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Technology and controls improvements on the continuous casting of Acciaierie di Calvisano for improvements on solidification process and new steel grades

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In last years Feralpi Group is following a route in the direction of increase production of special steel grades for application also in automotive and for mechanical components.
The main actions adopted have been the completion of production chain of special steels coupling the steelmaking facilities of Acciaierie di Calvisano and the rolling mill for wire rods of Caleotto (100 % acquired in 2020) included in the new Business Unit Specialties realized to promote the production of new products.
For this reason Acciaierie di Calvisano is devoted mainly to improve the product quality and the capabilities of a reliable processes realization in whole steelmaking area.
The solidification process in continuous casting of billets is the core step in this route and for this reason several technological developments have been adopted regarding new systems to improve capabilities and devices for casting realization, for process monitoring and control to reach assessed quality aims.
To reach these targets Acciaierie di Calvisano promotes R&D projects and collaborations with technology ad research partner to be supported with an high level of technical contributions in a continuous route of development starting by technological devices availability, process management and simulation/controls.

KEYWORDS: CONTINUOUS CASTING, SIMULATION, PROCESS CONTROL, SOLIDIFICATION MODEL;

INTRODUCTION

For the continuous casting of billets following aspects can be the origin for process or quality limitations:

- breakout events and process instability (steel level in mold, temperature, steel flows....)
- internal and surface cracks
- porosities
- Segregations
- Not correct shape
- Inclusions content
- Scale formation

For this reason, efforts on capabilities improvement should be adopted for following aspects:
- To control properly the steel feeding from tundish, the liquid steel level and the casting speed depending by steel temperature in arrival it is necessary to

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maintain the correct metallurgical length, uniform and stable solidification conditions reducing possible local defect formations

- To correctly control the lubrication in mold with appropriated powder and with correct feeding is fundamental to enable a correct solidification since the beginning having enough shell thickness at the exit of primary cooling and to avoid steel sticking on the mold reducing possible surface defects.
- To define and control the proper parameters of mold oscillation is important to maintain correct solidification front formation and to avoid steel sticking on the mold
- To control heat flux in mold by primary cooling it is necessary to avoid breakout conditions enabling a good surface shell thickness and a proper internal solidification formation.
- To control the secondary cooling depending by steel temperature in arrival it is necessary to maintain the uniform and stable solidification conditions to avoid local high reheating (cause of internal cracks) to enable a correct liquid pool closure avoiding porosities.
- To control and manage the internal liquid pool through Electromagnetic stirring or soft plastic deformations it is necessary to obtain homogenous internal solidification reducing eventual porosities and segregations.
- To have the correct view of whole process parameters and to have a feedback from the product results on-line enable the possibility to correct in real time eventual abnormal conditions as shapes deformations or possible reducing quality conditions.

CALVISANO STEELMAKING PLANT AND VIEW OF CONTINUOUS CASTING DEVELOPMENTS

Acciaierie di Calvisano was founded in 1972 and is located nearby Brescia as part of Feralpi Group.

The plant produces quality and special steel billets, the intermediate product used for making rebar and wire rod. The process route at Calvisano steel plant includes an AC EAF, LF and CCM.

Continuous Casting Machine of Calvisano is characterized by 4 casting strands that produce High, Medium and Low-Carbon Steels billets with different section dimensions, typically from 120x120mm to 160x160mm. Continuous Casting Machine is characterized by presence of:

- ladle, tundish, mold, SEN (for special steel grades),
- primary water cooling system, secondary nozzle spray cooling system, air cooling bed,
- M-EMS, S-EMS, F-EMS,
- withdrawal rollers and cutting system.

New installations and developments have been performed mainly within R&D projects as: SteelPro4.0, Support Cast and Quality Integration (Figure 1).

