, 7 – ready product; cross-section of 740 mm HSS surfaced rolled mill roll (b), lab-scale enlarged ingot 70/110 mm (c) and hollow ingot wall (d) were produced by ESR/ESS LM (Medovar, L.B. et al. 2018)

Central ingot can be done by ESR or other methods providing the required quality. When the central ESR ingot is settled upside down, the parquet-like arrangement of its dendrites to dendrites of deposited layers increases metal properties.

Having an inner cooler inside the enlarged ingot solidification occurs at much better conditions than a solid one with the same diameter: sizes of carbides and the distance between axes of secondary dendrites in each layer, including the central ingot, are sufficiently less according to both modelling and experimental results (Medovar et al., 2009). Due to the two-stage process, the enlargement of ingots by surfacing is a priori more expensive than conventional ESR or ESR LM, so it is advisable to use this method for expensive alloys prone to segregation. We believe the enlargement method will find its place primarily for large-diameter forging ingots from superalloys. Since today, the maximum diameter of such ingots has been less than 1050 mm because of freckle formation. The deposition of a 500-800 mm thick layer around the central ingot with a critical diameter of 1050 mm makes it possible to obtain an ESR ingot of a size desirable for forging rotors or large rolling rolls. The appropriate equipment and slags were designed and tested to ensure the reliable connection of similar or different composition layers in composite ingots into a single whole and also hollow ingot manufacturing (Medovar et al.,2018 b; Stovpchenko, G. et al., 2018), making possible start wide implementation of the ESR/ESS LM technologies.

Employing ESR technology with current supplying mould and, especially, using liquid metal, including for electro slag enlargement and hollow ingots, to produce large-diameter forging ingots with prevented development of segregation due to dividing cross-section and reducing metal overheat is prospective.

CONCLUSION

The concept of metal cleanness in ESR ingots is considered in terms of refining the metal from sulphur and nonmetallic inclusions in combination with solidification control.

Analysis of trends in engineering further development and comparison of modern ESR technological varieties show prospects of electroslag technologies, including techniques with a liquid metal to achieve high-quality ingots and final products, including forgings for power engineering.

It has been demonstrated through modelling and experiments that metal melt refining from sulphides and oxysulphides most effectively goes in the contact surface between the slag bath and liquid metal pool.

The experimental studies conclusively prove that ESR has the potential to purify titanium from nitride inclusions (hard alpha phase) having high melting temperature, which are otherwise impossible to remove using other remelting methods for producing ingots from titanium and titanium alloys.

The potential of employing ESR technology with liquid metal, including electroslag enlargement, to produce large-diameter forging ingots with prevented development of segregation due to dividing cross-section and reducing slag and metal overheating is substantiated.

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