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 losing 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 the 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 on 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
of a retracting baseplate, whose downward movement is set by the control system according to the melt rate 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.
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...
vacuum suction device operating from the mould top before the removal of the billet

- Remelted billets property definition and comparison to the traditional ESR product: 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!

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.
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.
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
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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 austenitic 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 steel grades 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.

### OPERATIONAL TESTS RESULTS

#### 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.

<table>
<thead>
<tr>
<th>Grade</th>
<th>Melting rate (Kg/h)</th>
<th>Step (mm)</th>
<th>Back step (mm)</th>
<th>Slag</th>
</tr>
</thead>
<tbody>
<tr>
<td>AISI 304</td>
<td>500</td>
<td>4</td>
<td>0</td>
<td>CAF3 + 15 % Ti</td>
</tr>
<tr>
<td>AISI 660</td>
<td>460</td>
<td>4</td>
<td>0</td>
<td>CAF3 + 15 % Ti</td>
</tr>
</tbody>
</table>

*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.*
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.

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 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)

<table>
<thead>
<tr>
<th>Melting rate (Kg/h)</th>
<th>Step (mm)</th>
<th>Back step (mm)</th>
<th>Slag</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>6</td>
<td>0</td>
<td>CAF3</td>
</tr>
</tbody>
</table>

Table 3 – Process parameters, during ESRR® processing.
Tabella 3 – Parametri del processo di test.

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).

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.
Table 6 – Mechanical characteristics.

Table 6 – Caratteristiche meccaniche.

<table>
<thead>
<tr>
<th></th>
<th>HB (N/mm²)</th>
<th>Rm (N/mm²)</th>
<th>Rp0.2 (N/mm²)</th>
<th>E%</th>
<th>RA %</th>
<th>KV (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Required according to Customer 1</td>
<td>240 max</td>
<td>850 max</td>
<td>560 – 660</td>
<td>15 min</td>
<td>50 min</td>
<td>35 min</td>
</tr>
<tr>
<td>Required according to Customer 2</td>
<td>217 – 248</td>
<td>690 min</td>
<td>550 min</td>
<td>20 min</td>
<td>60 min</td>
<td>81 min</td>
</tr>
<tr>
<td>Hard &amp; temp in lab furnace</td>
<td>243</td>
<td>770</td>
<td>615</td>
<td>25.3</td>
<td>68.6</td>
<td>134</td>
</tr>
<tr>
<td>Hard &amp; temp in manufacturing</td>
<td>230</td>
<td>729</td>
<td>569</td>
<td>25</td>
<td>67</td>
<td>126</td>
</tr>
</tbody>
</table>

- 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.
### Table 9 – Mechanical characteristics.

<table>
<thead>
<tr>
<th></th>
<th>HB</th>
<th>Rm (N/mm²)</th>
<th>Rp₀₂ (N/mm²)</th>
<th>E%</th>
<th>RA %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Required</td>
<td>215 max</td>
<td>500 - 700</td>
<td>190 min</td>
<td>45 min</td>
<td></td>
</tr>
<tr>
<td>Solution treated in manufacturing</td>
<td>175</td>
<td>590</td>
<td>288</td>
<td>64.0</td>
<td>78.8</td>
</tr>
<tr>
<td>Solution treated in laboratory at 1080°C → wq</td>
<td>598</td>
<td>272</td>
<td>65.2</td>
<td>77</td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 22 – Micrographic examinations on 40x40 square.**

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

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### Table 10 – Mechanical characteristics.

<table>
<thead>
<tr>
<th></th>
<th>HB core</th>
<th>HB _R</th>
<th>HB surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot rolled condition</td>
<td>230</td>
<td>230</td>
<td>240</td>
</tr>
<tr>
<td>solution treated in laboratory at 1080°C → wq</td>
<td>180</td>
<td>200</td>
<td>192</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>HB</th>
<th>Rm (N/mm²)</th>
<th>Rp₀₂ (N/mm²)</th>
<th>E%</th>
<th>RA %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Required</td>
<td>180</td>
<td>187</td>
<td>195</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solution treated in laboratory at 1080°C → wq</td>
<td>190</td>
<td>194</td>
<td>176 - 162</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
for the making of this work. Special thanks also to Monika Boh and Harald Holzgruber at INTECO for their great help and useful advices.

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Fig. 23 – Micrographic examinations on 70x70 square.
Fig. 23 – Esame micrografico su un quadrato 70x70.