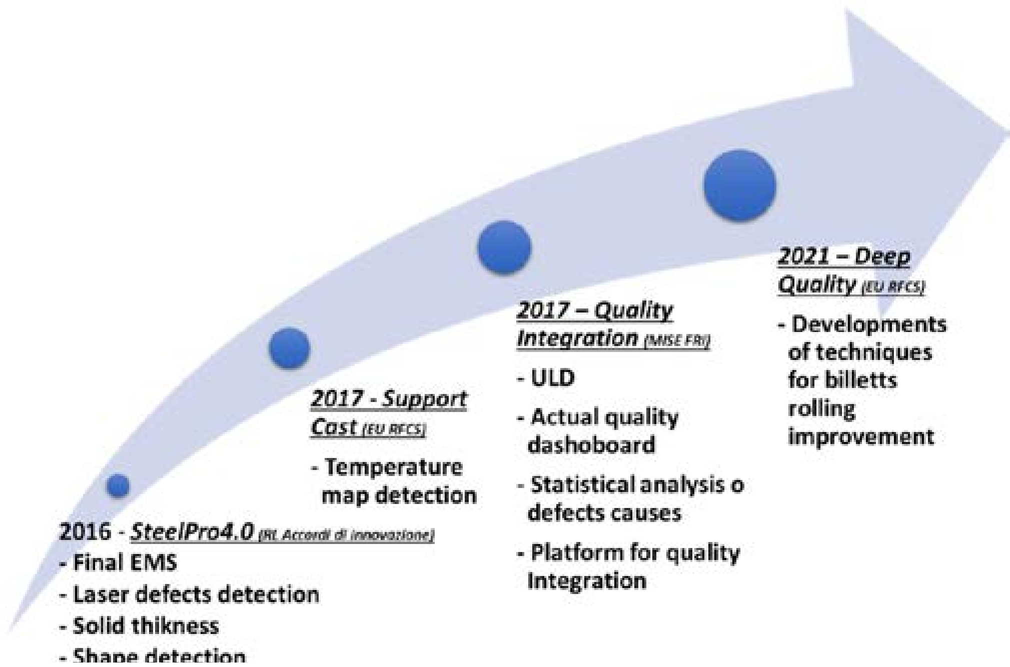

Fig.1 - R&D project supporting roadmap continuous casting improvements in Acciaierie di Calvisano.

With the upcoming of new measurement systems technologies and their actual combination, a new approach is under development in Calvisano to improve the process quality in Continuous Casting.

The developments have also been supported by a preliminary phase of solidification process off-line simulation taken by Politecnico di Milano in different configurations in order to assess in optimal way the casting configu-ration for the new devices.

Acciaierie di Calvisano is following development of the global route in figure 2 including as main points:

- Technological improvements on the devices for liquid pool stirring and mold management
- Application of new technologies for casting billet monitoring
- Application of new systems for process management and control
- Decision level (alert and guidelines for Decision Support System).

This approach with the main scopes to implement systems ford:

- process and quality improvements; as application of final stirring for internal segregations reduction and to guarantee internal and shape quality
- process control and results stability also through process and product monitoring;
- process data analysis and decision support to enable a route of continuous improvement.

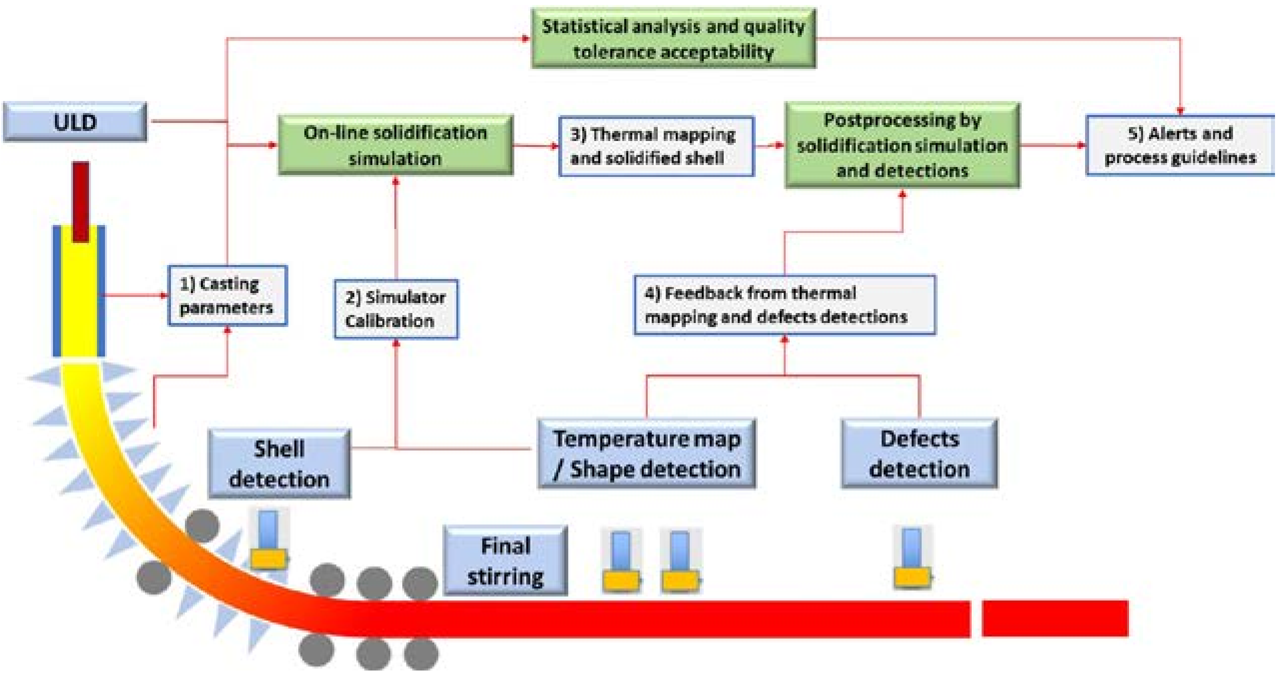

Fig.2 - View of the control system including on-line solidification model coupled with relevant detections.

