Large ESR forging ingots and their quality in production

P. Bettoni, U. Biebricher, H. Franz, A. Lissignoli, A. Paderni, H. Scholz

ESR is known as an alternative step on the continuous improvement in single ingot production for heavy forgings. In the recent past a new state of the art ESR remelting system was installed with the possibility to produce ingots in diameter from 1000mm for 45tons till 2000mm for 145tons. Consumable electrodes from traditional fabrication processes which consist of melting with electrical arc furnace, refining, degassing of the steel and bottom pouring will be used to produce one single heavy ingot with best cleanness with the help of electrode exchange technique. This paper tells about the furnace characteristics and the efforts to be made to ensure high quality level in material and furnace preparation as well as save automatic production performances during remelting and electrode exchange. Finally the results of ingots characterized by an elevated level of chemical homogeneity and internal quality such as to ensure the absence of defect greater than 0.5mm AVG during the final inspection of the forged part from the ESR production will be presented. The ESR process serves for the reproducible quality in heavy ingot making and tightens the limits in specifications together with high material yield.

Keywords: Remelting - Iingot - Homogeneity - ESR - Micro-inclusion

INTRODUCTION

ASO Siderurgica is a steel mill dedicated to the production of raw ingots, from carbon steel to high alloy grades. From more than 20 years, the company is deeply engaged in a continuous qualitative improving of the product in terms of chemical homogeneity, strong reduction of gas content, and, primarily, lowering the content of micro and macro inclusions. Along this path of continuous improving, one of the main challenge has been investigating new metallurgical, productive and plant engineering solutions which allowed us to satisfy the needs of our forging customers involved in the realization of forged pieces for steam and gas turbine. During the years in fact, the needs of turbine producers, already from the beginning particularly demanding, have become increasingly restrictive, especially in terms of UT cleanness, transparency and maximum acceptable defect.

The traditional ingots fabrication processes which consist of melting with electrical arc furnace, refining, degassing of the steel and bottom pouring had been pushed to the limits of their possibility in order to guarantee the maximum cleanness. In spite of this, in some case forgemasters are anyway "forced" to reduce the yield, increasing top and bottom discard especially on large products, in order to cut down the risk of rejections during the final testing, sometimes because of defects that do not even reach 1 millimeter AVG. And on the other side, the same binding characteristics of the finished product push steel producers to increase the hot top ratio and to do some modification on the bottom part in order to improve the global quality. Both this situation obviously reduce the total efficiency and consequently weighs considerably on the overall costs of production. In addition, it must be considered that the negative characteristics of the bottom poured ingots are emphasized increasing dimensions and weights mainly because of the long solidification times resulting in more pronounced micro and macro segregation.

As a new step on the continuous improvement, a couple of years ago ASO installed a new ESR remelting system from ALD Vacuum Technologies. (fig. 1) The plant follows the principles of the short collar mould with an ingot withdrawal and only one electrode feeding. This investment can cover a wide range of sizes and weights: final ingots dimensions are from round 1000mm to round 2000mm and, as a result, the weight goes from 25tons to 145tons. At this moment ASO has not installed the maximum of the capacity but we put beside the mould 1000mm an intermediate measure of 1600mm which corresponds to ingots weight of 95tons. The melting workspace is served by two towers dedicated to the handling of electrodes themselves.

Considering the materials target to remelt in ASO's plant,

A. Paderni, A. Lissignoli, P. Bettoni
ASO Siderurgica
Ospitaletto, Italy

H. Scholz, U. Biebricher, H. Franz
ALD Vacuum Technologies, Hanau, Germany

Paper presented at the 2nd Int. Conf. Ingot Casting Rolling and Forging - ICRF 2014, Milan 7-9 May 2014

each of them is obviously equipped with slag system addition, alloys element addition and inert gas atmosphere during remelting.

START-UP WITH INGOT 1600

The stat-up of the plant has been made with the mould diameter 1600mm. ASO arrived at this moment with only an experience accumulated in the previous years of managing the VAR plant, but in a short time it has been clear that precautions which must be taken for the ESR ingots are more extensive and complex. Part of the differences are linked to the dissimilar sizes of the products: it's easy to understand that the preparation of the electrodes, welding of the stub and alignment with the axis of the electrode, handling by the operators are strongly affected by dimensions and weights. Of course, some of the problems that must be taken into account for a good remelting are widely known from literature and direct experience of some competitors. As a common example we can quote the possible pick up of Hydrogen especially during the first stages of remelting or the risk of reoxidation of the material due to the contact with air. Unfortunately, while the problems are known, solutions are not so easy to find especially because causes are multiple and different from one situation to another; that's why it took a lot of afford to reach the actual safe situation.

From a practical point of view, the main question mark for the people in charge of the new plant was for sure the electrode changes. Even in the case that it is conducted in best possible way, we must never forget that it is still an interruption in the continuity of the process. Consequently, it was a necessary prerequisite to reduce as much as possible the time between the end of the first electrode and the beginning of the second. About this, we have to admit that, after performing the necessary settings on the first two ingots, electrode change has been a point that has never reserved particular complications and has always done on a regular basis without ever exceeding the time limit of 70 seconds.

