From ESR to continuous CC-ESRR process: development in remelting technology towards better products and productivity

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This work describes the development of the Electro Slag Remelting process at Valbruna, starting in the 1997 with an innovative INTECO ESR plant equipped with protective gas hood (for inert atmosphere remelting), electrode change system and fully computer controlled. The second step was made a couple of years later when the plant was upgraded to ESRR® (Electro Slag Rapid Remelting). With this new feature Acciaierie Valbruna was able to obtain ready to roll remelted billets (145, 160 and 200 mm square), getting rid of the traditional forging or blooming operations needed in case of traditional ESR ingot remelting. This was surely a dramatic cut off in product cost accounting and production lead time without loosing any of the special characteristics typical of ESR products. Unfortunately the ESRR® process, very promising in terms of cycle complexity reduction and quality of the product, because of its "batch-type" operation, was uneconomical in regard of productivity of the plant and not feasible in industrial scale. The final step of this development was made at the beginning of 2002 when t he ESRR® plant was upgraded again and equipped with an innovative INTECO automatic manipulator, which resulted in a continuous process. This was the birth of the very first CC-ESRR® (continuous casting electro slag rapid remelting) plant in the world. The first part of this paper focuses o n the development of processes and equipment, giving a brief description of ESR, ESRR® and CC-ESRR® process while the second part describes the results of a series of test remelting used for product and CC-ESRR® process characterization.

Key words: steelshop, processes, stainless steel, solidification

THE STANDARD ESR (ELECTRO SLAG REMELTING) PROCESS

The standard ESR process can be summarized in the above picture: by remelting a consumable electrode in a superheated liquid slag bath a new ingot is built up in a water cooled, copper mould. The energy required for the melting of the electrode is produced by an electric current passing through the liquid superheated slag which is acting as an ohmic resistance. The steel, which melts off from the electrode tip drops through the hot reactive liquid slag thus forming ideal conditions for slag metal reactions.
The constant metal level in the mould is realized by means

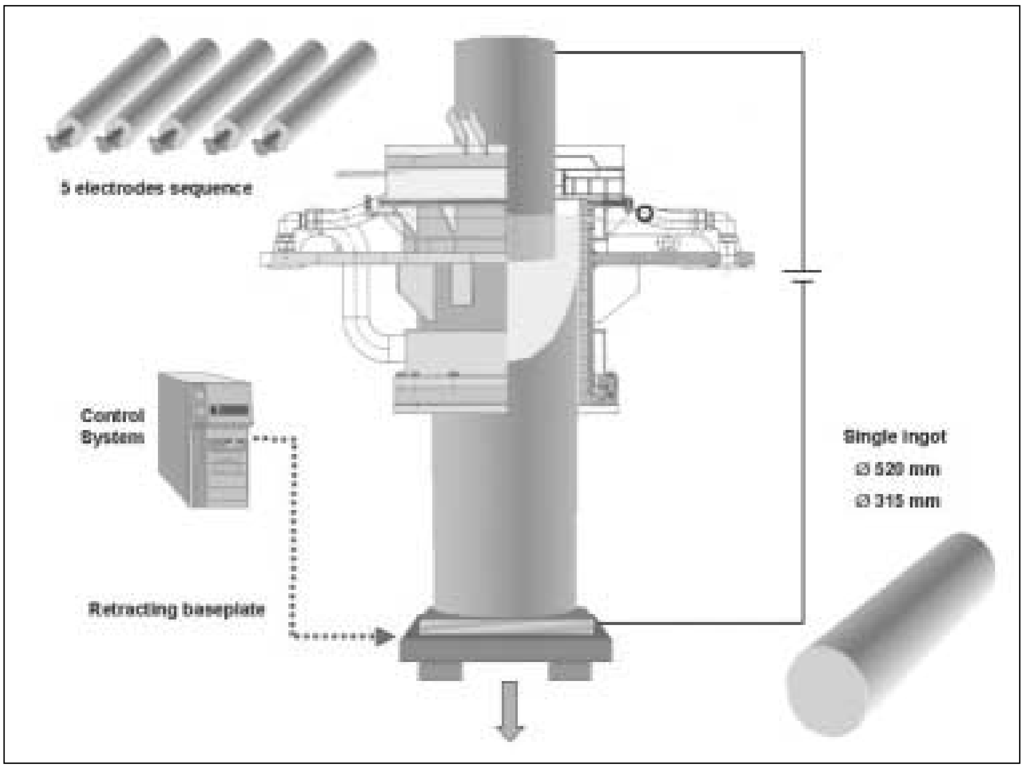

Fig 1 – ESR Process schematics.

Fig. 1 – Schema del processo ESR.

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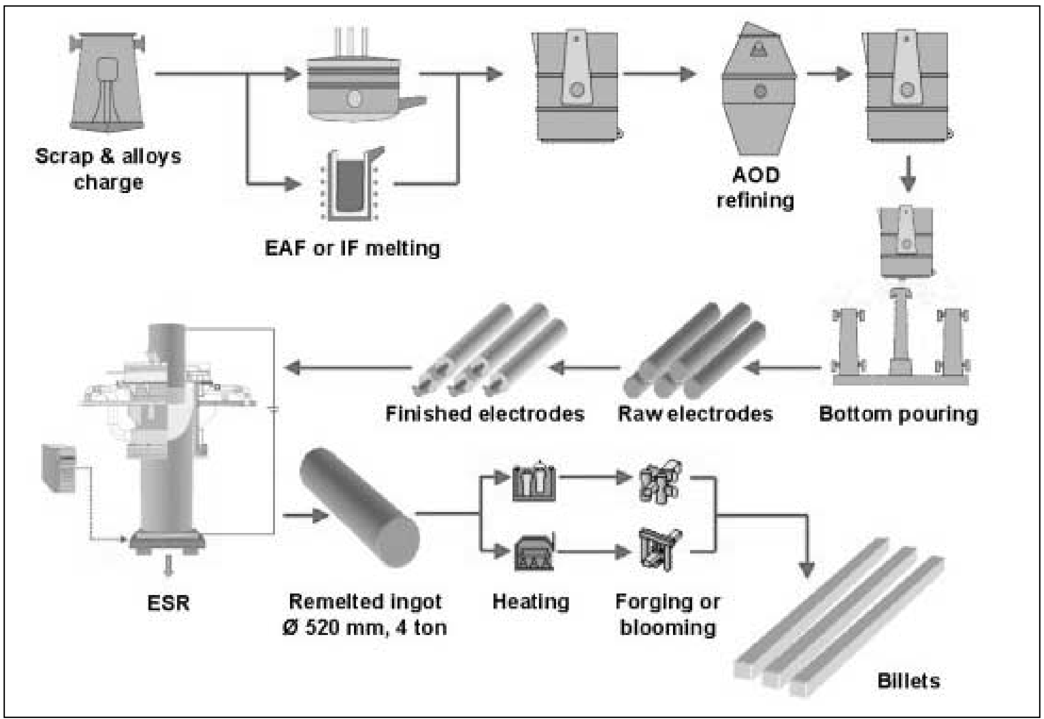


Fig 2 – The complete ESR production cycle.

Fig. 2 – Il ciclo completo della rifusione ESR.