ACTIONS FOR PROCESS AND QUALITY IMPROVEMENTS

The main actions reported for process and quality improvements are:

- Application of Ultrasonic Level Detection system for process improvement through automatic powder feeding in mold
- Application of Final Stirrer to enable reduction of internal segregation

Ultrasonic Level Detection system for process improvement

In order to support the on-line process monitoring and control the continuous casting machine has been pro-vided with a new Ultrasonic Level Detection (ULD) system developed by Ergolines (Figure 3) to obtain:

- On-line monitoring of the covering powder thickness on the meniscus
- Automatic powder feeding
- Mold thermal mapping

The quality of casting billets is influenced by the fluid flow of powder in the mold, particularly at the meniscus. In order to minimize inclusion entrapment, it is especially important to keep at the setting values the liquid steel level in the mold and the powder feeding rate. As the solid powder is added on top of the mold, the powder melts generating a liquid slag pool first and a thin, vertical film of liquid slag then. The final effect consists of a protection the steel meniscus from oxidation, providing thermal insulation, preventing solidification of the steel surface and absorption of non-metallic oxide inclusions.

The new ULD system it is able to measure the powder thickness in mold based on temperature measurement by ultrasonic signals, by this measurement and having set a reference value the automatic control of powder is enabled to maintain the stable value of powder thickness fixed as target so the powder film can be maintained also when changes occur on actual process parameters.

The system is applied for the 4 casting strands and functionalities are continuously on improvement.

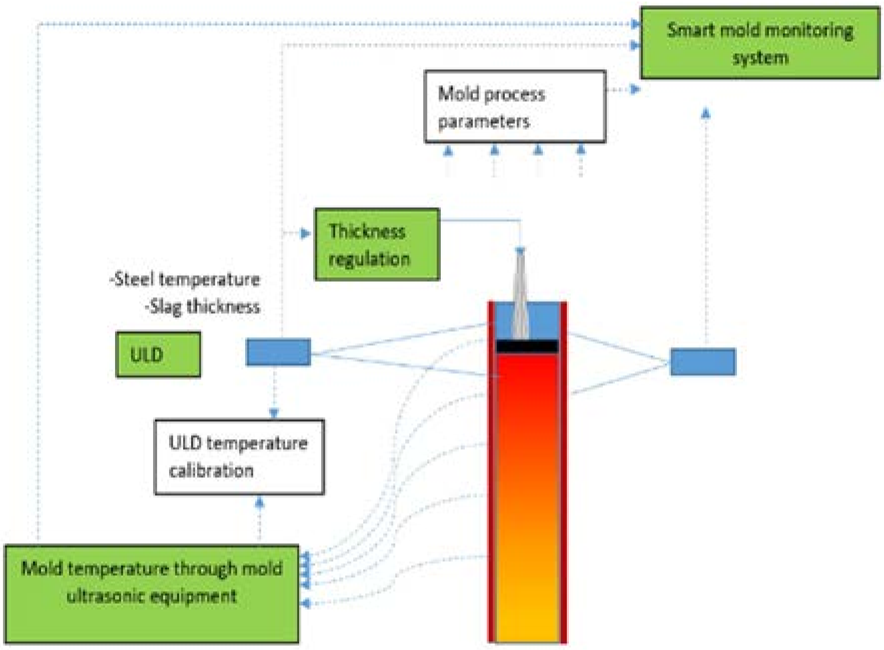

Fig.3 - Scheme of the application of the Ultrasonic Level Detection system.

<u>Application of final Stirrer to enable reduction of internal segregation</u>

The installation of Final EMS Stirring equipment required the best configuration determination first, then a single line trial installation till prosecution with the completing of the whole 4-line casting machine tooling.

To take into account physical, chemical, electrical and magnetic phenomena, a conspicuous and deep studying phase has started with PoliMi and Ergolines. From Calvisano side, the improvement of the internal quality through a mitigation of carbide and sulfide segregation phenomena between dendrites is one of projects ac-tivities focuses. The optimization of quality corrective action consists simultaneously both of:

- identification of the optimal electromagnetic stirrer frequency and current to be applied to different steel grades and billet sections;
- identification of the optimal positioning on Continuous Casting machine, considering the present plant constraints.

Steel temperature, liquid diameter estimation and effect of final EMS on liquid steel velocity has been calcu-lated by PoliMi and Ergolines (Figures 4, 5). For the simulation of Electric and Magnetic module and Turbulent flow a model with liquid pool and coils of electromagnetic stirrer has been designed. Induction current gener-ated acts with the magnetic field of the inductor to induce electromagnetic Lorentz force in the molten steel. Along the center line of the liquid pool a Lorentz force up to 240 N/m3 is produced. The same force works on every unit of volume of liquid steel and generates a torque effect that gives to the liquid steel a global rotational movement. The effect of final EMS on liquid steel velocity at billets core at condition of induced magnetic field at 4.8×10^7 A/m surface current density has been simulated as shown in Figure 5.