In addition to all these aspects, the biggest conceptual difference approaching the ESR is due to the presence of the slag. First of all it represents an external factor in respect to the system electrode/ingot so it must be considered as an additional risk in the remelting. This means also that, while on the VAR the main electrical parameters chosen in the recipe are "directly" applied to the electrode and consequently can be evaluated also according to the quality of the primary steel mill product, in the ESR they can "reach" the steel only through the behavior of the molten slag.

Consequently the slag become the key player in determining some fundamental aspects of the finished product among which we can point out the surface quality and the extension of the shrink hole on the top of the ingot. There are some general lines to follow in order to choose the best slag composition for that peculiar steel but they are mainly qualitative and only the experience and deep knowledge of your system allow a rapid choice of the correct chemical composition.

Farther more, it's not possible to forget that even small modification in the chemical equilibrium can lead to different electrical behavior in the ESR. According to this, some of the main parameters contained in the melting profile like resistance, current and swing must be carefully balanced on the expected slag performance. At the beginning it took us a lot of effort and time to set a good slag equilibrium.

Consequences of our inexperience were evident in a marked undulation of the skin, in a too limited cap of slag

Fig. 1 - Basic furnace design.

Fig. 1 - Schema dell'impianto installato in ASO.

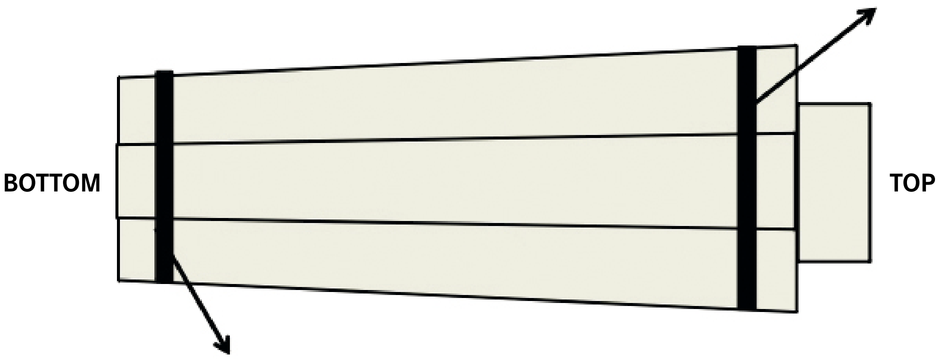
Fig. 2 - First ingot with electrode change.

Fig. 2- Primo lingotto realizzato con cambio elettrodo.

Fig. 3 - Examples of hot top cavites.

Fig. 3 - Esempi di cavità inizialmente presenti sotto materozza.

C%	Mn%	Si%	P%	S%	Cu%	Cr%	Ni%	Mo%	Al%	V%	
0.27	0.70	0.29	0.006	0.002	0.10	1.17	0.49	1.13	0.007	0.275	Outside 1
0.29	0.71	0.29	0.007	0.002	0.10	1.18	0.50	1.15	0.006	0.278	1/2R
0.31	0.73	0.30	0.008	0.002	0.10	1.12	0.52	1.18	0.006	0.29	Centre



	C%	Mn%	Si%	P%	S%	Cu%	Cr%	Ni%	Mo%	Al%	V%
Outside 1	0.26	0.69	0.29	0.006	0.002	0.10	1.16	0.49	1.11	0.006	0.270
1/2R	0.26	0.69	0.29	0.006	0.001	0.10	1.15	0.49	1.1	0.007	0.267
Centre	0.24	0.68	0.28	0.006	0.002	0.10	1.14	0.47	1.1	0.007	0.265

Fig. 4 - Typical chemical distribution of a bottom poured ingot.

Fig. 4 - Tipica analisi chimica di lingotto tradizionale.

at the end of remelting, in an evident ring in correspondence with the electrode change.
All this points do not represent big problems themselves but they have to be read as external evidence of bigger possible internal problems: for examples, a small cap should immediately suggest a possible shrink hole wider than desired and a too manifest electrode change position can be easily linked to a non optimal internal structure of the ingot.
At the end, the result of all the efforts done during remelting can be "measured" by the top and bottom scrap percentage. While the lower part of the ingot should be discarded because of some metallurgical reason related to the chemical composition variation and solidification direction strongly influenced by the copper base plate, the upper part is affected by porosity and shrink hole cavity strictly connected to how good is the hot top part of the melting profile (fig. 3) : better you are able to manage the closing of the process, more material you can save on your ingot.
Unfortunately, this is absolutely not easy to obtain, in fact the hot top part of the recipe is the most difficult part to optimize during remelting and often it required more than one cast to obtain a satisfactory result.
Starting from a situation on the first ingot which can be compared almost to a complete absence of hot topping, actually we can assure a limited entity of the natural cavity present below the upper extremity of the ingot and it is reasonable to think this can be reduced to a nearly total absence after several melt of the same combination material/ingot.