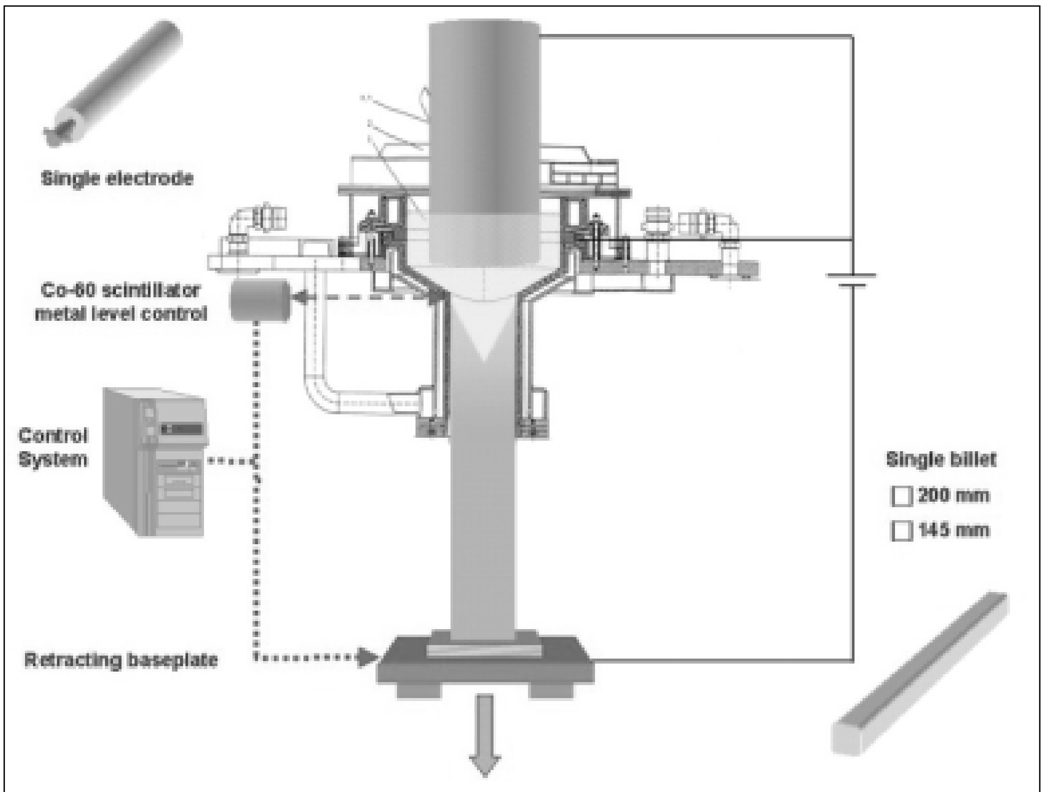


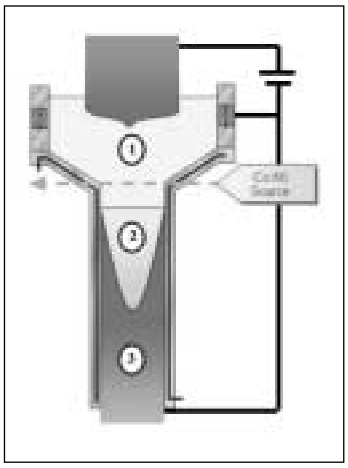
Fig. 3 – ESRR® process schematics.

Fig. 3 – Schema del processo ESRR®.

of a retracting baseplate, whose downward movement is set by the control system according to the meltrate and therefore ingot growth.
The ingot length is limited by the maximum baseplate range of 4 meters; as soon as the baseplate reaches the bottom position, the remelting process is stopped to remove the ingot.
The maximum capacity of the plant is limited to a 7 ton ingot produced out of five electrodes in sequence in a 520 mm round mold.
The 520 Ø mm ingots need to be forged or bloomed in a roughing mill to be ready for hot rolling long products as the ones produced by Valbruna.
Unfortunately the forging or blooming operation, in addition to be a further cost in terms of production cost accounting and lead time, eliminates some of the structural characteristics of the remelted product, for example the axial growing direction and the grain dimension.

THE ESRR (ELECTRO SLAG RAPID REMELTING) PROCESS

The aim of the ESRR® process is to remelt near-net shape billets that can be directly hot rolled without any additional forging or blooming operation.
This leads to a dramatic economic advantage and a real lead time reduction due to the elimination of some process phases:
• Reheating + Forging + grinding
• Reheating + Blooming + grinding.



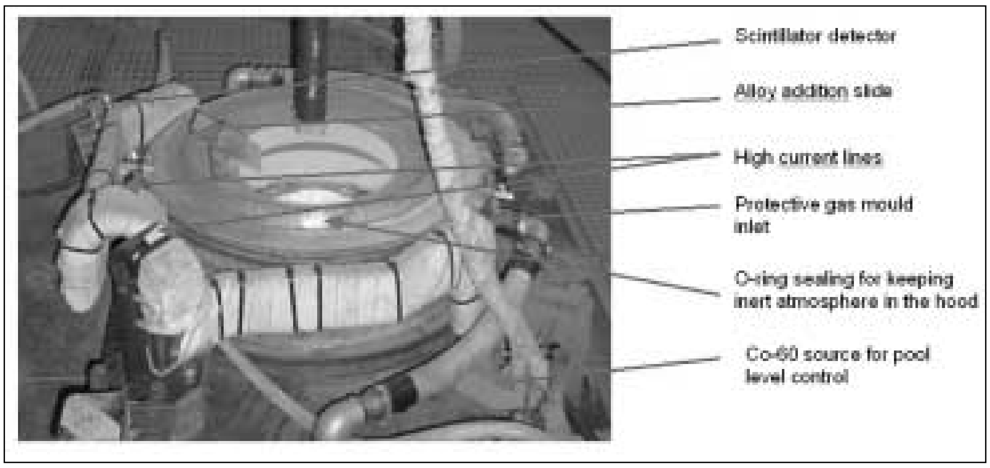


Fig. 4 – The ESRR® mould during process.

Fig. 4 – Schema della lingottiera ESRR durante il processo di rifusione.

Fig. 5 – The complete mould assembly during CC-ESRR® process.

Fig. 5 – La lingottiera ESRR.

Fig. 6 – Cobalto 60 scintillator. In the photo the device is covered by a yellow chassis for radiation protection.

Fig. 6 – Lo scintillatore al cobalto 60. Nella foto il dispositivo è coperto da un carter di sicurezza.

Fig 7 – Details from the new 145mm ESRR T-shaped mould body. Details of the particular distribution system of the cooling jacket.

Fig. 7 – Dettagli del corpo lingottiera da 145 mm per il processo ESRR. Dettaglio del particolare sistema di raffreddamento a camicia.

Furthermore the “as cast” remelted billet shows a structural direction of solidification and a fine and uniform grain size that are ideal for hot rolling. Those particular features were (as seen before) generally lost after reheating and forging operations.
The core of the electro slag rapid remelting process is indeed the particular copper T-shaped square mould whose design has been optimised (by using a FEM analysis) to perform a proper heat transfer. The lower-narrow and upper-wider part of the copper mould are both water cooled to perform a constant and uniform heat subtraction over the whole mould.
During ESRR® process, by remelting a consumable electrode in a superheated slag bath (1), a new ingot is built up in a water cooled copper mould. The energy required for melting the electrode is produced by the electric current passing through the liquid superheated slag which is acting as an ohmic resistor.
The liquid metal droplets from the electrode tip are collected (2) in the narrow, lower part of the mould, where the initial solidification takes place and the remelted billet (3) is continuously formed.
The remelted billet is withdrawn (as in standard ESR operation) by means of a retractable base plate.
The baseplate movement can’t be controlled only by the standard meltrate signal (as in standard ESR), as the position of the metal level must be safely kept under the T-shaped extension.
In fact, if the metal would solidify in the wider part of the mould it would be impossible to withdraw the billet, the process would have to be interrupted and the whole mould assembly has to be dismantled.
Therefore a new and more precise and reactive signal was installed to control the baseplate retraction.
The signal for controlling the liquid metal level is generated by a radioactive Co-60 isotope scintillator.
As shown on the process scheme both measuring devices are installed at the top end of the narrow part of the mould. If the metal level (2) grows too high, the signal, which is sent by the radioactive source and detected by a scintillator installed at the opposite side of the mould, will be reduced.
Such a signal change forces the PCS to retract the base plate resulting in a lowering of the metal level.
As in the standard ESR, the baseplate retraction is limited by the pit depth, resulting in a maximum billet length of approx. 4 meters. The net length will be a little bit shorter due to losses at the bottom and top of the billet.
Furthermore it is impossible to remove the billet without breaking the power circuit, so only one billet can be produced at a time out of one single electrode.
The ESRR® process turned out to be a fundamental, primary testing phase, a first step for further development. This phase was very important for three main reasons:

- Plant-design optimization: For better understanding of the heat transfer mechanism and to receive further ideas regarding optimization of the mould design to obtain better quality billets without deformation or internal stress, a FEM thermal analysis has been made in collaboration with AVL LIST.
- Process design optimization: An innovative deslagging device has been developed. Various attempts were made in the past to remove the slag from the mould as long as it is still liquid. The latest utilized method consists in a slag

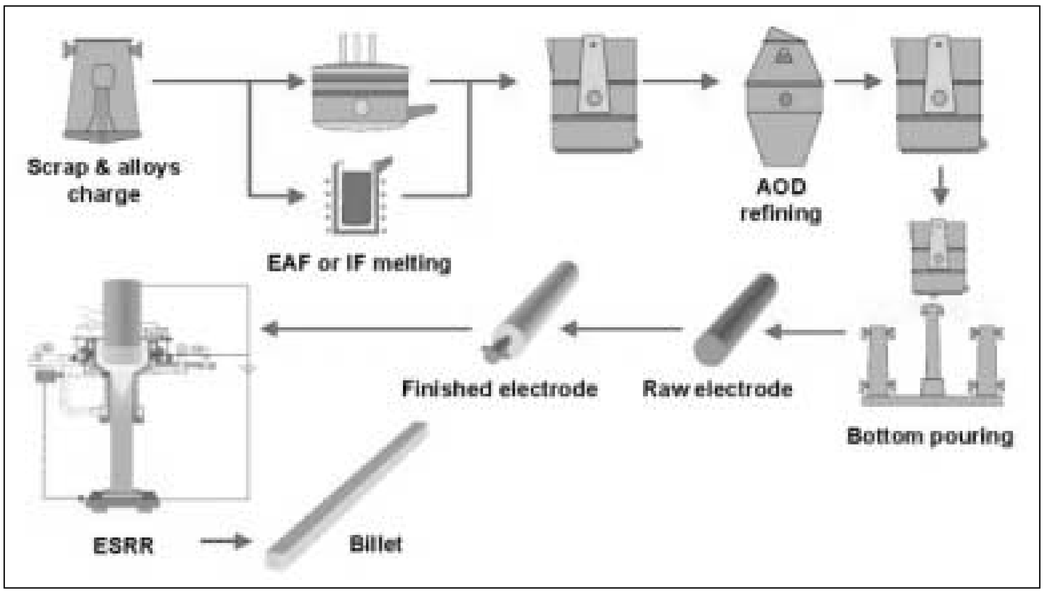


Fig. 8 – The complete ESRR® production cycle.

Fig. 8 – Il ciclo completo della rifusione ESRR®.

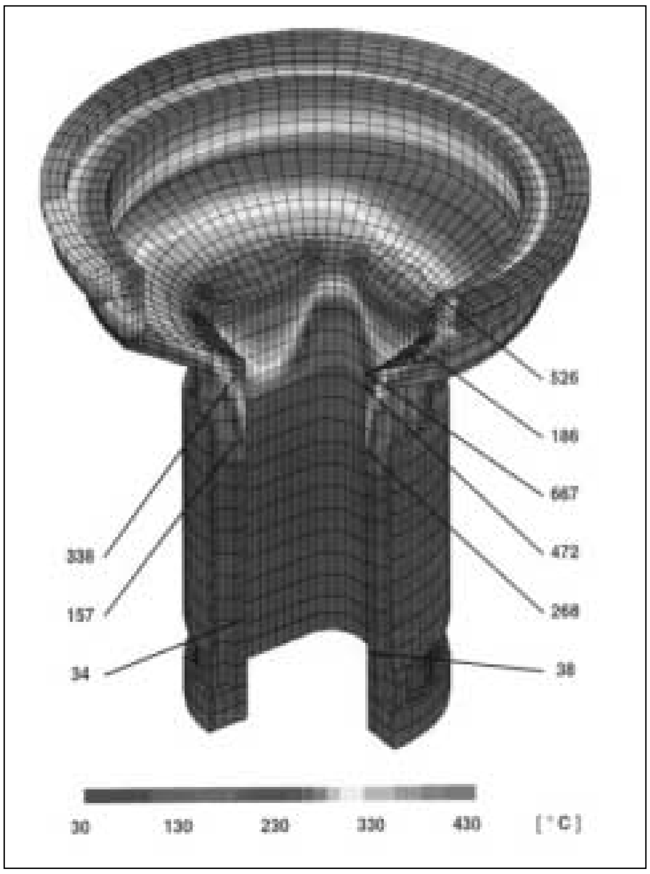


Fig. 9 – FEM analysis of the mould during the process: the mould temp. distribution. Photo Courtesy of INTECO / AVL LIST.

Fig. 9 – Analisi agli elementi finiti della lingottiera durante il processo.

Fig. 10 – The slag suction device ready to operate.

Fig. 10 – Il sistema di aspirazione della scoria.

vacuum suction device operating from the mould top before the removal of the billet

- <u>Remelted billets property definition and comparison to the traditional ESR product:</u> the excellent results have been described in another work, in any case the quality of the billets is comparable (and in many cases better) to the traditional ESR-ingots in terms of soundness, inclusion contents as well as physical and chemical properties.

Out of the experience gained in the batch-type ESRR®-operation the next step, the CC-ESRR® process has been developed!

THE CC-ESRR® (CONTINUOS CASTING ELECTRO SLAG RAPID REMELTING)

In the beginning of 2002, after a plant revamping, INTECO has equipped the ESRR® plant with a special automatic manipulator, which results in a continuous Rapid Remelting process (CC-ESRR®).

In the CC-ESRR® the baseplate for the retraction of the billet is replaced by 2 drive and 4 guiding rolls, whose movement is again managed by the Control System based on the signals of the metal level detector.