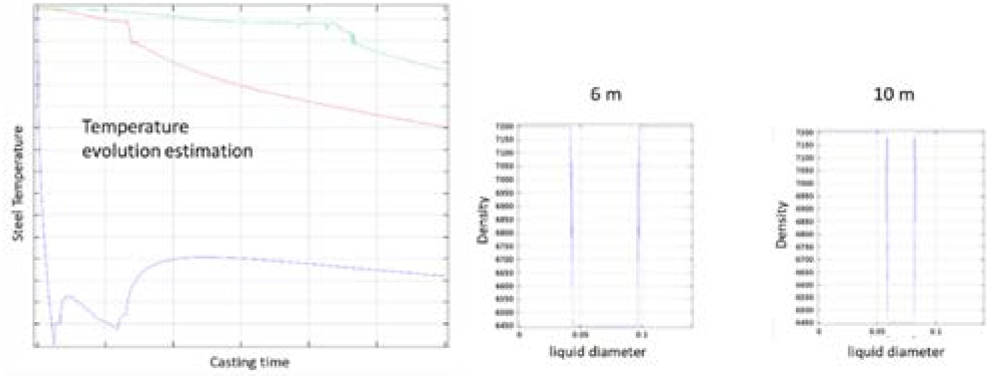

Fig.4 - Steel temperature and liquid diameter estimation by predictive solidification modelling.

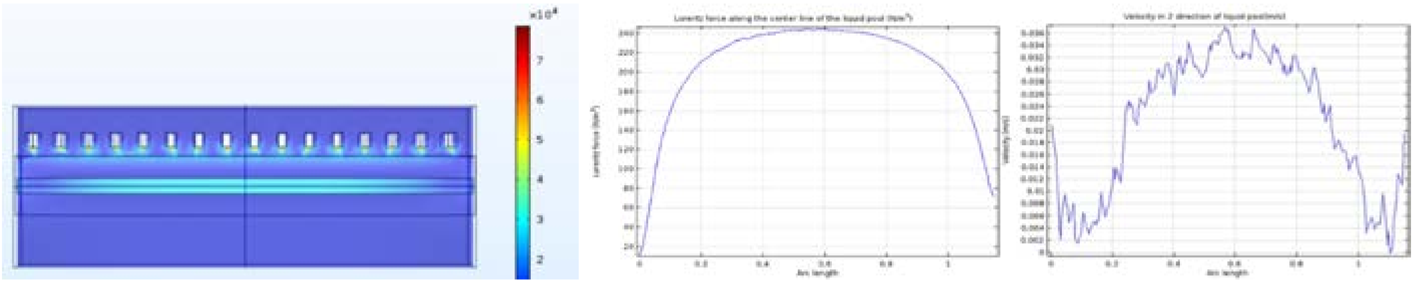

Fig.5 - Simulation of Lorentz force and effect of final EMS on liquid steel velocity at billets core.

Main benefits obtained with application of final EMS have been (Figure 6) :
- reduction of inner porosity
- reduction of inner carbide and sulfide segregation
- improved homogeneity and hardenability
- possibility of increase of casting speed and productivity.

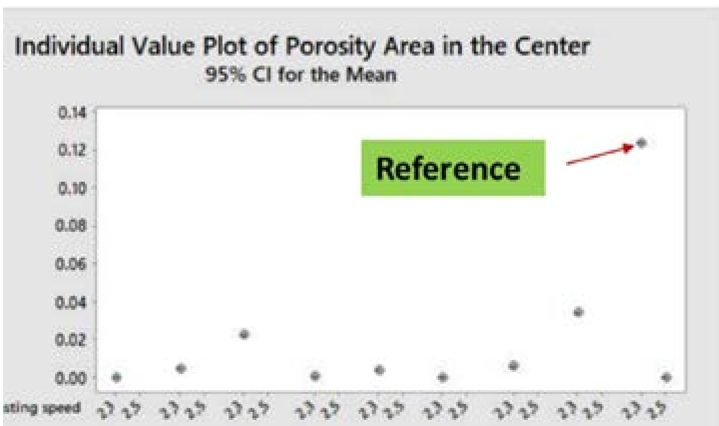

Fig.6 - View of reduction of porosity in the center area of billets with final EMS.

ACTIONS FOR PROCESS AND PRODUCT MONITORING

For the control of the process, it is important a direct feedback from product detection to support both:

- Deeper understanding of phenomena and relation between results and process management
- Have faster alerts in case of abnormal behaviors and final results on the product

In this way the main billets detection on development are:

- Thermal mapping of the billets for surface defects detection during casting realized with BFI
- Surface defect detection based on laser scanning and deep learning realized with Visiorobotics.
- Shape measurement based on double laser scanning realized by Ergolines/AIC
- Solidified Shell Thickness measurement realized by Ergolines/AIC

Thermal mapping of the billets

In the frame of the RFCS project SupportCast a system of defect detection has been developed by BFI coupling thermal detection through Thermal Camera and a software for on-line data analysis realized in order make evident eventual surface crack presence in case of abnormal temperatures variability (Figure 7) .