COMPARING METALLURGICAL RESULTS OF THE NEW INGOTS AND EQUIVALENT TRADITIONAL ONE.

As everyone know, remelted ingots are, from a purely metallurgical point of view, preferable to the traditional bottom poured ingots because of a series of reason: chemical homogeneity, micro inclusions content, ultrasonic results test, absence of segregation, fine and uniform structure.
Consequently, after the plant became fully operational, we were strongly interested to see if these benefits were really found also on ESR ingots with an important section like our 1600mm. For a better understanding, we tried to compare characteristics of a remelted ingot weighting around 40tons, with a polygonal ingot with a similar traversal section of 1500mm and a gross weight near 32tons.

C%	Mn%	Si%	P%	S%	Cu%	Cr%	Ni%	Mo%	Al%	V%	N ppm	
0.30	0.71	0.31	0.010	0.001	0.13	1.19	0.49	1.15	0.015	0.244	40	Outside 1
0.30	0.72	0.32	0.010	0.001	0.13	1.19	0.48	1.16	0.013	0.252	40	1/2R
0.32	0.72	0.33	0.011	0.001	0.13	1.20	0.50	1.15	0.013	0.251	42	Centre

	C%	Mn%	Si%	P%	S%	Cu%	Cr%	Ni%	Mo%	Al%	V%	N ppm
Outside 1	0.28	0.71	0.28	0.011	0.001	0.12	1.16	0.47	1.09	0.018	0.238	36
1/2R	0.29	0.70	0.31	0.000	0.001	0.13	1.17	0.48	1.11	0.017	0.242	35
Centre	0.29	0.71	0.31	0.010	0.001	0.13	1.17	0.48	1.13	0.017	0.246	36

Fig. 5 - typical chemical distribution of the remelted ingot.

Fig. 5 - tipica analisi chimica di un lingotto rifuso ESR.

	ESR 1600						Pol. 32 tons					
	Top			Bottom			Top			Bottom		
TYPE GO	Outside	1/2 radius	Center	Outside	1/2 radius	Center	Outside	1/2 radius	Center	Outside	1/2 radius	Center
grade 0	7	11	15	6	23	15	18	21	43	8	26	26
grade 1	12	3	12	4	6	1	9	13	7	1	10	3
grade 2		2					2	2	1		1	1
k0	**5**	**3**	**4**	**1**	**4**	**2**	**7**	**10**	**14**	**2**	**7**	**5**
	avg K0=4			**avg K0=2,3**			**avg K0=10,3 (+157%)**			**vg K0=4,7 (+104%)**		
	ESR 1600						**Pol. 32 tons**					
TYPE GO	Outside	1/2 radius	Center	Outside	1/2 radius	Center	Outside	1/2 radius	Center	Outside	1/2 radius	Center
grade 0	0	0	0	0	0	0	0	5	7	0	0	0
grade 1	0	0	0	0	0	0	0	0	3	0	0	0
grade 2	0	0	0	0	0	0	0	0	0	0	0	0
k0	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**2**	**0**	**0**	**0**

Fig. 6 - Comparison of micro inclusion content between standard ingot and remelted ingot.

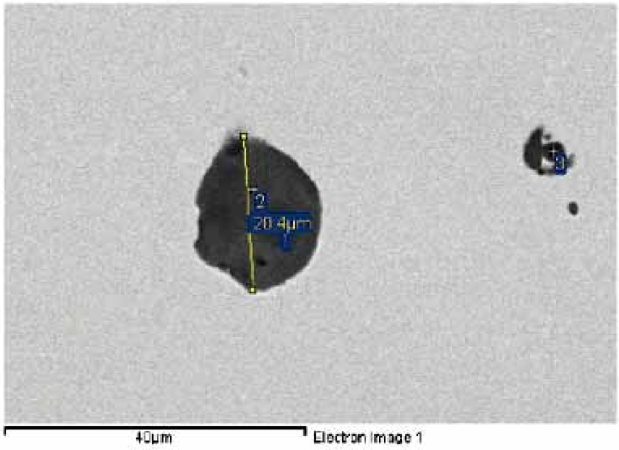
Fig. 6 - Confronto del contenuto microinclusionale tra un lingotto tradizionale ed il corrispettivo rifuso ESR.

COMPARING CHEMICAL COMPOSITION OMOGENEITY.

The easier and first thing to compare is for sure the chemical composition, especially in terms of uniformity between top and bottom of the ingot and along a given section. As many investigations already confirmed, traditional ingots are characterized by a negative segregation in bottom half and by a positive one on the upper part and the effect is more evident going from the outside to the inner part. This situation is mainly of interest with regard to the carbon distribution but also other alloy elements are affected, although to a lesser extent.
On the contrary, one of the main benefit of remelted ingot is the homogeneity of the material. As we have witnessed directly, after remelting, the segregation tendency is drastically reduced: it's easy to verify that the difference from top and bottom are almost completely crossed out. It's interesting to notice that on the bottom, just below the surface, the composition of the steel is a bit "poorer": this can probably be related to the faster solidification during first part of remelting due to the strong cooling effect of the copper mould and plate. Obviously, the more uniform chemistry results later in a better response to heat treatment with a more consistent behavior testified by mechanical properties.