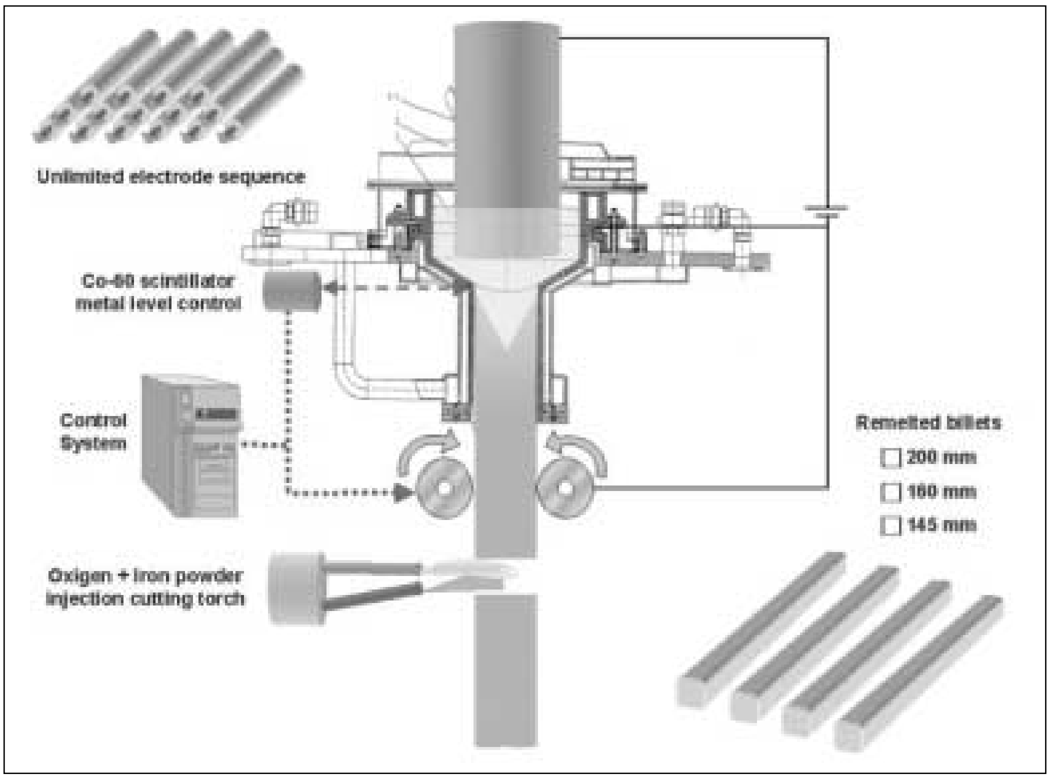


Fig. 11 – CC-ESRR® process schematics.

Fig. 11 – Schema del processo CC-ESRR®.

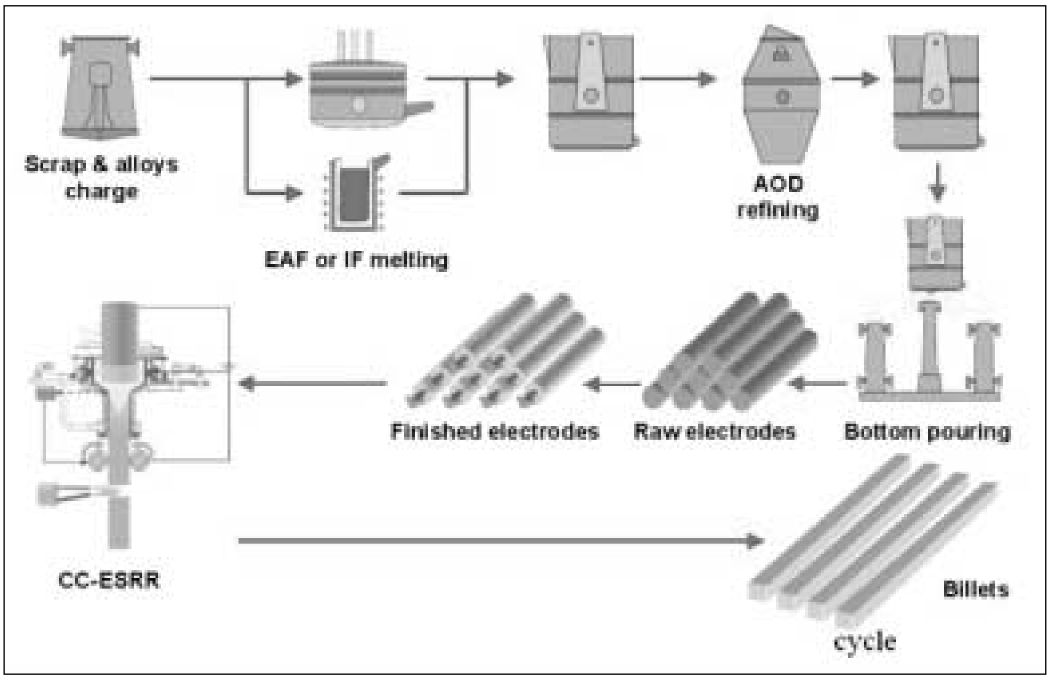


Fig. 12 – The complete CC-ESRR® production cycle.

Fig. 12 – Il ciclo completo della rifusione CC-ESRR®.

As soon as the billet reaches its required length, a powder cutting torch (oxygen + iron powder injection) automatically cuts the billet which is then removed in an unloading position. The revolutionary innovation is that all the continuous production of up to 40 billets in one remelting sequence out of multiple of electrodes.
This results in a decrease of the slag, tooling and starting costs due to the continuous production by an increase of the productivity of the plant.
This is surely the definitive step versus a price competitive product that incorporate all the advantages of ESRR® product with the advantages (in terms of volumes and economic impact) of continuous production.
The excellent results in terms of process efficiency makes the CC-ESRR® the definitive development of the ESR process for producing hot rolled long products.

The product remelted with the continuous process incorporates in fact all the advantages of the ESR process (in regard of quality of the metal), of the ESRR® process (in regard of reduced cycle complexity and overall process lead-time) and the efficiency, volumes and low-running-cost of the continuous processes.
The core of the process is once more the T-shaped mould that is exactly the same that is used during batch-type ESRR® process.

The automatic withdrawal manipulator

The main innovation in the CC-ESRR® plant is indeed the automatic manipulator. The manipulator must:
• Retract and guide the produced billet
• Keep the electrical contact to close the power circuit
• Cut the billet as soon as it reaches the required length.

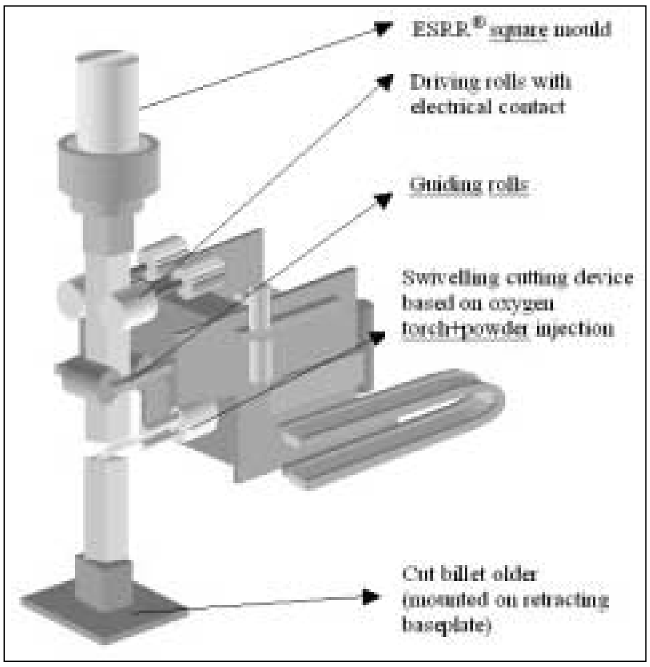


Fig. 13 – The CC-ESRR® manipulator schematics.

Fig. 13 – Schema del manipolatore CC-ESRR®.

