STATE OF THE ART IN VAR AND ESR PROCESSES – A COMPARISON

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ABSTRACT

The increasing demands of modern manufacturing technologies place ever higher requirements on the engineered steels and alloys used for casting, rolling and forging, which can no longer be met by classical steel manufacturing processes. Both the Vacuum Arc Re-melting (VAR) and Electro Slag Refining (ESR) processes have been used for five decades to further refine and improve the ingot structure, homogeneity and cleanliness of these materials. Whereas the fundamental VAR process has remained consistent, the ESR process has evolved to be totally enclosed under protective atmosphere. The traditional VAR and ESR methods and recent trends in process technology and process control will be reviewed in detail, particularly as they influence cleanliness, segregation, solidification structure, and finally product quality. Finally, a thorough analysis of re-melted ingots having similar dimensions and comparable materials will show that while both processes increase the homogeneity of the final product, other benefits are the direct result of the unique physical and chemical transformations of the VAR and ESR processes.

KEYWORDS

Re-melting, ESR, VAR, Homogeneity, Cleanliness, Segregation, Inclusion

INTRODUCTION

Conventional steels are produced using secondary metallurgical processes like Electric Arc Furnace (EAF) with subsequent treatment in ladle using Ladle furnaces (LF) and vacuum degassing systems (VD, RH). At the end of the refining the liquid will be casted using top and bottom pouring to produce ingots or billets using the continuous casting process with all its limitations in refining of the material and solidification structure in the final ingot. For small batch sizes with a yearly production up to 20 000t/a and by selection of raw materials the above mentioned liquid production route can be replaced by a vacuum induction melting furnace (VIM) which becomes more economical.

For heavy forging having batch weights starting from 50t single piece weight the ingot casting processes are modified using BEST (Böhler Electro Slag Topping) or TREST (Terni Refractory Electro Slag Topping) techniques to avoid material shrinkage cavity on the top and to improve the final material yield [1, 2]. The ingots are heated from the top after conventional casting to increase the final piece weight as the shrinkage cavity will be reduced but these hot top treated ingots have less effect on the solidification structure of the final ingot. Nowadays it has not been possible to meet the increasingly stringent requirements with regard to gas contents, cleanliness, and homogeneity either with conventional melting and casting processes or with the vacuum induction melting furnace alone. Therefore ingots or billets casted in the conventional secondary metallurgy with top shrinkage cavity can be used for further processing in re-melting technology to achieve additional refinement of the structure and increase the cleanliness of the end-product. Re-melting furnaces like Electro Slag Remelting (ESR) or Vacuum Arc Remelting (VAR) can be used to achieve best material quality.
PROCESS ROUTES AND PRODUCTION

Nowadays in special steel mills ESR and VAR are in use to increase the cleanliness and homogeneity of the ingots. Both re-melting processes have their field of application e.g. for iron-based material in the tool- and die- steel production and Ni-based material in corrosive environmental conditions. Additionally both processes are used for the production of materials used in the aviation industry [3, 4]. The first steps in steel production such as phosphorus removal, desulfurization, chemistry control and degassing can be achieved in the secondary metallurgical vessels whereas the final structure control will be done in the re-melting units. The re-melting processes itself needs the electrodes processed with theses pre-melting equipment’s (Figure 1).

Fig. 1: Process Characteristics in Melting and Re-melting

Producing electrodes for remelting the steel shops are following the route of melting - EAF-followed by secondary metallurgical steps – LF/VD depending on the yearly production and batch weight. For small heats the use of the vacuum induction furnace is becoming more and more economic but this process is limited by its refining capacity of the raw material in respect to lowest phosphorus contents and desulphurization despite the good melt bath temperature control. This means the vacuum induction furnace needs selected raw material in small batch sizes.

The electrodes used in the ESR and VAR furnaces will be produced using the secondary metallurgical route with sizes up to 1300mm and more in diameter and 30t in weights showing all the well-known metallurgical disadvantages of conventional cast material but by using single electrode/ingot technology the re-melting equipment balances the segregation in the re-melted ingot. In ESR the ingot sizes can be extended further due to the possibility of electrode exchange technique under atmospheric pressure [5].