Experimental trial campaign and surface temperature values have been registered and postprocessed. The system is under testing to improve performances of defect detection and in particular, a defect due to steel level variation in mold has been detected as reduction of local average temperature. Moreover, an external longitudinal crack (Figure 8) has been detected on the cooled casted billet at room temperature.

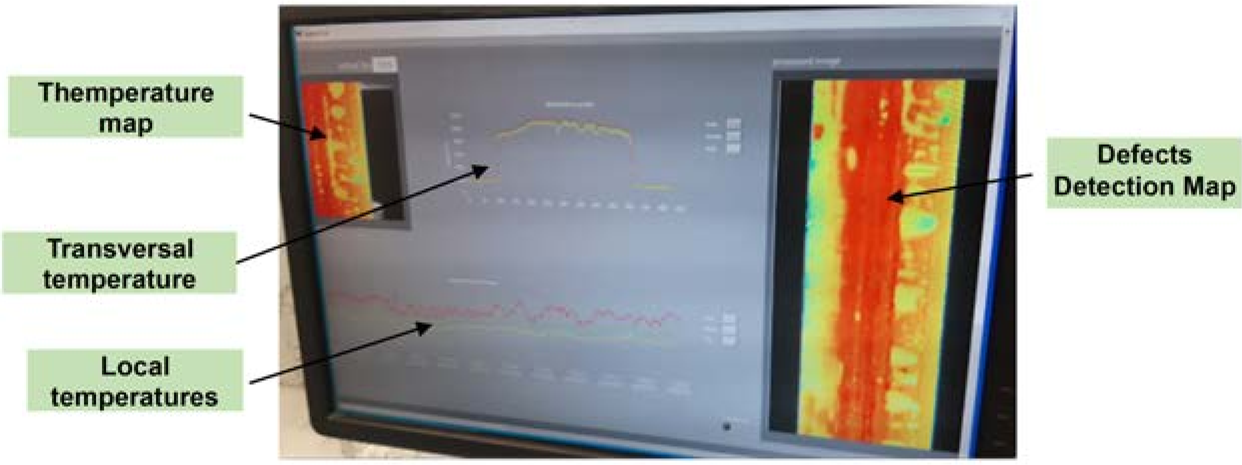

Fig.7 - View page of surface defect detection and thermal mapping realized by BFI.

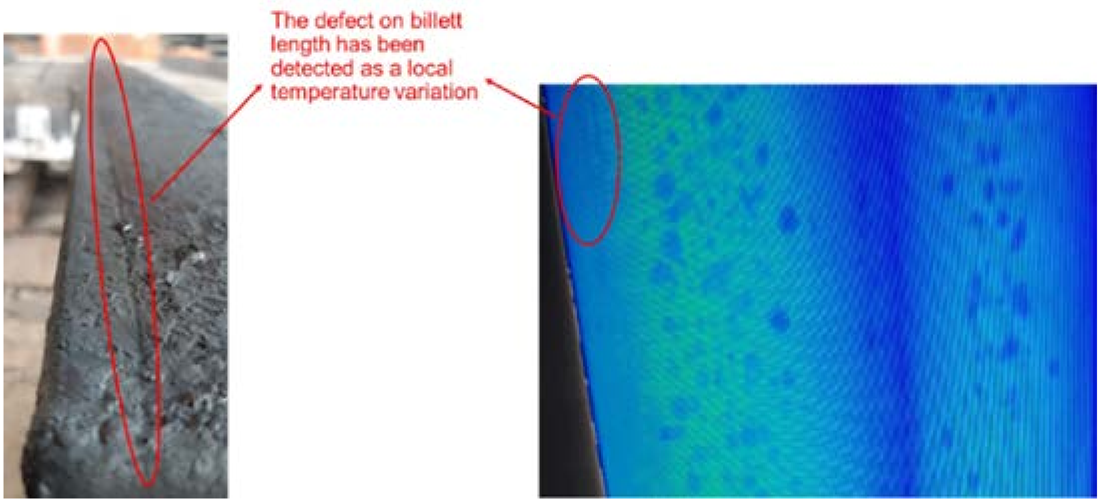

Fig.8 - Evidence of defect detection obtained through thermal mapping of BFI.

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Surface defect detection based on laser scanning and deep learning

A system for surface defect detection has been developed by Visiorobotics within the SteelPro4.0 project using a laser scanning and signal postprocessing for surface status representation (Figure 9).

As off-line application the system has been used to evaluate the accuracy in detection of relevant defects. In particular, the laser scanning is able to measure the surface profile through line scanning with a resolution around 0,2 mm than signals acquired are coupled to show a representation of the billets surface through combination of subsequent profiles. Billets with relevant defects have been used for trials, and capability to detect some defects has been shown when surface aren't covered by scale.