COMPARING MICRO INCLUSION CONTENT

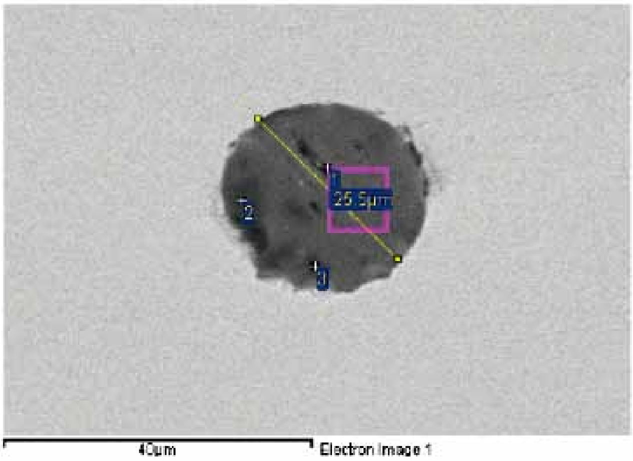
A work of comparison similar to one just presented for chemical analysis was also performed to verify the contents of micro impurities in the steel. The table below shows, as reference, typical result from the micro-inclusional counting of traditional ingot and remelted one. In both situation, the characteristic impurities are represented mainly by the globular oxide type (OG class - DIN 50602) and some Sulfur compounds (SS class), only in traditional ingots. It's more than evident how the steel treated in the ESR plant is subjected to a purifying action



Processing option: All elements analysed (Normalised)

Spectrum	In stat.	O	Mg	Al	Si	Ca	Fe	Total
1	Yes	41.38	17.06	39.35		0.68	1.54	100.00
2	Yes	38.17	3.48	42.84	0.50	13.62	1.39	100.00
3	Yes	43.34	14.20	36.73		1.48	4.26	100.00

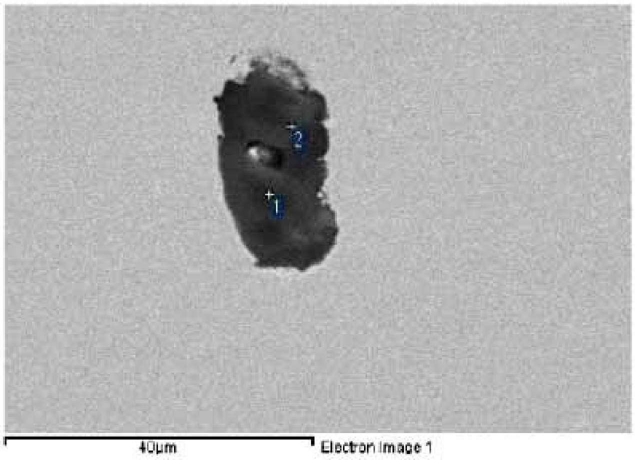
All results in weight%



Processing option: All elements analysed (Normalised)

Spectrum	In stat.	O	Mg	Al	Si	S	Ca	Fe	Total
1	Yes	37.12	2.02	22.41	3.51	0.50	32.75	1.70	100.00
2	Yes	41.73	17.52	38.98				1.77	100.00
3	Yes	42.65	17.10	28.95	0.78	0.85	8.36	1.31	100.00

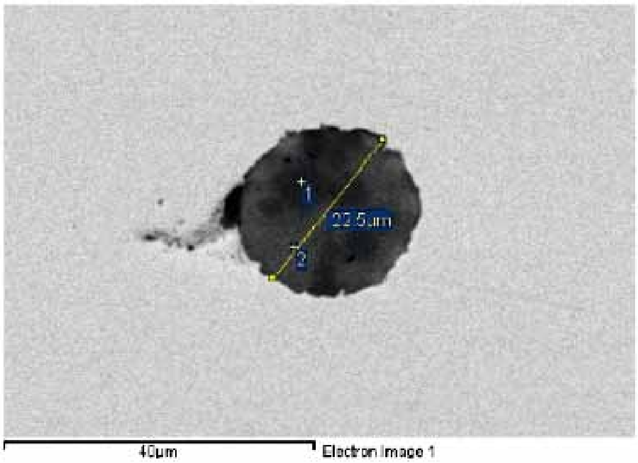
All results in weight%



Processing option: All elements analysed (Normalised)

Spectrum	In stats.	O	Mg	Al	Ca	Fe	Total
1	Yes	40.02	14.98	40.14	3.42	1.44	100.00
2	Yes	40.22	2.62	32.45	23.20	1.50	100.00

All results in weight%



Spectrum	In stats.	O	Mg	Al	Si	S	Ca	Fe	Total
1	Yes	42.91	17.53	38.77				0.79	100.00
2	Yes	33.37	2.71	22.09	3.76	3.24	33.31	1.51	100.00

All results in weight%

Fig. 7 - Typical chemical composition of inclusion present in ESR and traditional ingots; pictures showing biggest inclusions for better illustration.