Fig. 24 – The very first billets produced sequentially by CC-ESRR®.
Fig. 24 – Le prime billette prodotte col sistema CC-ESRR®.
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 dall’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 studi 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.
Modern secondary cooling technology in continuous casting of steel

R. Boyle, J. Frick

Continuous casting machines are now required to cast a wide range of steel grades while maximising production output. Consistent production of prime quality product requires increased operational and maintenance flexibility of the caster so that the optimum casting parameters can be maintained for each steel grade. This flexibility extends not only to the machine elements and control systems, but also to the secondary cooling system and demands more efficient and reliable spray cooling. Attentive design of secondary cooling systems, through cooling zone positioning, nozzle layout, nozzle selection and the use of appropriate secondary cooling control systems can provide these requirements. Minimum down time for maintenance is a key factor in maximising caster production; the use of the latest piping header systems and nozzle mounting arrangements can contribute to minimum secondary cooling maintenance. These header systems provide a rigid and self-aligning mounting for the nozzle, ensuring both nozzle alignment and maintenance accessibility.

Key words: secondary cooling, air mist nozzle, water distribution, vertical piping design

INTRODUCTION

Continuous casting machines are now required to cast a wide range of steel grades, in particular slab casters must cast steels ranging from ULC and low carbon grades to high carbon and high quality pipeline grades. This must be achieved while maximising production output. Consistent production of prime quality product requires increased operational and maintenance flexibility of the caster so that the optimum casting parameters can be maintained for each steel grade. This flexibility extends not only to the machine elements and control systems, but also to the secondary cooling system and demands more efficient and reliable spray cooling. Of particular concern when designing a secondary cooling system are:

- Steel grades to be cast and their casting speeds.
- The roll support geometry and machine segment layout.
- Ease of maintenance.
- Secondary cooling control systems.

This paper focuses on the design of a secondary cooling system that uses the latest nozzle technology to fulfil the production requirements of today’s casters. Unlike in the early days, the layout of the secondary spray cooling system is one of the first steps when a new continuous casting machine is designed, or when an existing machine undergoes a major revamp.

NOZZLE LAYOUT

A good nozzle layout is paramount in fulfilling the operational and production requirements. It is essential that nozzle arrangements produce an even heat removal across the strand while maintaining a stable spray pattern. Spray collision with support rolls should be avoided as this will result in inefficient use of spray water and a reduction in heat transfer. Generally multi-nozzle layouts should be the preferred arrangement. In the final area of solidification of non-critical steel grades, typically the horizontal section of curved casters, it is possible to reduce the number of nozzles in a roll gap to one or two as this is a less critical area for solidification. The staggering of nozzle pairs in consecutive roll gaps, see Figure 1, will ensure even surface temperatures.

Spray width control can be achieved with a multi-nozzle configuration. In a multi-nozzle arrangement the outermost nozzles are systematically turned off in relation to the strand width as shown in Figure 2 where a nozzle layout which alternates the number of nozzles in consecutive roll gaps can be used. If a more finer control is required then an inline arrangement as shown in Figure 3 can be used.

Heat removal from the strand is not only a function of spray cooling; other mechanisms are also prevalent, for example heat removal by the support rolls. Heat removed by rolls can have a significant effect on the strand surface temperature.
and strand solidification conditions. If the heat removed by rolls is considered even across the strand width together with even heat removal by the sprays then ideal solidification conditions as shown in Figure 4 should exist.

**NOZZLE SELECTION**

Nozzle selection can only occur after derivation of the solidification profiles, the cooling zone layout and the nozzle layout. The heat extraction required to achieve the solidification profiles is converted into cooling zone water flows using nozzle heat transfer coefficients. The specific nozzle flows can then be derived from the maximum water flow associated with each cooling zone. Prior to final nozzle selection, operational factors must be considered, these factors include:

- Spray water temperature compensation factor – heat extraction capability reduces with increasing water temperature, see Figure 5 and can lead to both operational and quality problems. Typically this factor would be applied during hot summer periods.
- Increased flow rate on the outer radius – this is used to equalise cooling on both the inner and outer strand faces by compensating for the gravitational effect on the outer radius.
- Safety factors – any allowance above the calculated water flows.

It is important for today's caster designers to have access to nozzles which have high turndown (control range, min./max. water flow) capabilities for not only operational reasons but also to minimise the nozzle varieties in one particular machine. Both maintenance and inventory managers appreciate this effort. Latest achievements in air mist nozzle research and development are now providing designs with turn down ratios wider than ever before and with lower air consumption. The flow diagram in Figure 6 of a Lechler Mastercooler air mist nozzle shows that a turn down ratio of more than 1:20 at a constant air pressure of 2.5(bar) is not impossible between water pressures of 0.5(bar) and 7(bar).