In on-line application following steps are available (Figure 10):

- Processing of the data are realized online in real time during the hot billets casting process.
- Surface conditions are shown during the casting in order to support the operators when defects detected

By this approach it has been shown the capability of the systems to detect surface defects while subsequent trials will be necessary to improve the evaluation of smaller defects (till 0,2 mm), selecting areas of scale presence, through a training system in order to alert in case of defect detected.

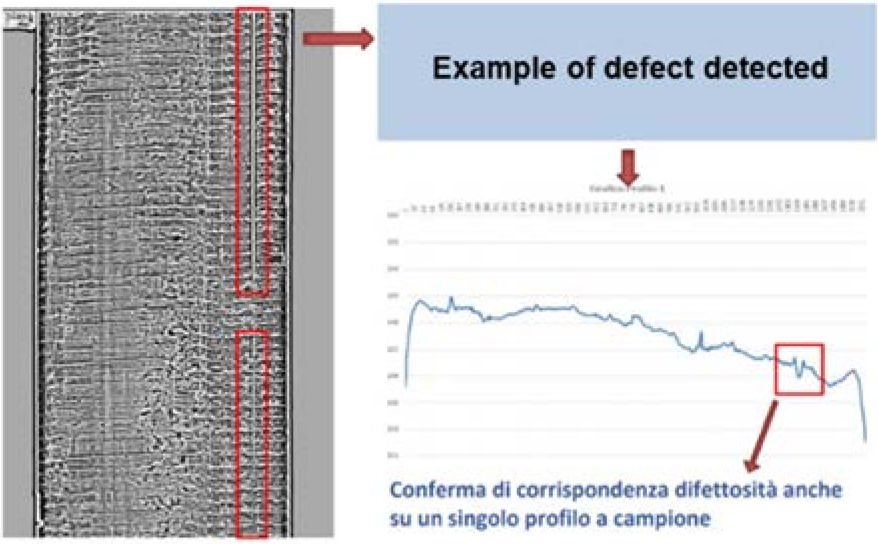

Fig.9 - Offline detection with laser scanning and surface representation through Deep Learning.

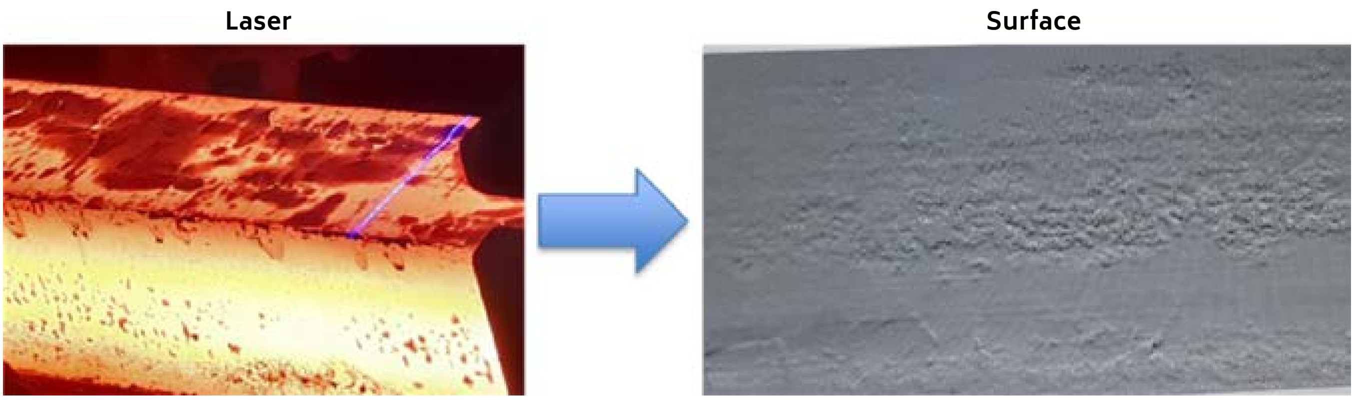

Fig.10 - On-line laser scanning and billets surface reconstruction through Deep Learning.

Shape measurement by laser scanning and solidified shell thickness measurement

Solid skin thickness measuring system, laser geometry measurement system and Final EMS Stirrers were also designed and tested with the partners Ergolines and AIC.
A solid skin thickness measuring system, positioned as first trial configuration in correspondence of the Strand EMS Stirrer, has been tested in Calvisano plant (Figure 2).
The aim of the new system is to send feedback to the solidification simulator in order to:
- calibrate the model parameters based on the measurement of solid steel phase thickness,
- improve the control of the solidification process, the microstructure of billets and consequentially the quality of the billets product.

The system for laser geometry measurement has been designed (Figure 11) to send feedback to the Decision Support System (DSS) in order to:
- alert and recognize cases of abnormal casting conditions
- discard abnormal billets for subsequent billets welding process.