Fig. 7 - Tipica composizione chimica delle microinclusioni presenti nel lingotto tradizionale e nel corrispettivo rifuso; per una migliore chiarezza di illustrazione sono qui riportati I casi di dimensioni maggiori.

by the slag through which the material must pass before going to produce the new ingot. This improvement is most evident when we focused our attention to the upper part which is normally the "dirtier" one in the bottom pouring because of its proximity to the top part that is the last one to complete the solidification. The disappearance of the Sulfur inclusions is further evidence of the slag effect and reduced segregations and is also confirmed by the reduction of this element in the chemical composition from before to after remelting.

COMPARING MICRO INCLUSIONS COMPOSITION

Another interesting aspect to verify is if the presence of the slag in the remelting has some effects also on the chemical composition of the microinclusions, as well as remove part of those present in the starting electrodes. The faster way to investigate this characteristic is through a series of SEM analysis. From its experience, ASO already knew the typical inclusion present in traditional products is a calcium aluminate with trace of other elements like Si and manganese sulfurs finite to the top area. In ESR steel is confirmed that the main elements which make up these natural impu-

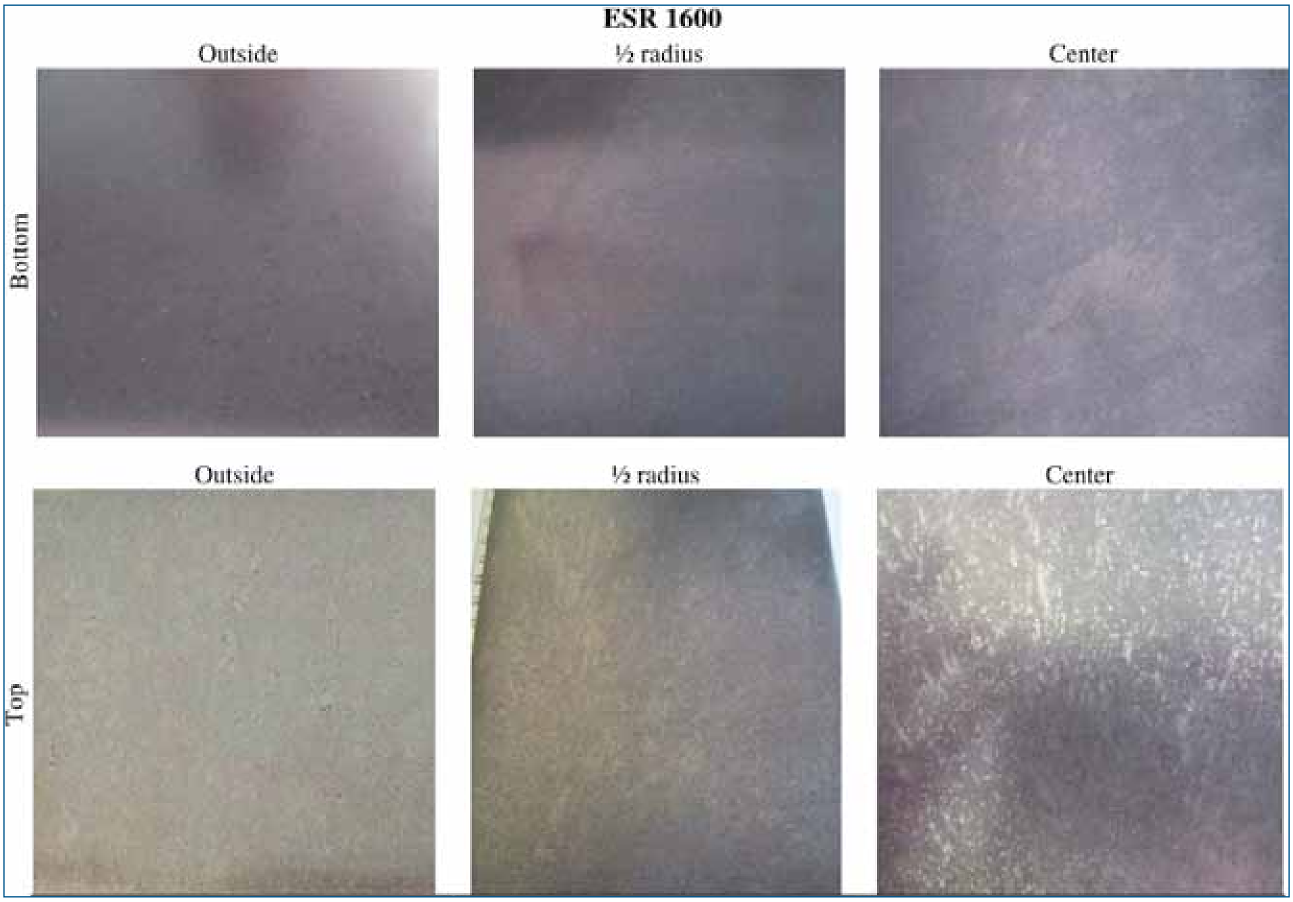


Fig. 8 - Macrostructure ESR ingot (HCl 50% etch)