**NOZZLE DESIGN**

Within the last 5 years the vertical segment piping developed for the Lechler Mastercooler air mist nozzles with vertical square header pipes has almost become an industry standard design. The air mist nozzles now equipped with plates are bolted vertically onto adapter plates as shown in Figure 9. Once the secondary cooling system layout is completed and the mechanical design of the segments is known, it is the spray nozzle manufactures task to design nozzles which provide a uniform water distribution across the strand surface and over the entire turn down ratio. Tolerances of ± 15% from the mean value can be achieved with a multi nozzle arrangement at water pressures between 1.0 and 7.0 bar. Figure 7 shows the water distribution measurements of a twin nozzle arrangement. The nozzle pitch is 400(mm), the spray height 200(mm), and the air pressure 2(bar) constant and 7(bar) water pressure. All nozzles are mounted outside of the framework at the rear side of the segment with only the nozzle pipe, carrying the spray tip, extending down to the spray position. A very rigid header system becomes a standard. Frequent replacement of many expensive water and air hoses is no longer required.
Because of their internal mixture, air mist nozzles require two separate feed pipes for compressed air and water. Until recently small diameter pipes were used to feed both the fluids and to hold the nozzles in place. Only in special cases, where one fluid was fed directly by a hose, additional supports were provided. Nozzle staggering between the roller gaps within one segment becomes much easier since different nozzle positions can be served from only one header pipe manifold, see Figure 10. The conventional air mist nozzles mounted on these small pipes are hidden inside the segment framework as shown in Figure 8.

Having the nozzles mounted so close to the strand makes maintenance (cleaning or adjustment) impossible unless the segment is removed from the machine. In the case of a breakup nozzles must be completely replaced, which is very costly. Strand surface defects can often be traced back to misaligned spray nozzles. Header pipes such as shown are one source of such misalignments. The many small air and water pipes are often out of position due to mechanical impact or thermal reasons. The large number of small, individually bent pipes, are also expensive to manufacture. The nozzles and header pipes with the vertical plate connection are also an ideal solution for beam blank casters with air mist cooling. Instead of a complex manifold only two square header pipes with two nozzles bolted on, are required. The advantages described above are also true here. The bends of the nozzle extension pipes can be made to suit. With the aid of the "Split pipe" design the two nozzles on either side (Pos. 1 and 2 of Figure 11) can be identical with the front pipe turned by 180°, hence one nozzle type can serve both positions in one gap.
NEW AIR MIST NOZZLES FOR BILLET AND BLOOM CASTING

When air mist cooling becomes necessary for a billet or bloom caster, flat jet nozzles may not always be the best choice. This is especially true where the formation of Halfway Cracks may be experienced. This type of crack has been shown to be caused by reheating of the strand surface after it has passed the sharp heat extraction zone beneath a spray jet. During this reheating process the surface expands and imposes a tensile strain on the hotter and weaker inner material, which can then crack. The use of flat jet nozzles intensifies this effect. Full cone nozzles or oval cones provide a softer cooling by extracting heat over an extended surface area. These two spray patterns are the standard for single fluid water secondary cooling systems, however there has not been an adequate version using air mist. Common full cone air mist nozzles show unstable spray performances, very high air consumptions and a tendency to clog very easily. Oval cone air mist nozzles are often flat jet nozzles with multi slot orifices. Non uniform spray patterns and the very narrow easy to clog slots, made these nozzles barely more than a compromise. With the new Lechler Billetcooler Figure 12, a new generation of full and oval cone air mist nozzles it is now possible to utilise air mist cooling in billet and bloom casters as effectively as in slab casters. The compact block design allows mounting both on horizontal spray bars and on vertical “Banana” nozzle headers. Turn down ratios as wide as 1:14 have been achieved at water pressures between 1.0 and 10.0(bar) at 2(bar) air constant. Nominal spray angles for circular full cone nozzles range between 60° and 90°. Free passages with 2.0mm in diameter are approximately three times larger than before for a nozzle size with flows ranging from 0.5(l/min) at 1(bar) water pressure and 5.0(l/min) at 7(bar) water pressure at a constant 2(bar) air pressure. Extremely critical cooling problems have successfully been solved in a 5-strand bloom machine casting more than 250 steel grades and also critical stainless steel rounds.

CONCLUSION

The benefits for the user but also for the machine designer described in this paper are well established facts. The most important of them are: o Reduced incidence of surface defects and crack formation o Reduced maintenance and operation costs o Improvement of operation safety o Enlargement of caster product mix o Increased caster production

The modern air mist nozzle and header pipe technology can be incorporated into new machines as well as into existing casters for billets, blooms, beam blanks, slabs and thin slabs.

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Development of high grade seamless pipes for deepwater application by metallurgical design

E. Anelli, D. Colleluori, G. Cumino, A. Izquierdo, H. Quintanilla

New solutions for the metallurgical design of high performance quenched and tempered (Q&T) seamless pipes of high grades from X65 up to X80 were found throughout a systematic work involving metallurgical modelling, laboratory tests, pilot and industrial trials. Both linepipes and risers for deepwater offshore fields such as Gulf of Mexico were considered. The target microstructure in the as-quenched condition has been identified as refined low-C bainite/martensite matrix (> 70%). This is promoted through the control of austenite grain growth during the heating stage (austenitization before quenching), proper alloy additions and through a very effective quenching. Promising low-alloy steels and suitable quenching and tempering conditions identified by metallurgical modelling were verified by laboratory heats (80 kg ingots) that were processed at a pilot scale and submitted to microstructural examination and mechanical testing. The best solutions were used in preliminary industrial trials, also utilised for a fine tuning. The Ni-Cr-Mo-Nb-V alloy system showed very interesting combinations of strength-toughness and field weldability, suitable for the production of heavy wall X65 grade linepipes for sour service and X80 top tension risers.