The advantage of the ESR and VAR material compared with conventional casted material is mainly due to the improved segregation ratios for e.g. chromium and molybdenum and therefore higher homogeneity of the ingot. By increasing the alloying of elements in steel grades the segregation become an issue in conventional cast ingots. This will be minimized in re-melting processes like VAR or ESR due to the direct and controlled solidification.
Both re-melting processes will be used in re-melting alloys of higher concentration of alloying elements which also differs in density therefore leading to segregation problems. Each process has their own field of applications and benefits in refining.

In Ni-base production various process routes are running producing the electrodes and ingots. In the primary melt VIM or VOD (AOD) are used on a routine basis. Further refinement will be done mainly by ESR or VAR as a single step or ESR/VAR as a part of so-called triple melting depending on the final application of the material. In off shore and chemical application ESR becomes the final refining step whereas the aviation/aerospace industry still requires VAR as a last step in alloy production. Triple melting will be used to first clean the electrode in ESR and to avoid the center shrinkage hole in the electrode before VAR prevents ingot defects.

GENERAL PROCESS DESCRIPTION

Nowadays there are two main re-melting practices employed in modern metallurgy, namely, re-melting in the Vacuum Arc Furnace (VAR) and refining by the Electro Slag Re-melting process (ESR). These processes do not only enable the metallurgical condition of the material but also its primary crystallization.

It is common procedure in both re-melting processes to melt and refine material already casted as an ingot (now named as the electrode) in a water-cooled copper crucible (Figure 2). Whereas in VAR a DC- arc is used to melt the electrode in ESR the electrode is immersed inside a slag layer heated with AC, the electrode is consumed - remelted- an ingot is formed underneath both heat sources in water cooled copper crucible.

In VAR only round ingots can regularly be produced. In ESR the electrode shape can vary from round to rectangular shape. The size will be ruled by its subsequent forming process like forging or rolling. The electrode for ESR as well as the ingot prior to forging needs no mechanical processing. This increases the material yield out of the process line using ESR.

![Fig 2: Re-melting Process Principles](image)
The melting of high quality alloys demands an exact matching of the melting parameters. Nowadays thanks to highly developed computer technology the melting itself can be controlled precisely to achieve best performance in material production. The variables in VAR are well known and can be easily adjusted to achieve high-end quality. The electrode re-melting is controlled by using the current and the arc gap is controlled by using the voltage or drip short control. Throughout the process the current and voltage must not be changed drastically due to the cylindrical shape of the crucible and electrode. After a short start phase the process maintain steady over a longer period of time. At the end the current is ramped down to minimize the top shrinkage cavity in the ingot. The vacuum level can be influenced using inert gas but is kept be more or less constant over the re-melting time.

In ESR the process the variables have a higher degree of freedom. Different types of slag can be used to control the chemistry of the final ingot. The slag height must be chosen to compensate the slag skin losses on the surface and to serve the electrode exchange technique. The process itself is controlled by the power with its focus on slag temperature control and pool shape respectively melt rate. The slag in ESR is resistance heated from the power used to melt the electrode. Highly sophisticated controls use the resistance value to control the positioning of the electrode inside the slag (immersion depth control). The total resistance value depends on slag temperature, slag type, slag height and the geometric set up. As mentioned before the slag pool changes during the re-melting according to the loss of slag to the skin and chemistry changes inside the slag due to metal-slag reactions. To compensate this effect the resistance swing value is used deriving from the resistance signal when the electrode is immersed in the slag. Therefore the resistance signal tells the history of slag re-melting and the operator uses this value to get a better understanding of the process. The resistance value does not change with the power input or furnace size as the voltage will do.

THEORETICAL PROCESS CHARACTERISTICS IN RE-MELTING

In VAR the main metallurgical reactions take place under vacuum at the substantially increased surface area of the molten metal droplets to reduce the gas content of the material. Low density oxide inclusions from the electrode will be collected on the liquid pool and transferred to the solidification rim on the crucible wall. The employment of the vacuum necessarily also results in the removal by evaporation of tramp elements with a high vapor pressure such as Pb, Sn, Bi, Te, As, and Cu, as would normally be required [6]. Those elements will condensate on the crucible wall and collected on the surface. However undesired losses also occur in alloying elements such as Manganese (Mn) in iron-based material. Furnace and process efforts can be made to minimize those high Mn losses and to be within its final desired chemical range [7].