Fig.8 - Macrostruttura di lingotto ESR (attacco con HCl 50%)

rities are almost the same, Al, Ca and of course O, but it's possible to notice that at the same time other components are almost disappeared while the MnS are strongly reduced till to be completely disappeared. At this point it is possible to hypothesize how the refining action of the synthetic slag during remelting have not the possibility to affect the main constituents because itself is composed primarily of CaO and Al2O3 but, due to the new chemical equilibrium and reactions it takes with the steel passing through, the slag can retain some of these undesirable elements. On the same line, it will be very interesting for the future also investigate the effect of the slag on other types of inclusions characteristics of more particular steels containing for example titanium or Zirconium.

COMPARING MACRO STRUCTURE

Considering the big difference in the solidification process between the two products we are considering here in term of time for the complete solidification, possibility to influence the direction of the solidification, reduce the segregation tendency and distribution, we extend the evaluation also to the macro structure condition. Here it's presented some pictures in different position (external, mid radius and center) both for the top and for the bottom.

It's easy to observe how on the not-remelted material, and in particular in the part that corresponds to the center of the ingot, the presence of segregations is more evident. This can be also related to already mentioned difference observed about the chemical behavior of the different products.
Furthermore it's simple to image how this condition can lead to the often experimented situation of different results on the forged parts in terms of mechanical characteristic and hardness.

COMPARING ULTRASONIC PERFORMACIES.

Of course, in order to have a good base for a complete comparison about performances of the two production ways in terms of UT defects, it's necessary to have a substantial historical trend and, about ESR, ASO at this time cannot say to have a similar one. Some preliminary considerations can be done in any case. First of all, if the slag is managed in an accurate way, its presence can play a positive role in removing macroinclusions as well as already seen on micro impurity. This means that all the defect included in the dimensional band between 0.5 and 1mm AVG, where traditionally the