Key words: Seamless pipe, linepipe, riser, strength, toughness, microstructure, quenching, tempering, metallurgical modelling

INTRODUCTION

The technological evolution in the offshore sector exhibits a trend towards an increasing use of high strength steels (grade X65 to X80, and higher) both for risers and flowlines, although the service conditions and the performance required for the two systems are different. This trend is supported both by economical and technical reasons, because the development of deepwater oil and gas reserves is continuously facing the challenge of containing/reducing costs in all components. [1-2]

For instance, riser system costs are quite sensitive to water depth and there is a need to explore new technical solutions and reduce raiser weight for ultra-deep water environments (greater than 2000 m). The use of high strength steels can decrease the wall thickness up to 30%, resulting in a more efficient design. Thinner wall risers mean reduced buoyancy requirements and less hydrodynamic loading on these components, with consequent improvement in riser response. For large field developments employing floating production facilities, with many heavy risers attached directly to the surface structure, payload limitations will receive higher consideration. Therefore, in this context the availability of higher-grade weldable steel risers, with a wall thickness to outside diameter ratio (WT/OD) adequate to the expected collapse performance is of engineering importance.

On the other hand, flowline wall thickness is increasing to provide sufficient resistance for the very high operating pressures. The trend in flowline specifications for deepwater offshore fields is a consequence of both complex oil-gas field conditions, such as high pressure and high temperature (HPHT) and developments in design criteria (i.e. limit state design), welding and laying technologies. Often the requirements are close to the manufacturing limit of welded pipes, therefore seamless pipes that allow a higher (WT/OD) are preferred.

As a matter of fact pipe manufacturers are facing new challenges coming from new and/or more demanding material requirements, often related to specific performances and applications, including sour service which set limitations such as maximum material hardness (HV ≤ 248). During the past years technologies have been developed in the field of quenched and tempered (Q&T) seamless pipe. In particular, the heat treatment capabilities of heavy wall pipes have been improved through the introduction of external and internal water quenching, which decreases the through-thickness temperature gradient.

Modern seamless pipes can combine high strength (grade X65) with good toughness properties and good girth weldability. For instance, in the case of pipes with WT = 15 to 34 mm, a reasonable balance between customer specifications, processing capabilities and product properties was found for low-C low alloy steels with 1%Mn and optimized contents of Mo, Nb and V. Such Q&T seamless pipes, which also showed good resistance to strain aging and HIC, were successfully delivered for HPHT offshore production lines. [3]

However, for pipe wall thickness greater than 34 mm, the required strength (grade X65) cannot be easily achieved maintaining the required toughness level. Similar difficulties are experienced in the case of WT = 15-25 mm for higher strength levels (e.g. grade X80). Therefore, new solutions which are outside of the conventional pattern for (micro)-alloying additions followed so far for Q&T seamless pipes, have to be found for high performance seamless pipes throughout a more systematic work.

In this paper, a description of the results of studies on high strength steel materials manufactured by Q&T processing is given. This work represents an on going development pro-
Program on high performance Q&T seamless pipes for special deep water applications, involving metallurgical modeling, laboratory tests, pilot and industrial trials. The role of chemical composition and Q&T process conditions on microstructure and precipitation has been investigated, together with their effect on strength and toughness. These results have been exploited for the production of sour service grade API 5L X65/X70 for heavy wall flowlines (WT from 30 up to 42 mm) and X80 risers (WT = 16 to 25 mm) for deepwater offshore fields.

METALLURGICAL BACKGROUND AND MODELLING

Seamless pipes of medium O.D., i.e. up to 406 mm (16") are presently produced by a hot rolling process carried out in the following main stages: hot piercing, rolling at retained marden mill and sizing. Quenching and tempering treatments are performed on the pipes in order to refine the microstructure and obtain the required properties. [3,4]

A rational approach to the design and production of these materials requires the quantitative knowledge of the effects of steel chemistry and heat treatment variables on the microstructure and final mechanical properties. The influence of microalloying additions and Q&T practices on austenite refinement, phase transformation and response to heat treatments of low-C steels for seamless linepipes was investigated by dilatometry and pilot trials.