The primary advantages of the VAR process are:
- Removal of dissolved gases, like hydrogen and nitrogen
- Minimizing the content of undesirable trace elements with high vapor pressure
- Improvement of oxide cleanliness
- Achievement of directional solidification from bottom to the top of the ingot in order to avoid macro segregation and to minimize micro segregation.
- Resulting density of ingot approaches theoretical density
- Copper crucible and inert atmosphere
- Lowest melt rate possible but not essential necessary

The disadvantages (limitations) of the VAR process
- Heavy inclusion formation on liquid pool disturbs the arc gap control
- Possible evaporation losses of desired alloying constituents
- No electrode exchange possible to produce bigger ingots
- Electrode must be free from deposits like rust and adherences (machining of surface)
- Ingot surface contains entrapments and needs to be machined before subsequent forming

In contrast; the ESR process does not promote the degassing reactions. As a liquid metal film forms on the immersed electrode tip, it is extensively cleaned of undesired, removable impurities such as oxides. The high degree of slag superheating and also of metal superheating which takes place has a favorable influence on the metal/slag reactions. In contrast to the vacuum arc furnace characteristic slag reactions such as desulfurization can take place in the ESR, thus favorably influencing the metallurgical results. Easily oxygen affine elements such as Si, Al, Ti, and Zr do, however, tend to be depleted by oxidation as a result of the thermodynamic relationships which prevail, although such losses can be extensively restricted or controlled through the perpetuation of certain specific re-melting conditions. It should be mentioned that the de-oxidation technology and use of different slag in combination with an inert gas atmosphere will overcome these challenges.

The major advantages of the ESR process:
- Removal of oxides and sulfide inclusions to a great extent. The remaining inclusions in the ingot are a very fine and are evenly distributed.
- Solidification and ingot structure are similar to VAR ingot - no macro segregation and reduced micro segregation.
- Homogeneity in the distribution of non-metallic inclusions.
- Uniform mechanical properties in the longitudinal and sectional directions
- Density in ingot is close to theoretical density
- No formation of white spots compared to VAR
- Due to the formation of a thin slag skin round the ingot, the surface is very smooth and does not require any conditioning for subsequent forging.
- Very flexible process in regard to its physical dimensions
- Very large ingots such as 3000 mm diameter and more than 200 t weights can be produced.
- Ingot cross-section is not limited to round only. Square, rectangular or polygonal ingots can easily be produced.

The disadvantages (limitations) of the ESR process are:
- Slag treatment to achieve lowest hydrogen in ingot.
- Closed re-melting to avoid hydrogen pick up from atmosphere
- Gases (like hydrogen and nitrogen) need to be adjusted to lowest level in the electrode.
- Adjustment of slag chemistry and the composition of the electrode.
- Melt rate adjusted according to the slag system, alloy composition and furnace size.

Main process differences are illustrated in table 1. In both processes the ingots solidify in a water cooled copper mold. In ESR the ingot is surrounded by a solid slag layer whereas in VAR the ingot shrinks creating a gap. To improve the heat transfer in VAR a helium-gas can be introduced inside the solidification gap to increase the heat transfer to the mold wall. The pool shape becomes V-shaped in ESR and U-shaped in VAR and stands for less dendrite arm spacing which promotes less segregation and best material homogeneity.
Table 1: Main Process Differences in Re-melting using Electro Slag and Vacuum Arc

<table>
<thead>
<tr>
<th></th>
<th>VAR</th>
<th>ESR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum gas contents due to removal of dissolved hydrogen, nitrogen</td>
<td>vacuum</td>
<td>No removal of hydrogen and nitrogen</td>
</tr>
<tr>
<td>Minimizing the content of undesirable trace elements with high vapor pressure</td>
<td>vacuum</td>
<td>Minimum sulfur contents</td>
</tr>
<tr>
<td>Lowest Manganese losses in alloys</td>
<td>Pressure control</td>
<td>No Manganese losses in alloys</td>
</tr>
<tr>
<td></td>
<td>Uniform carbide distribution in tool steel applications</td>
<td>Less dendrite arm spacing</td>
</tr>
<tr>
<td>White Spots possible</td>
<td>Crown, Torus, Electrode</td>
<td>Less material defects – white spots – due to re-melting of dendrite clumps</td>
</tr>
<tr>
<td></td>
<td>Fine trimming of Al content (narrow range) and to balance slag-salt melt reactions</td>
<td>Feeding into slag</td>
</tr>
<tr>
<td></td>
<td>Keep elements with high affinity to oxygen</td>
<td>Inert gas on top of slag</td>
</tr>
<tr>
<td>Electrode must be ground or peeled</td>
<td>Re-melting under higher than atmospheric pressure possible</td>
<td>Chamber type furnace</td>
</tr>
<tr>
<td>Ingot must be machined prior to forging (surface not acceptable)</td>
<td>Electrode can be used in as cast condition</td>
<td>Cleaning by slag</td>
</tr>
<tr>
<td></td>
<td>Smooth surface</td>
<td>Slag skin on surface</td>
</tr>
<tr>
<td>Less dendrite arm spacing Low segregation ratio</td>
<td>Lowest melt rate possible</td>
<td>Melt rate chosen to slag skin (slag temperature)</td>
</tr>
<tr>
<td></td>
<td>Equal dendrite arm spacing</td>
<td>Equal dendrite arm spacing</td>
</tr>
</tbody>
</table>