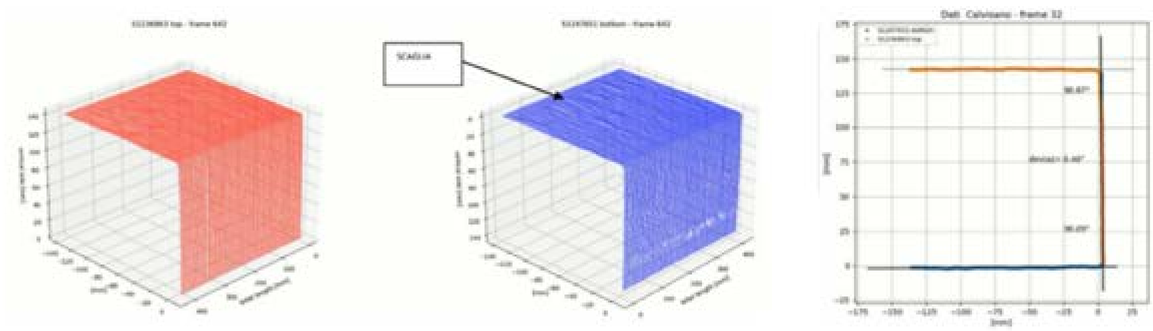

Fig.11 - Geometry measurement system designed output.

SOLIDIFICATION SIMULATIONS AND CC PROCESS DATA ANALYSIS SYSTEMS

As by the global scheme in figure 2 an off-line solidification model has been implemented by Visiorobotics based on mathematical modelling provided by Polimi (in the frame of the project SteelPro4.0) in order to collect data with the objective to give indication about the status of the solidification evolution for the different casting strands in real time.
The mathematical approach realizes a thermodynamic simulation of the solidification evolution during casting taking into account the process parameters as:
- Conditions of steel from tundish (Temperature, Steel grade, liquidus and solidus temperatures)
- Casting speed
- Water flow rate and temperature in primary cooling
- Distribution of water flow rate in secondary cooling (spay nozzels)

Based on these data are given as output of the simulation of:
- heat fluxes between the hot steel and the cooling system resulting in enthalpy decrease due to the water cooling and to liquid/solid transformation (latent heat).
- Temperature evolution and thermal mapping of each section of the billet along casting line
- Liquid, solid and mushy phases mapping.

Relevant parameters taken into account for results validation and as alerts functions are (Figure 12):
- the metallurgical length of the complete solidification of the caster strand.
- the solidified thickness and liquid diameter in relevant sections of the casting line
- the whole thermal mapping of the billets in all sections

The system is improved with continuity and next steps of development will be:
- Adaptation of the simulator to different steel grades of special steels;
- Representation of the effects with different spray nozzles in secondary cooling.

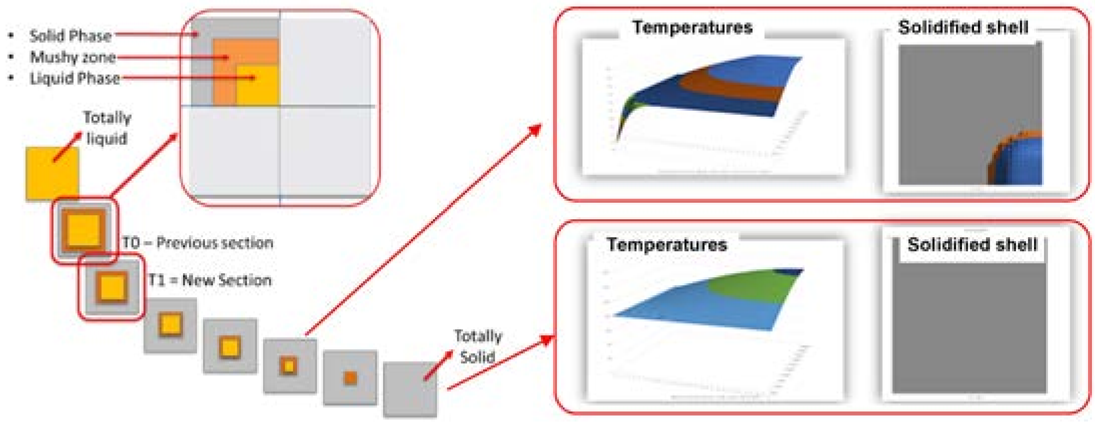

Fig.12 - Scheme of calculation for Solidification off-line model.

The online application follow the general scheme in figure 2 including following steps (Figure 13):

• On-line casting parameters acquisition
• Thermal mapping measurement
• On-line defects detection
• Comparison of solidification estimation with real on-line detections
• Relevant parameters representation
• Postprocessing and process guidelines and alerts.

The on-line application of solidification model has been realized and the whole configuration and coupling with the on-line detection and alert systems are under development as shown in Figures 13, 14.