Also an integrated model, containing a thermal routine for simulating pipe quenching, based on the integration by finite differences of the general Fourier heat equation, coupled with a microstructural model, has been applied for the design of both the chemical composition and Q&T conditions of seamless pipes. The thermal-metallurgical model is able to calculate the fraction of microstructural constituents and hardness of a steel subjected to rapid continuous cooling after austenitisation (i.e. quenching). The calculation is carried out by an Artificial Neural Network (ANN) trained on a selected database of CCT diagrams of linepipe steels. [5,6]

ANN is a powerful tool to obtain empirical non-linear models of complex phenomena whose analysis by ordinary statistical techniques or by modeling through fundamental physical process is not possible or very difficult. [7]

The program is able also to simulate a subsequent tempering treatment, predicting hardness (HV), yield strength (YS) and ultimate tensile strength (UTS) by an empirical approach. Different modules, each one describing an elementary process (e.g. austenitizing, quenching, tempering) can be managed by a user-friendly interface which allows to select the steel chemical composition, pipe diameter and wall thickness, and to set-up the process conditions. [5]

Austenitizing

The austenite grain size (AGS) depends on the austenitizing temperature and holding time, nature and size distribution of precipitates present in the as-rolled pipe. The more uniform the as-rolled microstructure, the easier it would be to homogenize the austenite. Laboratory tests and industrial trials have shown that to avoid the formation of coarse austenite grains (AGS > 25 µm) in low carbon steels (0.08-0.11%C) the heating temperature has to be lower than 900 °C for C-Mn steels; however, V-Nb steels and V-Ti steels can be safely austenitized up to 920 to 950 °C to dissolve V-rich precipitates, without problems due to the pinning effect of Nb (C, N) and Ti (C, N) fine particles which hinder grain boundary movement.

Quenching

Of concern in a quenching process of seamless pipes are the effects of through-thickness cooling rate gradients, induced by surface water cooling, and the sequence of transformation and the resultant microstructure and hardness profile. A specific test program was performed with the main objective of measuring the phase transformation characteristics of austenite under continuous cooling conditions by dilatometry and metallography (construction of CCT diagrams). Mathematical modeling, which links the basic principles of heat transfer and microstructural phenomena was effectively applied in this field.

The volume fraction of microstructural constituents and hardness of as-quenched linepipes were predicted as a function of the local cooling rate, calculated by the thermal model, by means of ANN.

Input data of ANN are the chemical composition of the steel, the austenitizing temperature, the austenite grain size and the cooling rate (CR). The output contains information on the as-quenched state of the steel in terms of harness and amount of microstructural constituents (e.g. ferrite, pearlite, bainite, martensite). The ANN was trained on a huge database of continuous cooling diagrams of Nb-V micro-alloyed linepipe steels (C=0.05-0.2%, Mn=0.5-2.0%), with possible Mo, Ni, and Cr alloy additions. Standard deviations of the regression lines between computed and experimental fractions were generally below 5%. The standard deviation for the hardness was 11 Vickers. In all cases the associated correlation coefficient was greater than 0.91. [5,6]

In order to check the prediction capability of ANN, new experimental CCT diagrams, not used for training, were determined on a Nb-V-microalloyed pipeline steel. Two diagrams were determined by austenitising the steel for 10 minutes at 930 and 1100 °C in order to obtain AGS of 9 and 40 µm, respectively. Hardness of the as-quenched samples were measured and the related microstructures analysed by optical microscope to evaluate the volume fractions of the microstructural constituents. Experimental data were compared to the predictions of the microstructural ANN model. The good results are presented in Figures 1 and 2.

Other experiments, including quenching of pipes by various industrial devices, were carried out. Both pipes instrumented by thermocouples and through-thickness hardness profiles on as-quenched pipes were employed to tune the heat transfer coefficient as a function of process conditions (e.g. water flow, etc.).

Fig. 1 – Comparison between the ANN predictions and the experimental data for hardness in a Nb-V linepipe steel.

Fig. 1 – Confronto tra previsioni con la rete artificiale neuronale e dati sperimentali sulla durezza di acciai al Nb-V per linepipe.
Simulations carried out by the model and industrial trials showed that linepipes with wall thickness less than 16 mm can be effectively quenched passing continuously through water jets produced by nozzles arranged in a series of rings forming a tunnel. In the case of heavy wall pipes, external and internal quenching is needed to reduce hardness gradients and make more homogeneous the as-quenched structure. This type of quenching is carried out by dipping the pipe in a tank containing stirred water. During quenching the pipe is under rotation and an internal water jet is used, too.

**Tempering**

The tempering conditions, mainly temperature and the presence of elements able to give precipitation hardening and to slow the recovery/recrystallization process, are the controlling factors for the combination of strength and toughness, for a given as-quenched microstructure. The integrated model system is also able to simulate a subsequent tempering treatment of the microstructure after quenching. In this case an empirical approach was used, which permits the estimation of the final hardness taking into account also the effect of secondary hardening phenomena due to precipitation of second phases in steels containing V and/or Mo. The yield strength (YS) and the ultimate tensile strength (UTS) of the Q&T material were estimated from hardness using empirical equations. [6]

A comparison of calculated and experimental strength values of as-quenched industrial specimens submitted to tempering under very well controlled conditions in the laboratory are shown in Table I.