The direction of the dendrites corresponds to the direction of the temperature gradient or the direction of heat flow at the moment of solidification at the solidification front. Therefore the direction of the dendrites is a function of the metal sump profile during the solidification of the material. Since the sump profile has in a first approximation a rotationally-symmetric parabolic shape in water cooled molds, the gradient of the dendrites increases in regard to the ingot axis with increasing melting rate.

Best results in regard to less micro-segregation can be achieved with dendrites which grow as close as possible parallel to the ingot axis. This theoretical point of view cannot be maintained in re-melting because a minimum energy input is required to melt the electrode with a certain melt rate. With increasing melt rate and energy input the gradient of the dendrites become larger and in extreme cases the dendrites break down and the structure become irregular. However the heat flow in ESR is different to the heat flow in VAR. In VAR the ingot shrinks away from the crucible wall and opens a gap between crucible wall and ingot surface. This lowers the heat transfer to radiation only towards the mold wall and promotes a deeper melt pool at a given melt rate. In ESR the slag skin acts as a convector and increases the heat transfer towards the crucible wall.

Whereas in ESR the melt-rate can be kept high to achieve a thin slag layer on the surface of the ingot resulting in a smooth ingot surfaces, in VAR the melt-rate is limited due to the forced inter-dendritic movement of the remaining melt when the pool depth increases. This means for each alloy an optimum melt rate exists to avoid failures in structures as separations and micro-cavities. The melt rates in VAR are significantly lower than in ESR.

With increasing diameters in re-melting it is recommended to use a pre-melted electrode with evenly distributes elements and without shrinkage cavities to avoid ingot defects. The risk of those defects coming from the electrode is increased with ingot diameter in case of VAR whereas the ESR is not so impacted by this. This ingot defect is called white spot having different chemistry than the matrix. Sources are dendrites fallen off from the shrinkage cavity of the electrodes or from the crown build up in VAR crucible on top of the ingot built up from splashing or condensates. Dense electrodes help to suppress this behavior. In VAR the power supply and precise electrode feed control becomes an important factor to avoid splashing on crucible wall or lower electrode surface.
Disturbances in heat flow during solidification can be found later in ingot structure showing up with light rings in a horizontal cut slice of the ingot. These tree rings represent a crystal separation which according to the available information has no influence on the material properties itself. In re-melting the heat extraction is limited according to the alloy to be re-melted and the process to be used as well as the cooling condition in the water cooled mold. Therefore the only way to control the shape of the liquid pool is the input of metal to the pool using the weight of the electrode to control the melt rate.

Additional defects are radial segregation caused from elements having high densities and not evenly distributed in the electrode. The interdendritic segregation is driven by the mushy zone and local solidification time and become critical in ingot casting processes. In VAR the local solidification time can be influenced by the arc gap and the He cooling between ingot and crucible wall. In ESR it is influenced by slag skin between ingot and crucible wall. The slag skin itself can be influenced by slag type and electrode immersion into the slag. The segregation ratio of both processes can be found equal. The comparison needs to be done with conventional casted ingots.

Freckles in origin are carbides or carbonic elements formed in the pool and indicated as colors when horizontal slices are cut from the ingot. Freckles will be formed easily when the pool becomes too deep (melt rate and flow caused by thermal gradient), when alloys containing, when the ingot diameter increases and when a stray or uneven magnetic field influences the liquid movement in the pool.

In modern furnace design the current path are designed in such a way that the magnetic field has less impact on the liquid metal pool. In VAR the crucible itself acts as a return conductor to allow a symmetrically current flow around the solidification area. The ESR furnaces are designed having four return conductors arranged symmetrically around the crucible to avoid live mold characteristics and uncontrolled current flow through the mold wall.