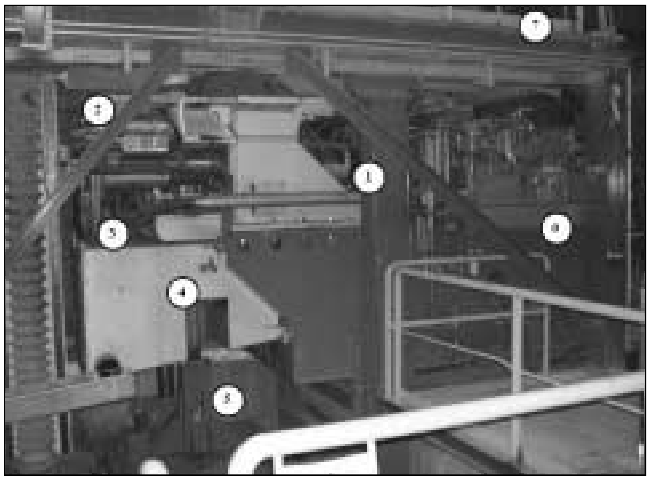


Fig. 14 – The CC-ESRR® manipulator during process:
1. Brushless electrical engines
2. Electrical contacts and driven rolls
3. Guiding rolls
4. Cutting device chamber
5. Retracting baseplate with billet holder
6. Manipulator body mounted on a rail system.
7. Operating platform.

Fig. 14 – Il manipolatore durante il processo:
1. Motori elettrici brushless
2. Contatti eletttici e rulli motrici
3. Rulli guida
4. Camera del dispositivo di taglio
5. Piastra base retrattile con alloggiamento della billetta
6. Il manipolatore in posizione di lavoro
7. Piattaforma di lavoro.

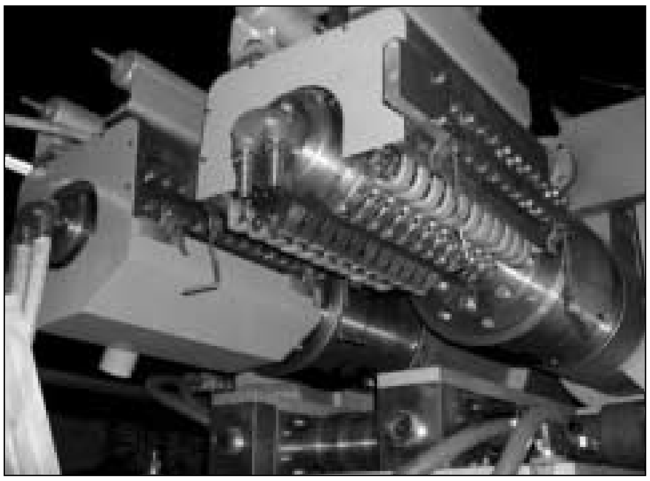


Fig. 15 – The complete sliding contact assembly.

Fig. 15 – Il gruppo dei contatti striscianti.

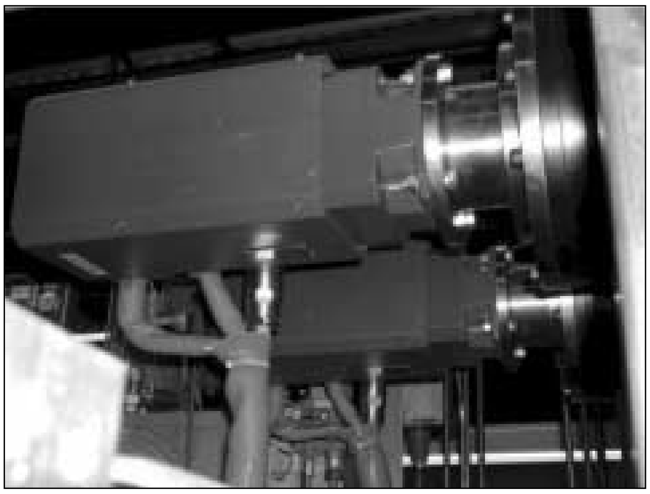


Fig. 16 – The brushless electrical engines that drive the rolls.

Fig. 16 – I motori brushless che azionano i rulli.

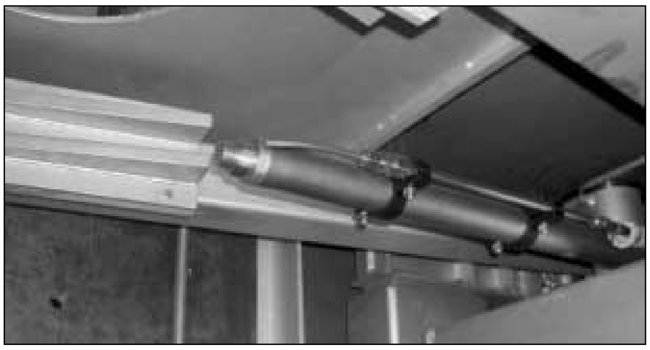


Fig. 17 – Overview of the cutting device, with the swivelling torch, the water spray system for the granulation of the generated slag and protection of the copper box.

Fig. 17 – Vista del dispositivo di taglio con la torcia , il sistema di granulazione delle polveri e la protezione di rame.

For an easy and quick change between standard ESR- and CC-ESRR®-operation the manipulator is installed on a rail system to move between an operating position (CC-ESRR®) and a parking position (standard ESR).

The driving-guiding rolls

To drive and guide the billet out of the mold, the manipulator is equipped with three pairs of rolls. One pair is driven and its movement is controlled by the PCS system according to the metal level signal. The other two pairs are used only to guide the billet out of the mold.
Furthermore, the driven rolls are equipped with a set of innovative sliding contacts whose task is to close the power circuit formed by the electrode, the slag, the billet and the bus bar system.

The cutting device

The cutting device is an oxygen torch equipped with an iron

Fig. 18 – The cutting device during operation. Note the billet and the billet holder are mounted on the retracting baseplate.

Fig. 18 – Il dispositivo di taglio durante il processo: notare la billetta e il porta-billetta montato sulla piastra base retrattile.

Fig. 19 – A sample slice cut by the oxygen-powder torch. Note the good surface.

Fig. 19 – Esempio dell'ottima superficie si una fetta di billetta dopo il taglio.

powder injection system, and is capable of cutting a 145 mm billet in less than a minute.
During the cutting operation, all the fumes and the slag generated by the process are collected within a fume hood with a special water spraying system.
As said before, in this case the billet holder is mounted to the retracting baseplate and moves the remelted billets (immediately after cutting) into the unloading position.

OPERATIONAL TESTS RESULTS

A lot of tests have been executed in the CC-ESRR® plant, in order to define process parameters as well as product characteristics. The grades used in those tests are commonly used and appreciated by our customers. Therefore a direct comparison of the new CC-ESRR® results to already achieved values (ESRR® and ESR) in terms of product quality and process parameters was possible.

- AISI 403: A martensitic steel grade used mainly for steam turbine blades.
- AISI 304L: An austentic steel grade used for corrosion resistant component
- WN 1,4980: Nickel alloy grade used for high temperature corrosion resistant bolts (Ti alloyed).

The following evaluations have been executed:

- Influence of a grade change during CC-ESRR® operation: it was evaluated, how the interface between two steelgrades looks like in case of a grade change during one remelting sequence
- Product characterization of the as cast billets: including chemical, metallographical and physical properties evaluation
- Product characterization of the hot rolled billets: including chemical, metallographical and physical properties evaluation.

GRADE CHANGE BETWEEN AISI 304 AND AISI 660

The change of electrode from AISI 304 to AISI 660 during one melting sequence was evaluated.
The test (with the aim to evaluate when the change of grade is completed) has been carried out on the following grades and process parameters.

Grade	Melting rate (Kg/h)	Step (mm)	Back step (mm)	Slag
AISI 304	500	4	0	CAF3 + 15 % Ti
AISI 660	460	4	0	CAF3 + 15 % Ti

Table 1 –Test process parameters.

Tabella 1 – Parametri del processo di test.