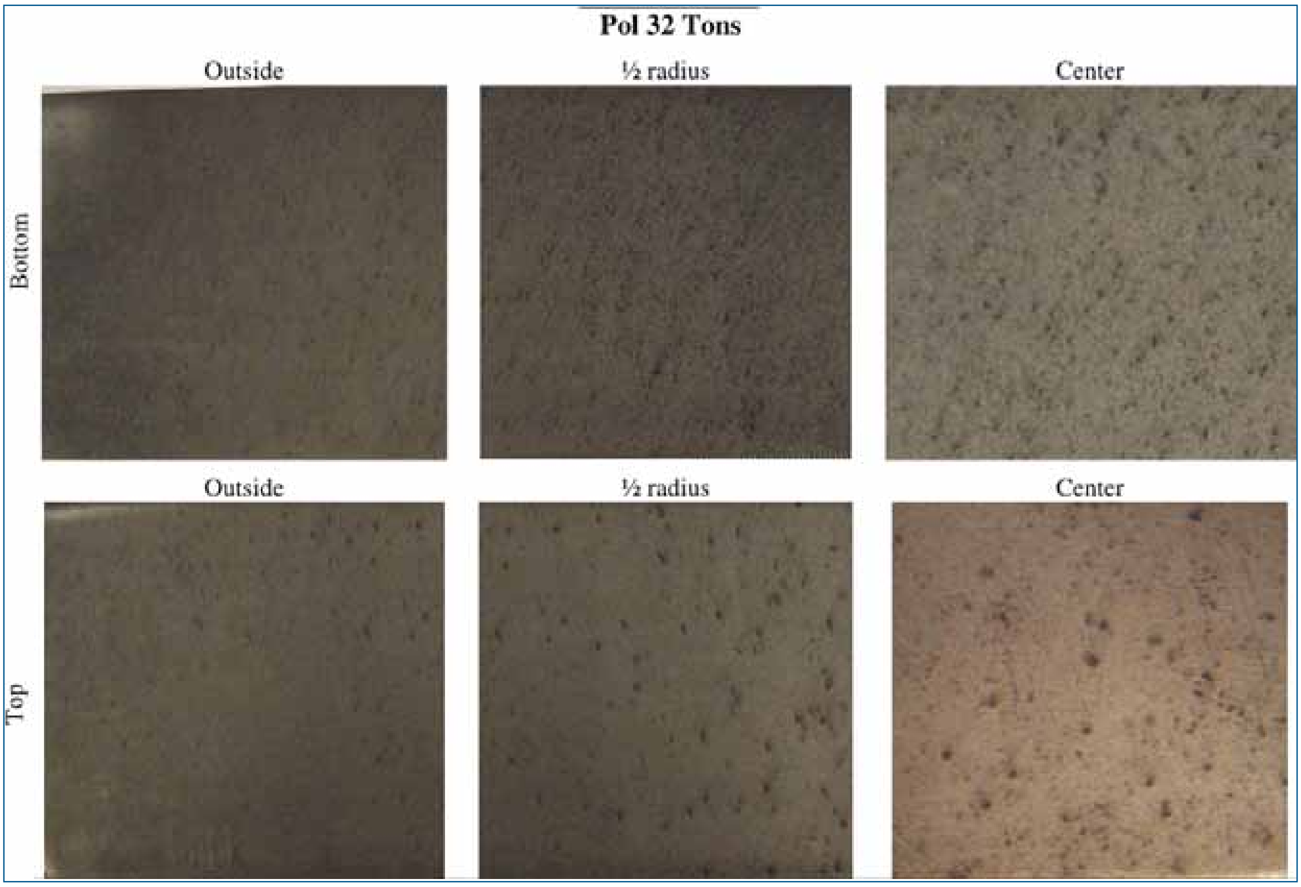


Fig. 9 - Macrostructure standard ingot (HCl 50% etch)

Fig.9 - Macrostruttura di lingotto tradizionale (attacco con HCl 50%)

quality of the steel produced in the traditional way begins to highlight the inherent limitations, could be definitely removed. In addition to this, just after few remelting, it was possible to observe that, for main part of materials, a further refining step also provides greater transparency to the ultrasonic inspection after forging, even with lower reduction ration than the traditionally accepted 3 to 1.

COST BENEFIT COMAPRISON BETWEEN ESR AND BOTTOM POURED INGOTS

As already mentioned, even if perfected over the years, the technology of bottom pouring shows in the last years its limits facing the new requirements over and over more restrictive. The qualitative performances required by the end users to forged pieces have become increasingly demanding in order to tolerate, for the same materials, operational situations increasingly challenging and a useful life longer and longer. For the same reasons, also the acceptable limits of the internal defects measured by ultrasonic tests have been pushed down clashing with the inherent limitations of the most widely diffused methodology for the molding of the ingots. And this last point is more evident if we look to the specification for the bigger forged parts addressed to generators and turbines required by the power generation field. From the point of view of the material quality, considering what is the benefit of a remelted ingot in comparison to the traditional one, the logical consequence is to shift from one to another. Unfortunately this cannot be done without taking into consideration also the additional cost of a further refining process.

ASO uses its experience in producing ESR ingot diam. 1600 to study in deep the economical comparison between the two different kinds of products and the results are summarized in three different graphs.

In order to have a wider understanding, we have to go a bit deeper in analyzing the main factors which determine these results. First of all the yield of the ingots (represented by the differencebetween the gross weight of the ingot and the final net weight). On the traditional products, the top quality is usually obtained using polygonal multiple face ingots. It's well know how them suffer a low yield especially due to the significant wastages it must be applied on top and bottom in order to remove all the risky zones. On the other side, ESR ingots are obtained from round electrodes and themselves are round in shape and it's easy to verify that in this condition the scrap part is substantially reduced. In addition to this, it must be always taken into consideration that, contrary to the bottom poured ingot, the top and bottom scrap of the remelted products can be considered fixed and consequently, increasing the total weight, they reduce in term of percentage. A direct consequence of what just described about the material to be discarded is that the use of the ESR is more and more convenient if the value of the material increases.

Furthermore some other aspect can eventually contribute to make the ESR ingot more attractive: due to the greater compactness of the material, it is possible to consider a reduction of forging cycles (in some cases, it may reduce or eliminate the step of upsetting); remelted ingots can be supplied with a specific weight specifically calculated for the particular that will be realized in the end; the transport costs can be reduced because of ESR ingot weighs less than the corresponding traditional one.

Therefore, it's possible to affirm that the advantages and disadvantages of using an ESR ingot must be evaluated for each individual project, as function of weight and material value, not being not automatic that the overall cost is always higher. Following this line, especially for expensive materials and big dimensions, although it is not explicitly required by the specific supply, it may be advantageous using an ESR ingot and, against a higher cost however limited, supply an higher quality product reducing the risk of receiving unwelcome surprises in the final testing phase of the forging piece.

CONCLUSIONS

In recent years, many companies have completed the installation of new ESR remelting facilities which, if compared to the average dimensions of the past ones, have now the possibility to produce ingots of much greater size. The present report describes the direct experience of ASO in producing remelted ingot with a diameter of 1600mm. Therefore it has been tried to highlight some quality aspects of this new materials by means of a comparison operation between the metallurgical characteristics of the ESR ingots with those of traditional polygonal ingots of high quality, produced by degassing and bottom pouring. The general results confirm the evident quality advantages, already known from the literature.

It has been also shown the results of an exercise in economic comparison. For our understanding, the gap in costs between the block obtained from ESR remelted ingot and the equivalent on from polygonal ingot tends to thin increasing the weight of the raw materials and the specific cost of the involved steel. As a natural consequence, in some conditions, especially when the quality requirements are very challenging, balance quality / price is in favor of the ESR product, so that in this situation it would be worthy to purchase the re-melted even when the final specification of the customer does not require it.