**Sensitivity Analysis**

A sensitivity analysis was performed on a reference steel, having the chemical composition shown in Table II, in order to identify the role of chemical composition and process conditions on the phase transformation and response to tempering. The well known effect of the austenite grain size in enhancing the hardenability of the steel clearly appears from Fig. 3. Hardness increases monotonically with AGS and with coo-

<table>
<thead>
<tr>
<th>Table I – Comparison between predicted and experimental strength for a Nb-V linepipe steel submitted to tempering at various temperatures for 60 min after industrial quenching (WT = 22 mm).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tempering Temperature (°C)</td>
</tr>
<tr>
<td>620</td>
</tr>
<tr>
<td>640</td>
</tr>
<tr>
<td>660</td>
</tr>
<tr>
<td>680</td>
</tr>
<tr>
<td>700</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table II – Chemical composition (mass %) of the reference steel used in the sensitivity analysis.</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>0.12</td>
</tr>
</tbody>
</table>
Fig. 4 – Calculated effect of AGS and cooling rate during quenching on microstructural constituents.

Fig. 4 – Effetto della dimensione media del grano austenitico e della velocità di raffreddamento durante tempra sulle frazioni dei costituenti microstrutturali. Valori calcolati da modello.

Fig. 5 – Calculated effect of carbon content and cooling rate during quenching on hardness.

Fig. 5 – Effetto del tenore di carbonio e della velocità di raffreddamento durante tempra sulla durezza. Valori calcolati da modello.

Fig. 6 – Calculated effect of manganese content and cooling rate during quenching on hardness.

Fig. 6 – Effetto del tenore di manganese e della velocità di raffreddamento durante tempra sulla durezza. Valori calcolati da modello.

Fig. 7 – Calculated effect of manganese content and AGS during cooling at 10 °C/s on microstructural constituents.

Fig. 7 – Effetto del tenore di manganese e della dimensione media del grano austenitico sulle frazioni dei costituenti microstrutturali formatisi per velocità di raffreddamento di 10 °C/s. Valori calcolati da modello.

Fig. 8 – Calculated effect of ferrite amount on YS of Q&T materials (tempering at 660 °C for 60 min).

Fig. 8 – Effetto della percentuale di ferrite sulla tensione di snervamento di materiali temprati e rinvenuti a 660 °C per 60 min. Valori calcolati da modello.

It can be noticed that the ANN has been extrapolated in the range of grain sizes from 50 to 100 μm with respect to the training interval for AGS. Apparently this has not caused any saturation effect in the output parameters.

Also the increase of carbon content (Fig.5) has shown a similar effect on hardness as that exhibited by AGS, in agreement, also in this case, with the experience.

In the third example the effect of Mn is considered for different values of AGS and cooling rate (Fig.6). The hardening effect of Mn is associated with the promotion of bainitic structures and this behavior is favored by large grains (Fig.7).

The application of the mathematical model indicates that to attain the required yield strength for grade X65 in the case of 40 mm (i.e. CR of 12-15 °C/s) it is necessary to have a fraction of polygonal ferrite below 30% (Fig.8).

The model is a very powerful and easy-to-use tool for designing the industrial Q&T processes taking into account all
the relevant process parameters. It has shown a very good reliability in reproducing the experimental data not only on the microstructure, but also on mechanical properties. For Q&T seamless linepipes, it is able to quantify both the through-thickness thermal gradients during the quenching process together with the related local microstructures and hardness, and the effect of subsequent tempering treatments. The model is an effective tool in defining the optimum Q&T treatments for a given steel to match the required tensile properties of the final product. However, no information on toughness is available from modelling. Therefore, a specific experimental activity has been designed and carried out to assess the effect of microstructure and precipitation on strength-toughness combination, starting from a promising chemical composition identified by metallurgical modelling.

**HEAVY WALL HIGH STRENGTH FLOWLINES**

Pilot Trials

A series of laboratory heats, with designed changes in the content of Mo, Ni, Cr, V and C, with respect to a base steel composition, were vacuum cast as 80 kg ingots. The carbon equivalent, Ceq (IIW) was in the range 0.33% to 0.43% and maximum Pcm parameter was 0.25%.

The ingots were hot rolled by a pilot mill simulating the typical thermo-mechanical process of heavy wall seamless pipes (40 mm final thickness). All ingots were instrumented with thermocouples and the evolution of temperature during hot rolling was recorded.

The hot rolled materials were quenched in stirred water and tempered under strictly controlled parameters (Table III), being each piece instrumented by a thermocouple embedded at mid-thickness.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Austenitizing Temperature (°C)</td>
<td>920</td>
<td>1020</td>
</tr>
<tr>
<td>Cooling rate during quenching (°C/s)</td>
<td>10</td>
<td>25</td>
</tr>
<tr>
<td>Tempering Temperature (°C)</td>
<td>630</td>
<td>690</td>
</tr>
</tbody>
</table>

Table III – Range of laboratory heat treatment conditions.

The Q&T materials were examined by light and scanning electron microscopy. Microstructures were observed on sections after 2%-nital etching. Islands of high carbon martensite with retained austenite (MA constituent) were revealed by selective etching. [8]

The austenite grain boundaries were revealed by etching in a saturated aqueous picric acid solution containing a few drops of teepol and HCl.