The billet has been cut to verify the transition between the two grades.
As the grade change is combined with an electrode change and therefore a power interruption the transition area and shape of the pool depth was clearly visible. It amounted to approx. ??? mm.
This part has to be cut out to ensure no mixing of the two grades at the top or bottom of the respective billets of different grades.

AISI 403 CC-ESRR® BILLET ANALYSIS

Four billets of AISI 403 have been examined as representative of 145x145 mm production.

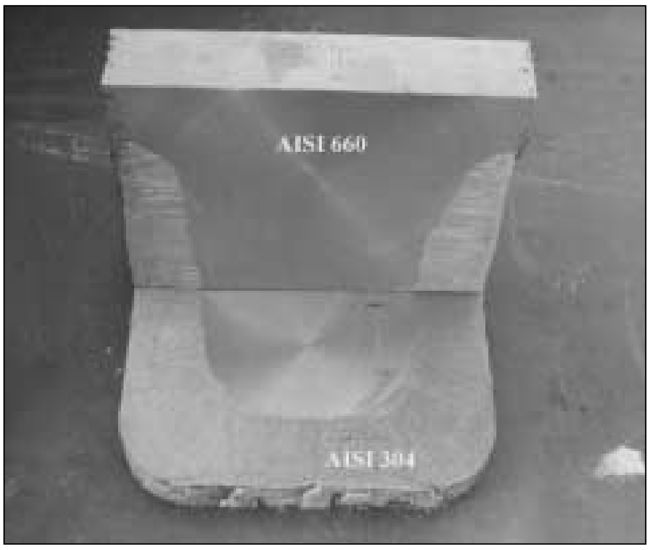


Fig. 20 – Transversal and longitudinal section of the transition zone.

Fig. 20 – Sezione trasversale e longitudinale della zona di transizione.

Heat n.	Billet n.	Melting rate (Kg/h)	Step (mm)	Back step (mm)	Slag
1	4	500	6	0	CAF3
2	8	450	6	2	CAF3
3	4	600	6	0	CAF3
3	7	400	5	2	CAF3

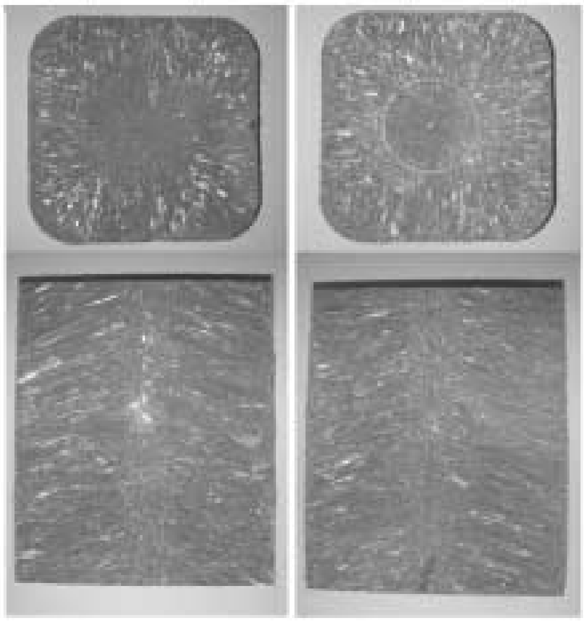


Table 2 – Process parameters, during ESRR® operation.

Tabella 2 – Parametri del processo di test.

AISI 403 FLAT BARS FROM CC-ESRR® BILLET PRODUCT ANALYSIS

One batch of AISI 403 has been manufactured employing billets coming out of the first CC-ESRR® campaign.
The final products are flat bars (117.47 x 41.27 mm) for steam turbine blades.

Melting rate (Kg/h)	Step (mm)	Back step (mm)	Slag
500	6	0	CAF3

Table 3 – Process parameters, during ESRR® processing.

Tabella 3 – Parametri del processo di test.

The results of these first tests show a product that fully meets our customer requirements. During the standard processing, no anomalies have been observed to our standard.
Surface anomalies observed during visual examination occurred during our manufacturing and not for CC-ESRR® process.

- Mechanical properties: Mechanical properties meet the required characteristics.
- Metallographic examinations: Metallographic examination after hardened + tempered shows a tempered structure with a grain size around 6 –7 ASTM and a percentage of d ferrite of about 0.5 %.
- Impurity level: The level of impurities observed is very low. According to E45, the worst inclusion size was 1.5. according to UNI 3288-80, K1 is 0.
- Macrographic examinations: Macrographic examinations show a fine grain, no segregations or other anomalies have been observed.

Chemical analysis

(See Tab. 4)

	Source melt analysis	Cast analysis	Product analysis
C	0.135	0.128	0.13
Si	0.33	0.30	0.28
Mn	0.44	0.43	0.42
Cr	12.05	12.17	12.12
Ni	0.45	0.44	0.44
Mo	0.12	0.11	0.11
Cu	0.11	0.08	0.08
Al	0.009	0.035	0.032
V	0.072	0.07	0.07
Co	0.022	0.02	0.02
P	0.017	0.017	0.018
S	0.0010	0.001	0.001
Sn	0.0060	0.005	0.004
N	0.0350	0.0410	0.0410

Table 4 – Chemical analysis.

Tabella 4 – Analisi chimica.

Impurity level

Evaluation according to: UNI 3244-82 K1 = 0
Evaluation according to: ASTM E45

	A		B		C		D	
	T	H	T	H	T	H	T	H
Required	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Found			1.0				1.5	

Table 5 – Impurity level according to ASTM E45.

Tabella 5 – Inclusioni secondo l'ASTM E45.

Mechanical characteristics

(See Tab. 6)
Hardening at 980°C → air
Tempering at 700°C → air

AISI 304 CC-ESRR® BILLET ANALYSIS

Two batches of AISI 304 have been manufactured employing two billets coming from the first CC-ESRR® campaign.
The final products are square bars (40x40 and 70x70).

Melting rate (Kg/h)	Step (mm)	Backstep (mm)	Slag
500	6	0	CAF3

Table 7 – Working parameters, during ESRR processing.

Tabella 7 – Parametri del processo di test.

The results of these first tests show a product that fully meets our customer requirements.
During the standard processing, no anomalies have been found out from our standard. Visual inspection after hot rolling shows some marks. These marks, after pickling, could not be found out.

- Mechanical properties. Mechanical properties meet the required characteristics.
- Metallographic examinations
  - Hot rolled conditions: grain size is correct.

	HB	Rm (N/mm²)	$Rp_{0.2}$ (N/mm²)	E%	RA %		KV	
Required according to Customer 1	240 max	850 max	560 ÷ 660	15 min	50 min		35	min
Required according to Customer 2	217 – 248	690 min	550 min	20 min	60 min		81	min
Hard & temp in lab furnace	243	770	615	25.3	68.6	134	137	143
Hard & temp in manufacturing	230	729	569	25	67	126	131	138

Table 6 – Mechanical characteristics.

Tabella 6 – Caratteristiche meccaniche.