![ALD Furnace Design of Stationary ESR and VAR](image)

It should be mentioned that those defects have major influences on material used in the field of high
end application in aviation and power generating stations, but still influences the material properties in conventional field of application. Figure 3 shows the two types of stationary furnaces.

**PROCESS PREPARATIONS AND ECONOMICS**

The electrode in ESR can be used in as cast condition whereas the electrodes scheduled for arc remelting must be surface processed (e.g. grinded, machined) for best cleanliness and less oxides on the surface layer. Later the VAR ingot must be scaled again prior to subsequent forming removing the deposits on the surface. In ESR the ingot shows a smooth surface due to a small slag skin formed on the surface which will fall off after removing the ingot from the crucible. In spite of the different electrode requirements, ingot treatment in both processes shows up with a similar material yield compared to the cast electrode weight at the end. High end quality in regard to the chemical homogeneity and cleanliness values can be achieved taking away approximately 20% started from electrode and ending with the final ingot piece. Those figures are the results from ingots delivered and sold to forging shops following customer demands.

Electrodes prepared for re-melting needs welded onto a stub or adapter to be connected to the furnace ram in order to be fed during the process for tight feed control. Therefore one side of the electrode needs to be cleaned and even for best electrical contact. If the stub will be welded onto the bottom side of the electrode no further material loss must be assumed. In case of a second electrode for ESR exchange technique both sides must be cut. After re-melting in both cases a short disc remains on the stub. State of the art furnace controls achieve small rest disc height and less shrinkage in the top portion using melt rate controlled hot topping procedure.

Further attention must be taken to the furnace preparation itself. The crucible where the ingot solidifies must be cleaned after the VAR process in order to clean the surface and to avoid contamination. The crucible in ESR is not effected by re-melting because the slag solidifies on the inner wall even and the skin will remain on the ingot or fall off after the removal of the crucible. Therefore the inner wall of the crucible show no deposits or adherence and can be used direct for the next melt.

<table>
<thead>
<tr>
<th>ESR diameter 1000 mm</th>
<th>Aspect</th>
<th>VAR diameter 900 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1100</td>
<td>Energy consumption during remelting [Kwh/t]</td>
<td>700</td>
</tr>
<tr>
<td>13.5</td>
<td>Melting rate [kg/min]</td>
<td>9</td>
</tr>
<tr>
<td>8</td>
<td>Time to weld one stub on electrode [hours]</td>
<td>8</td>
</tr>
<tr>
<td>Constant Nitrogen and Hydrogen, no modifications</td>
<td>remelting effect on gas content</td>
<td>Nitrogen and Hydrogen strong reduction (around 50%)</td>
</tr>
<tr>
<td>no modifications; maximal homogeneity</td>
<td>remelting effect on alloy elements</td>
<td>30% Mn evaporation; high level of homogeniety</td>
</tr>
<tr>
<td>normally not ground</td>
<td>surface electrode preparation</td>
<td>100% ground or peeled</td>
</tr>
<tr>
<td>used without ground</td>
<td>surface remelted ingot prior to forging</td>
<td>must be ground or peeled</td>
</tr>
</tbody>
</table>

Table 2: Key Parameters in Vacuum Arc and Electro Slag Re-melting
In ESR the power consumption depends on the contact area between liquid slag height, slag temperature and slag type. The slag height is mostly chosen considering the loss by the slag skin and on the end slag cap at the top of the ingot at a given electrode/ingot fill ratio. These parameters influence the slag temperature. This was optimized over a long period of time using the same type of slag which influences the heat transfer via the mold to the cooling water and influences the solidification of the final ingot.

In VAR the power consumption depends mainly on the alloy to be re-melted. The specific heat of the material is the most important factor due to the arc formation. Minor influences are the gas load of the material and the suction capacity of the pumping system and electrical efficiency.

Comparing the power consumption of both processes the VAR will consume approximately 70% of the power used on the ESR of comparable furnaces sizes up to 1300mm in diameter (table 2). The surface condition of the ingot is a key point for further processing. In ESR the formed slag skin on the circumference of the ingot allows smooth surface and direct processing using heat treatment and forging or rolling. Surface defects like rings or metal overlapping can be avoided using well defined process conditions and slag compositions without increasing the melt rate. High melt rate promotes good ingot surface in almost the same manner but create internal defects. Therefore the high melt rate should not adopt to produce good quality ingot.