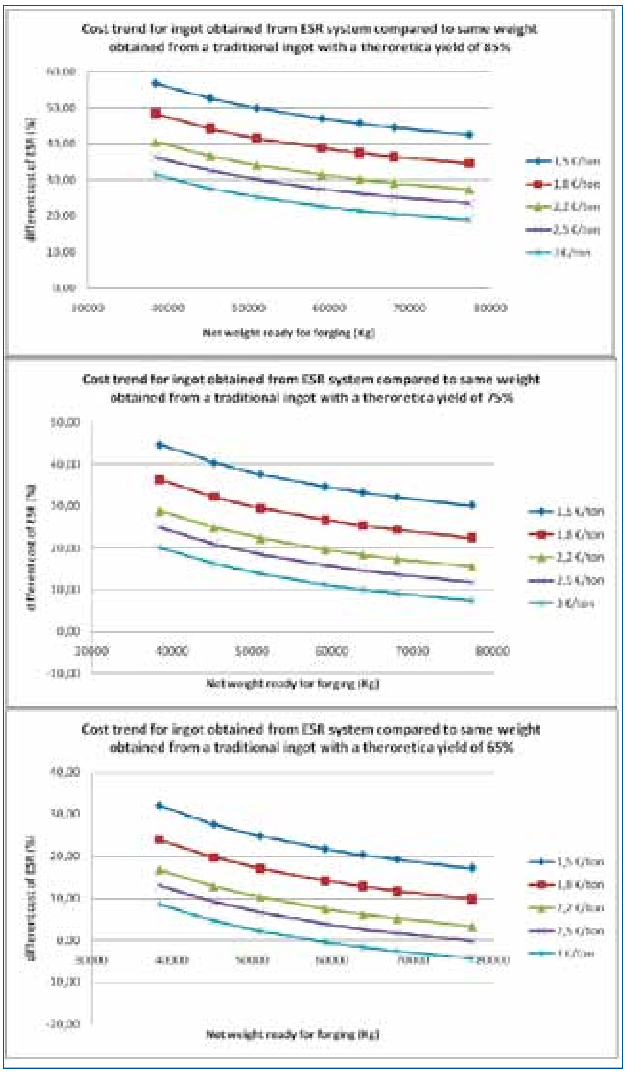


Fig. 10 - Graphs explaining economical behavior according to different parameters.

Fig. 10 - Grafici esemplificativi dell'andamento della differenza di costo al variare dei parametri fondamentali.

BIBLIOGRAPHY

1] F. Reyer-Carmona, A. Mitchell, "Deoxydation of ESR Slags",

2] R. Schumann, C. Ellebrecht, "The Application of Electroslag Remelting for the Production of Heavy Forging Ingots",

3] A. Mitchell - "Solidifcation in remelting processes",

4] H. Scholz, U. Biebricher, "ESR meets the Requirement for Bigger Forging"

Valutazioni qualitative su grandi lingotti da forgia realizzati tramite tecnologia di rifusione ESR

Parole chiave: Acciaio - Ossidazione - Solidificazione - Affinazione - Fusione e rifusione - Metrallografia

La rifusione tramite impianti ESR si sta sempre più affermando come un passo successivo nella direzione del miglioramento continuo dei lingotti di grandi dimensioni destinati alla fucinatura. Pochi anni fa, in ASO, è stato installato un impianto ESR di ultima generazione in grado di garantire la produzione di lingotti dal diametro di 1000mm per 45tons fino al diametro di 2000mm per 145tons. Grazie alla nuova tecnologia che consente un rapido cambio elettrodo, è possibile oggi, partendo da più lingotti realizzati con produzione tradizionale (EAF + affinazione + degassaggio + colaggio in sorgente), ottenere un unico grande lingotto di qualità superiore. Questa memoria, dopo una breve introduzione circa le caratteristiche tecniche dell'impianto, descrive sommariamente gli sforzi necessari a garantire un'adeguata qualità del materiale e gli elevati automatismi che accompagnano le fasi di rifusione e di cambio elettrodo.

L'attenzione viene poi focalizzata sulla valutazione dei risultati ottenuti i quali evidenziano un elevato livello qualitativo del lingotto ESR, caratterizzato da una ottima omogeneità chimica ed una elevata purezza tale da garantire l'assenza di difetti oltre i 0,5mm AVG sul pezzo finito. Nel complesso emerge chiaramente come il processo ESR sia fondamentale per ottenere un elevato e ripetitivo livello di qualità che possa soddisfare anche le più restringenti richieste delle varie specifiche e contemporaneamente assicurare un buon rendimento del processo produttivo. Viene infine riportato un confronto economico fra il costo di masselli ricavati da rifuso ESR ed il corrispettivo lingotto tradizionale degassato e colato in sorgente. I risultati di questo esercizio tengono conto di pesi, rese e valore del materiale. Si nota come il costo sfavorevole del lingotto rifuso venga via via riassorbito aumentando i pesi ed il valore del materiale considerato.