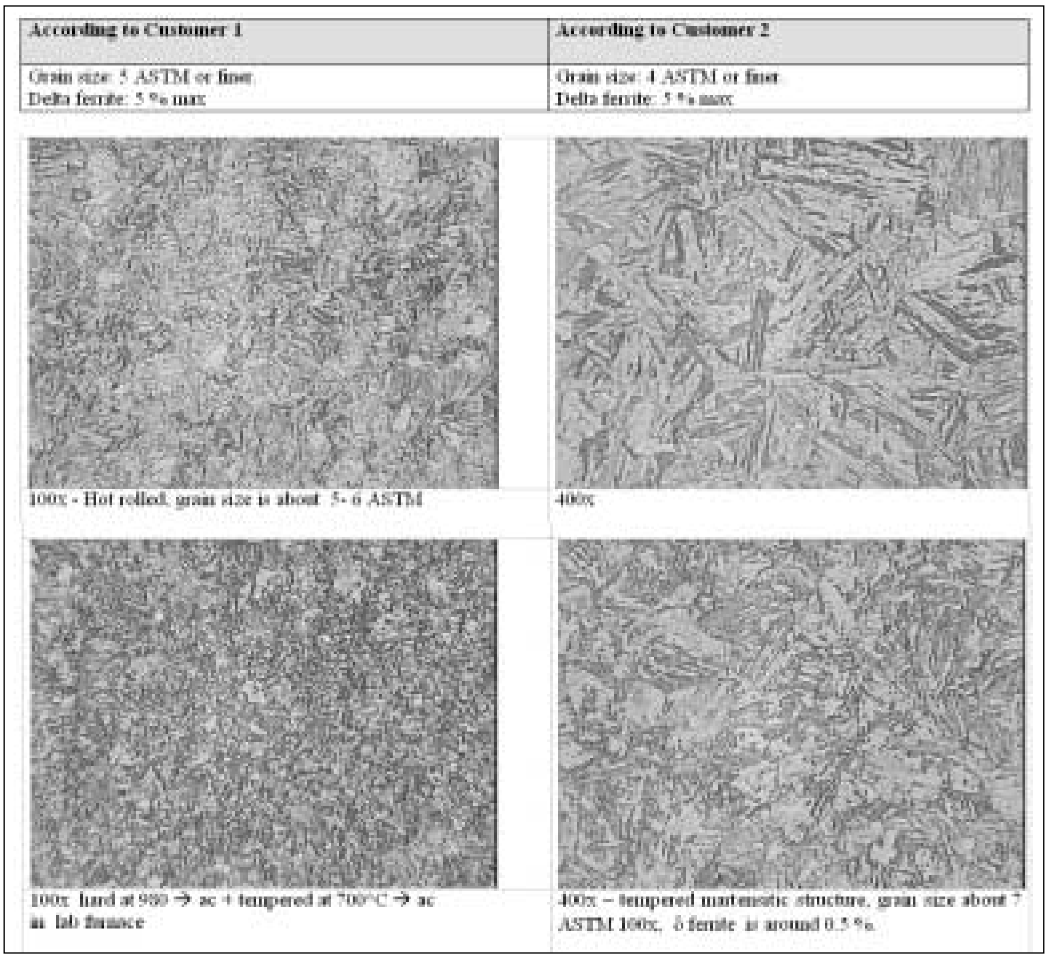


Fig. 21 – Micrographic examinations.

Fig. 21 – Esami micrografici.

- Solution treated in laboratory furnace: grain size is correct.
- Solution treated in manufacturing furnace: It can be remarked that after solution treatment, this material recrystallize with a grain finer than in the hot rolling condition. Grain size is correct.

• Macrographic examinations. Macrographic examinations show a fine grain, no segregations or other anomalies have been found out.

Chemical analysis
(See Tab. 8)

Mechanical characteristics on 40x40 square
(See Tab. 9)

Mechanical characteristics on 70x70 square
(See Tab. 10)

SPECIAL THANKS

Many thanks to everybody at Valbruna's laboratory, quality department and ESR plant for their time and concrete help

	Source melt analysis	Cast analysis	Product analysis
C	0.036	0.040	0.036
Si	0.53	0.46	0.46
Mn	1.48	1.46	1.46
Cr	18.16	18.17	18.17
Ni	8.07	8.11	8.11
Mo	0.44	0.44	0.44
Cu	0.43	0.44	0.44
Al	0.012	0.050	0.050
Co	0.10	0.10	0.10
B	0.0023	0.0017	0.0017
P	0.027	0.027	0.027
S	0.0010	0.0010	0.0010
Sn	0.0110	0.010	0.010
N	0.0672	0.0755	

Table 8 – Chemical analysis.

Tabella 8 – Analisi chimica.

	HB	Rm (N/mm²)	Rp $_{0.2}$ (N/mm²)	E%	RA %
Required		515 min	205 min	30 min	40 min
Solution treated + cold drawn	240	689	485	49.4	75.4
Solution treated in lab at 1080°C → wq		600	272	66.3	78.5

	HB core	HB _R	HB surface
Hot rolled condition	230	230	240
solution treated in laboratory at 1080°C → wq	180	200	192

Table 9 – Mechanical characteristics.

Tabella 9 – Caratteristiche meccaniche.

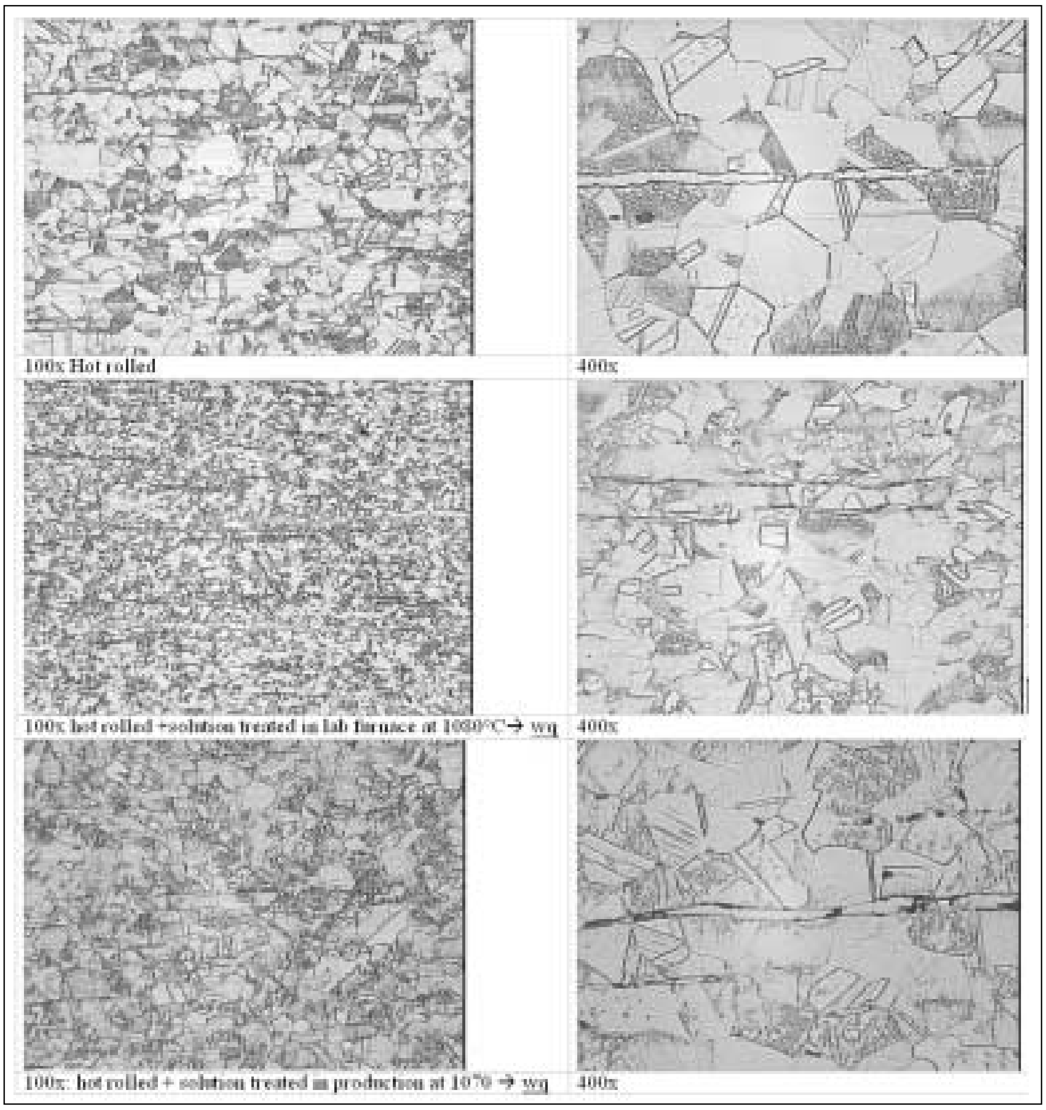


Fig. 22 – Micrographic examinations on 40x40 square.