In VAR the surface is determined by the cleanliness of the electrode and the stability of the process itself. Heavy crown formation at the rim of the liquid pool leads to rough surface which need to be machined prior to forging. This results in cooling down and machining of the ingot surface. It is known from the production of refractory metals in VAR a magnetic stirring of the liquid pool gains a good surface. This cannot be transferred to steel or nickel production because under this circumstance freckles will be developed easily.

Finally, at the end of the re-melting the ingot needs to be homogenized in order to avoid stresses during cooling down. Depending on the material grade further precautions must be taken to avoid cracking of the ingot. In some special cases a hot transport to the heat treatment furnace prior to forging or rolling is recommended.

**METALLURGICAL RESULTS FROM A PRACTICAL VIEW POINT**

ESR ingots do not typically show pipe or top shrinkage. The total ingot can be used for the subsequent processing. The difficulty of the shrinkage hole in ESR increases with the ingot diameter. The hot topping procedure should be followed in such a way keeping the slag temperature and filling the shrinkage volume with the appropriate material flow at the same time. The two processes produce high density ingots with good material yield as it is given from the controlled growing solidification front without cavities. The top and bottom discards of ingots are less compared to conventional cast ingots. The ingot density of re-melted material is higher than in conventional casted ingots. The forging ratio can be reduced due to the higher material density. The chemistry control in re-melting is excellent due to inert gas furnace atmosphere. In case of VAR a vacuum above the liquid pool rules the reaction of volatile elements which can be calculated to adjust the desired level in the VAR ingot. Sulfur removal is very limited in VAR due to the absence of a reactive slag. In case of ESR desulphurization occurs as well in an inert gas atmosphere by a metal-slag reaction and with dry air by a metal-slag-gas reaction. The cleanliness in ESR is improved by avoiding undesired reactions with the atmosphere in closed furnaces. In case of VAR desulphurization occurs as well under an inert gas atmosphere. The oxidation of the electrode surface does not take place and the reactions on the slag bath surface of elements with variable valences will be suppressed. Here the thermodynamic is no longer influenced by slag/metal reactions in combination with the atmosphere. However the avoidance of oxygen near the melting off area helps to increase the cleanliness level in the final ingot even when the re-melting time is extended in closed systems.
Figure 4 shows results from acceptance cast taken from constructional steel and bearing steel. Similar steels belonging to the mentioned group were re-melted in ALD furnaces with the presented results. The influences from the process on the changes in elements can be taken easily from this figure. In sulfur removal the ESR is superior whereas the VAR shows at least a less significant effect and could be influenced from analytical accuracy at lowest contents. Regarding the differences in evaporation losses in VAR presented by the element Manganese (Mn) it must be mentioned that one material was re-melted under elevated pressure resulting in lower losses. The oxygen content of the ESR ingots may be a little higher in ESR due to the re-melting using the slags.

The macroscopic ratings of the conventional ingots are done according to ASTM E381 for carbon and low alloyed steels whereas ASTM A604 should be chosen on re-melted material. In conventional casting the following parameters will promote defects. High pouring temperatures to compensate for temperature losses will increase the segregation inside and produce microspores (unsound) castings. This even happens when the pouring temperature is too low. The pouring rate creating a turbulent stream results in excessive surface splashes and bad ingot surface. Reduced pouring rate can minimize the unsoundness but needs higher pouring temperatures due to longer casting time. The pouring rate cannot be reduced under a certain value without avoiding capping, entrapment of inclusions or unsoundness. Oxides products introduced from ladle (secondary metallurgical processes) or lining (in case of VIM) and tundishes from erosions or insufficient shrouding technologies and casting powder must be accepted in conventional ingot casting. The weakest point of the chain is the workman ship for example preparing the casting set up. Last but not least the source of raw material input should not be neglected.

Focusing on the type of inclusions and defects we should have a view on the ability of both re-melting processes. The before mentioned disabilities will be solved using the consumable electrode re-melting. Segregations can be controlled, inclusions will be removed, a further refining of harmful elements in higher concentrations like Sulfur in case of ESR takes place, further contamination can be prevented using water cooled copper crucibles in re-melting. Defects can be suppressed using sound electrodes which may be already re-melted.