The average austenite grain size (AGS) was measured according with ASTM E112.

Tensile and Charpy V-notch testing was conducted on transverse specimens. Charpy-V transition curves were determined together with the fracture appearance transition temperature (50% FATT).

**Effect of Alloy Design on Microstructure**

It was confirmed, as suggested by model simulations that in order to achieve the required yield strength level after tempering it is a pre-requisite to maintain the fraction of polygonal ferrite well below 30% in the as-quenched material (Fig.9).

A judicious addition of Mo, Ni and Cr allows to develop after quenching a microstructure containing a suitable combination of constituents such as fine bainite (B > 75%), polygonal ferrite (PF < 25%) and fine islands of MA constituent, uniformly dispersed in the matrix. This predominantly bainitic structure was found to exhibit good toughness values especially when the AGS was fine (< 15 mm; > ASTM No.9) and homogeneous.

An example of the typical AGS (ASTM No.9.2) of Mo-Ni-Nb-V steel, quenched from 920 °C, is reported in Fig.10. The addition of Nb slows down grain growth and helps to maintain relatively fine and homogeneous the AGS during austenitization.

In the case of fine AGS, the increase of the cooling rate from 12 °C/s to 20 °C/s, refines the microstructure (Fig.11). Therefore, even better strength-toughness combinations are expected for linepipes with thickness smaller than 40 mm. Concerning the microstructure evolution during tempering, a better spheroidisation of cementite and a more extended transformation of MA islands into ferrite and carbides, was observed with increasing tempering temperature (Fig.12).
Fig. 11 – Mo-Ni-Nb-V Steel. Microstructure obtained after austenitizing at 920°C and quenching with CR=12°C/s and 20°C/S, respectively. The as-quenched microstructure was revealed by 2% Nital etching. a) CR = 12°C/s b) CR = 20°C/S.

Strength and Toughness Properties
The general pattern of strength/toughness properties as a function of (micro)-alloy design is reported in Fig. 13. The Mo-Ni-Nb-V composition gives excellent strength/toughness combination: yield strength well above 460 MPa (grade X65); 50%FATT as low as ~85°C.

With reference to the same base composition and Q&T conditions of Fig. 13:
- The increase of C content up to 0.13% gives strengthening (DYS = + 60 MPa), but is detrimental to toughness and weldability.
- The V-free version (Mo-Ni-Nb steel) allows to reduce FATT, but at expense of strength (DYS = – 35 MPa).
- Addition of Cr produces further improvement in toughness (50% FATT below ~100°C).

Therefore the Mo-Ni-Cr-Nb-V steel resulted to be the most promising for the production of heavy wall linepipes.
The laboratory materials exhibit the general trend of increasing yield to tensile (Y/T) ratio when yield strength increases. For the required strength levels (YS > 450 MPa) the Y/T values are in the range 0.83 to 0.87, being the highest ratios related to a predominantly bainitic structure.
The alloy design based on the Mo-Ni-Cr-Nb-V version exhi-
bits the best results in terms of low values of Y/T ratio.
Concerning toughness, when the as-quenched microstructure is fully bainitic and the volume fraction of MA is very low, the 50% FATT of QT material is practically independent of the tempering temperature, as expected. The increase of tempering temperature is effective in improving toughness if significant amounts of MA constituent, in the form of large islands, are present in the as-quenched material. In this case, usually, the rising of tempering temperature from 630°C to 680°C leads to a decrease in yield strength (DYs = – 20 MPa) and a slight improvement of toughness in terms of 50% FATT (DFATT = – 10°C).

**Industrial Production and Pipe Qualification**

Heavy wall seamless pipes of medium diameter (OD = 219 to 323 mm) and WT = 30 to 40 mm were produced at Teneris works by the seamless process, using the steel chemistry range and heat treatment conditions identified as promising by the metallurgical design. Water quenching was carried out by dipping the rotating pipe in a tank containing stirred water. Also an internal water jet is used to increase heat transfer at the inner surface.

All pipes were manufactured according to specific customer requirements for production risers and flowlines. In particular, in addition to weldability requirements, in terms of carbon equivalent, Ceq° (IIW) and Pcm parameter, suitable tensile properties at room and at 130 °C shall be guaranteed (minimum yield strength = 448 MPa).

The characterisation of selected pipes from the production was carried out by extensive metallography and mechanical testing, which included hardness measurements, longitudinal and transverse tensile testing, Charpy-V impact testing, crack tip opening displacement (CTOD) testing.

The industrial production confirmed the effect of main process parameters and metallurgical factors on microstructure and strength-toughness combination, as outlined by the laboratory experiments, and allowed to identify the actions for a fine tuning to develop a good combination of strength and toughness.

All hardness values on QT pipes were below 248 HV10.