Fig. 22 – Esame micrografico su un quadrato 40x40.

	HB	Rm (N/mm²)	Rp $_{0.2}$ (N/mm²)	E%	RA %
Required	215 max	500 - 700	190 min	45 min	
Solution treated in manufacturing	175	590	288	64.0	78.8
Solution treated in laboratory at 1080°C → wq		598	272	65.2	77

	HB core	HB _R	HB surface
Hot rolled condition	180	187	195
solution treated in laboratory at 1080°C → wq	190	194	176 - 162

Table 10 – Mechanical characteristics.

Tabella 10 – Caratteristiche meccaniche.

Fig. 23 – Micrographic examinations on 70x70 square.

Fig. 23 – Esame micrografico su un quadrato 70x70.

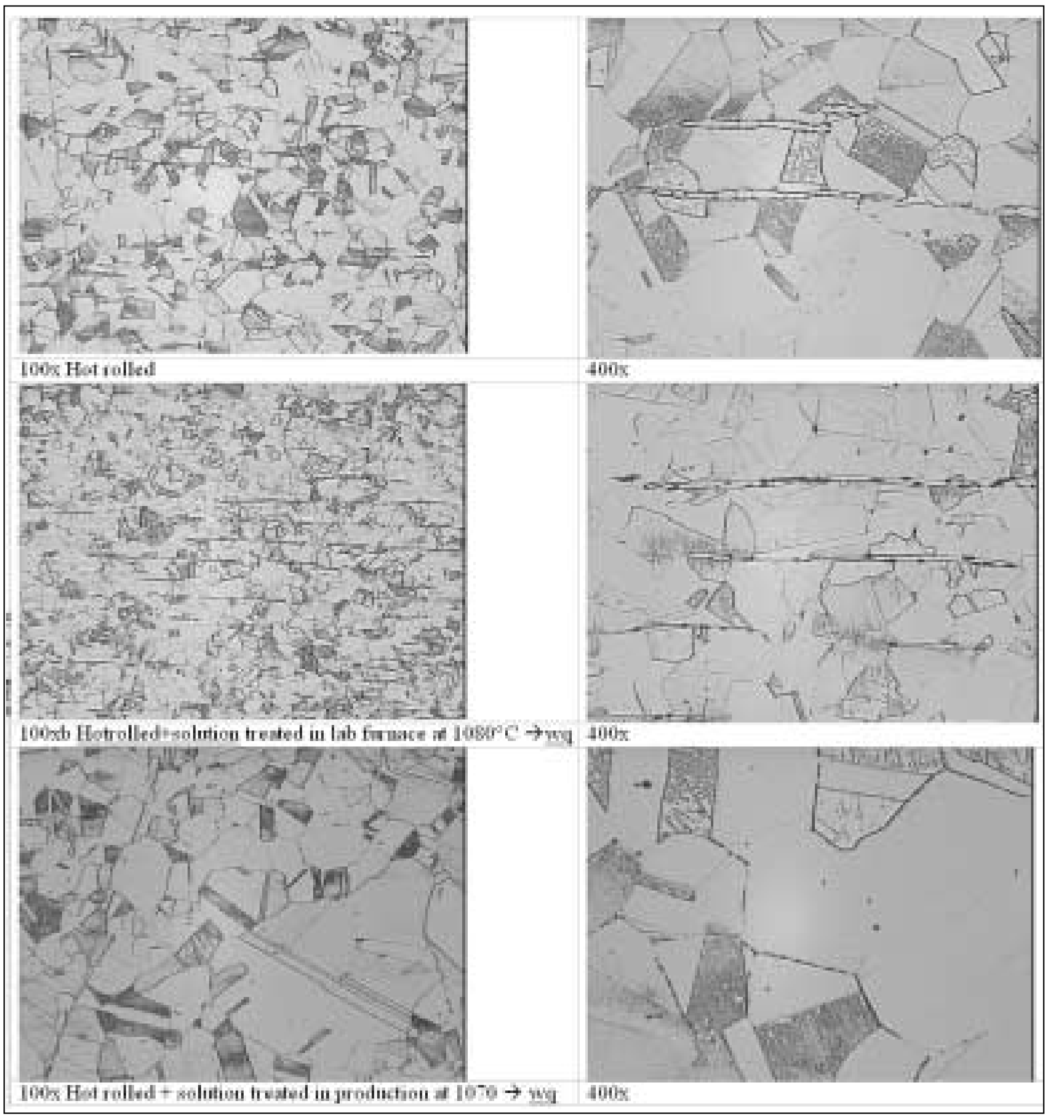


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Fig. 24 – The very first billets produced sequentially by CC-ESRR®.

Fig. 24 – Le prime billette prodotte col sistema CC-ESRR®.

ABSTRACT

FROM ESR TO CONTINUOUS CC-ESRR PROCESS: DEVELOPMENT IN REMELTING TECHNOLOGY TOWARDS BETTER PRODUCTS AND PRODUCTIVITY

PAROLE CHIAVE: acciaieria, processi, acciaio inox, solidificazione

Questo lavoro descrive l'evoluzione del processo ESR presso le Acciaierie Valbruna SpA a partire dell'installazione dell'innovativo impianto ESR (dotato di campana protettiva per la rifusione in atmosfera inerte) Inteco del 1997.

Il secondo passo è stato fatto un paio d'anni dopo con l'implementazione nell'impianto del processo ESRR® (Electro Slag Rapid Remelting). Con questa nuova caratteristica l'impianto è stato messo in grado di produrre billette (da 145, 160, 220 mm) pronte per la laminazione saltando a piè pari i processi di fucinatura o blumatura del lingotto rifuso necessari nel processo ESR tradizionale.

Questo processo è stato senza dubbio un incredibile passo avanti in termini di diminuzione della complessità dei cicli e del lead time senza per questo perdere nessuna delle caratteristiche qualitative tipiche del prodotto ESR. Sfortunatamente per quanto innovativo e promettente dal punto di vista tecnico, il processo ESRR non poteva essere che una "tappa intemedia" in un cammino di industrializzazione del processo: infatti a causa del suo approccio tipicamente "batch" era in grado di produrre una billetta alla volta con effetti negativi sulla produttività e sul costo di processo.

Il passo finale di questa evoluzione è stato fatto alla fine del 2002 quando l'impianto è stato equipaggiato con un innovativo manipolatore automatico in grado di rendere il processo ESRR continuo. Era nato il primo impianto su scala industriale di CC-ESRR (continuous casting electro slag remelting) al mondo

La prima parte di questo lavoro è focalizzata sulla descrizione dello sviluppo del processo e dell'impianto con attenzione particolare alle tappe innovative tra i vari stadi del processo (ESR-ESRR-CCESRR), mentre invece la seconda parte prende in esame i risultati sperimentali su alcuni prodotti utilizzati per la caratterizzazione del processo.