Metallic inclusions from secondary sources cannot enter in VAR if the electrode is grinded. In ESR the slag acts as a buffer to melt surface contaminations or clumps from electrode before entering the liquid pool. Therefore no white spot (ingot defect) exists in ESR ingots. Nitrides or oxides in electrode from casting process or insufficient melting practice (lining) in case of VAR will be transferred to the pool surface and agglomerate. Those particles will be transferred to the outer side of the pool having an influence on electrode feed control and the ingot needs to be scaled at the end. In ESR the oxides will be incorporated and dissolved by the oxides in the slag and the nitrides will be moved towards the slag skin. Therefore the contamination in oxide inclusions from melting practice can be absorbed by re-melting.

Further statement on the behavior of the oxide inclusion will be given. Four electrodes of same size and height were casted from one mother melt for gathering information on the inclusion behavior.
when re-melted using both processes. The crucible sizes in ESR and VAR divers due to the different fill ratios used.

Microcleanness was investigated using German Industrial Standard 50602. The examination was done using the severity number called $K_0$ which represents vacuum produced or re-melted steels. The findings on single re-melted steel 1.2343 (H11) from both processes show ESR $K_0$ equal and better 5 and similar in VAR. Statistically the results are similar to ESR and indicate $K_0$ from 2 to 4. In detail the test ingots shows up with more small inclusions in ESR material whereas in VAR material bigger sized inclusions exist. Because electrodes coming from the same melt practice in ESR the bigger sized inclusions will be absorbed by the slag or start to dissolve.

Figure 5 shows analytical results from inclusion screening. The inclusions are mostly belonging to the round shape and containing Aluminum (Al), Calcium (Ca) and in case of ESR Magnesium (Mg).

<table>
<thead>
<tr>
<th>Spectrum</th>
<th>Si</th>
<th>Mg</th>
<th>Al</th>
<th>Ca</th>
<th>Fe</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>43.34</td>
<td>14.20</td>
<td>36.73</td>
<td>1.48</td>
<td>4.26</td>
<td>100.00</td>
</tr>
<tr>
<td>2</td>
<td>43.34</td>
<td>14.20</td>
<td>36.73</td>
<td>1.48</td>
<td>4.26</td>
<td>100.00</td>
</tr>
</tbody>
</table>

Fig. 5: Analytical results from inclusions of re-melted material using ESR (left) and VAR (right)

The electrodes are coming from secondary metallurgical treatment and containing inclusions of alumina (Al₂O₃), Calcia (CaO) and magnesia (MgO) as explained above. According to the cleanliness evaluation the inclusions are of round shape only in respect to the melting practice of the electrodes [8].

Focusing on the single ingots and the cleanliness results different composition of inclusions were analyzed comparing the two re-melting processes. In ESR the inclusions are of similar composition as on the casted electrodes (globular type) whereas in VAR the magnesium component doesn’t exist.

**CONCLUSION**

The question which alloys are to be re-melted using the ESR or the VAR process only cannot be clearly answered. According to the history of both processes in case of high-strength constructional steels, stainless steels VAR is used in the United States whereas in Europe and Asia ESR is favorable. Only in case of re-melting of alloys used in aviation/aerospace the specifications ask for triple melting.

The VAR process guarantees low gas content in the ingot and with extreme low melt rate a very controlled ingot solidification and structure. The ESR process stays for sulfur removal in any case and an excellent ingot structure. The melt rate and the slag system have to be adjusted accordingly. Re-melted material shows less segregation, higher density material and in consequence controlled solidification resulting in excellent chemical and physical properties of the end-product. In addition the product life time is raised (tool and dies) or smaller cross sections in final product can be realized with the same work load. The piece weight/ strength ratio is enhanced.

Ingots produced in re-melting using optimized process conditions can be produced without shrinkage cavity and therefore the material yield in production from first melting up to the final billet is improved.

An additional re-melting step helps to improve the product quality and avoid deviations in material quality arising from the workmanship in steel casting shops. In some cases this is paid by less material back flow due to higher quality level detected in subsequent process steps.
Today’s best melting practice consists of multiple steps. Depending on the final application and/or specification of the material the melting process has to be designed. In case of low gas contents in final material the vacuum arc re-melting process should be chosen. Whereas the uniformity of mechanical properties in regard to different directions becomes important the electro slag re-melting process should be used. This may lead to a mixture out of both re-melting processes – ESR and/or VAR.

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