The mechanical properties of various industrial materials in terms of 50% FATT and yield strength are summarized in Fig.14. The materials produced using the Mo-Ni-Cr-Nb-V steel, have significantly improved toughness for a given yield strength level between 460 and 530 MPa, compared to the conventional chemistry without Ni. The productions indicated that suitable toughness levels (i.e. 50% FATT < – 50°C) have been achieved. Also high CTOD values at – 10 °C (> 1.1 mm) were measured on the QT seamless pipes. Best results were attributed to the following aspects:

- strict control of process parameters during heating in order to develop uniform and small PAGS;
- effective quenching to promote higher volume fractions of bainite and a more refined final microstructure.

Suitable strength levels of pipes for flowlines and production risers were also achieved at 130 °C.

Some pipes were girth welded by GMAW using low (0.6 kJ/mm) and high (3 kJ/mm) heat inputs. CTOD was also performed in the HAZ of girth welds performed by GMAW. CTOD specimens were located at both the Transformed-HAZ (THAZ) and Visible-HAZ boundary (VHAZ). Post-test validity checks were carried out by specimen sectioning followed by fractographic and metallographic evaluation. The CTOD results at 4 °C were quite good both for the THAZ (CGHAZ), with values of 0.6 - 1 mm and the VHAZ with values of 1 - 1.5 mm. At – 10 °C, CTOD remained always greater than 0.3 mm.

**HIGH STRENGTH RISERS (WT = 15 to 25 mm)**

Due to the higher cooling rates during quenching, these pipes can develop a predominantly bainitic-martensitic structure more easily. The tuning of Mn, Mo, Cr, V and Ni additions was done on the basis of the results from the metallurgical model and pilot trials (Table I).

A steel with carbon equivalent, Ceq° (IIW), in the range 0.37% to 0.40% and maximum Pcm parameter below 0.2% was selected.

The sizes and mechanical properties of the risers produced are shown in Table IV. Hardness near the internal surface is usually higher because a high-pressure water jet blows the steam generated inside the pipe during the immersion in the water tank, promoting a higher heat transfer coefficient, thus increasing the severity of quenching. However, it is important to mention that suitable hardness can be obtained adjusting the tempering

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**Table IV – Sizes and average mechanical properties of the produced risers.**

<table>
<thead>
<tr>
<th>Item</th>
<th>OD (mm)</th>
<th>WT (mm)</th>
<th>Ceq° (IIW)</th>
<th>HV max</th>
<th>YS (MPa)</th>
<th>UTS (MPa)</th>
<th>EI (%)</th>
<th>FAT T (°C)</th>
<th>YS (MPa)</th>
<th>UTS (MPa)</th>
<th>EI (%)</th>
<th>FAT T (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>323.9</td>
<td>16</td>
<td>0.38</td>
<td>243</td>
<td>589</td>
<td>677</td>
<td>42</td>
<td>- 60</td>
<td>596</td>
<td>672</td>
<td>25.4</td>
<td>- 50</td>
</tr>
<tr>
<td>2</td>
<td>298.5</td>
<td>22</td>
<td>0.40</td>
<td>248</td>
<td>594</td>
<td>678</td>
<td>41</td>
<td>- 50</td>
<td>602</td>
<td>681</td>
<td>25.0</td>
<td>- 40</td>
</tr>
</tbody>
</table>

* full strip specimen; ** round specimen

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*Fig. 14 – Toughness vs yield strength for heavy wall seamless pipes.*

*Fig. 14 – Tenacità in relazione alla tensione di snervamento per tubi senza saldatura di grosso spessore, per linepipe.*
treatment parameters. As all the hardness values were below 280 HV, these risers can be used for sour service applications.

An interesting feature found in these pipes is that there is not a significant difference between the longitudinal and the transverse tensile properties at room temperature. This is due to the high isotropy which is typical of seamless pipes.

The materials exhibited an absorbed energy value above 140 J up to –60 °C. This is a consequence of the microstructure promoted after external/internal quenching and tempering. Also high CTOD values (> 1.2 mm) were measured at –20 °C on these high strength Q&T seamless pipes.

Weldability trials proved that the selected chemical composition combined with proper welding procedure assures hardness values lower than 280 HV and satisfactory toughness levels both in the weld metal and heat affect zone.

CONCLUSIONS

New chemistries and optimized Q&T conditions were identified for the production of seamless pipes for both flowlines with thickness up to 42 mm and risers of grade X80 and 15 to 25 mm WT, through an extensive characterization of laboratory and industrial materials. A number of selected alloy systems have been systematically investigated. Main conclusions are:

- The as-quenched microstructure plays a primary role. The best toughness values are related to a predominantly bainitic microstructure after quenching (bainite > 70%) combined with a homogeneous and fine distribution of MA constituent. This is promoted through the control of austenite grain growth during the heating stage and an effective quenching.

- The tempering temperature has a secondary role. However, higher tempering temperature leads always to a slightly lower yield strength and, in the case of coarse MA islands and cementite particles, a slightly improved toughness.

- The CTOD results in the HAZ of GMAW girth joints were good.

REFERENCES