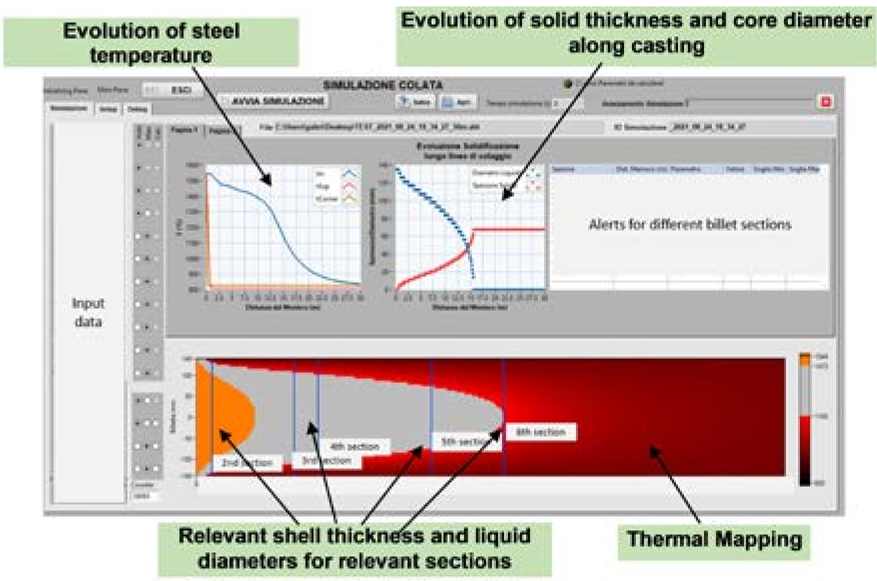

Fig.13 - Simulator interface for the single strand.

The main functions required to Decision Support System are:

• To Give an overview of billets solidification conditions along the casting line for each strand (Figure 13)
• Autocalibration of solidification modelling thanks to detection of temperature, shell thickness
• Obtain alerts in case of abnormal casting conditions respect (Figure 14):
- Acceptability ranges of casting parameters previously defined
- Casting length, shell thickness, Temperature simulated in reference positions
• Obtain alerts of defects detection thanks to the measurement systems in terms of (Figure 14):

- Defects detected by thermal mapping
- Shell thickness detected
- Laser surface defect detection
- Laser geometry defects detection

• To suggest guidelines for actions in terms of billets inspection, level quality assignment or casting parameters modification.

The main results aimed by the developments shown in Acciaierie di Calvisano are:

- Reduction of internal defect on billets for special steel in terms of porosity and segregation
- Availability of detection systems that can be used as support to on-line process monitoring
- Availability of on-line systems for data collection analysis and solidification process simulation that can be used for advanced process monitoring and as Decision Support to solidification correction
- Increase of internal competences on solidification, mathematical simulation and process control

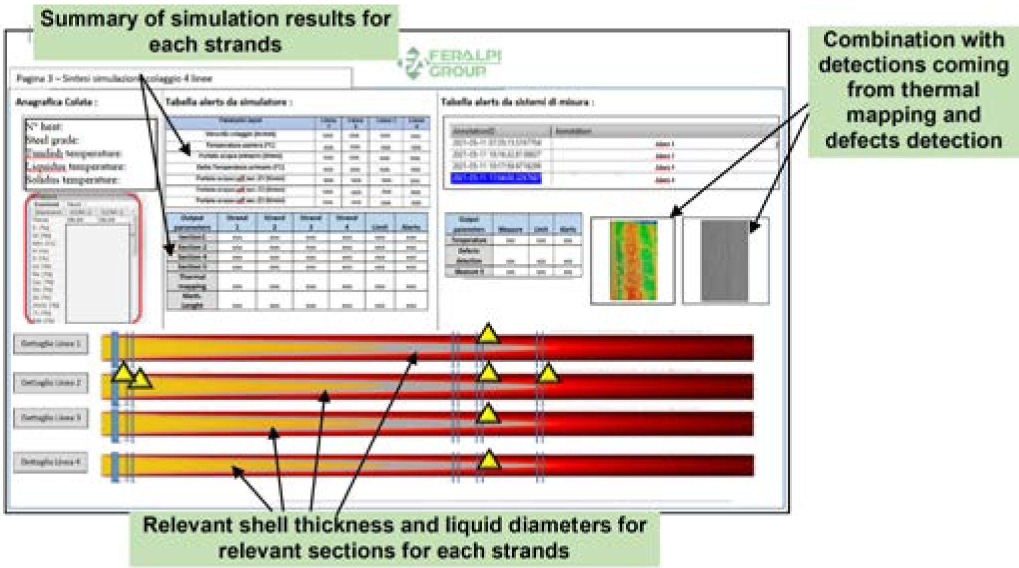

Fig.14 - Simulator interface with heat data, simulation output, measurement systems and alerts.

CONCLUSIONS

Acciaierie di Calvisano and Feralpi Group are following a route of strong increase of production of special steel grades with necessity to increase product quality and capabilities of a reliable process.

In this way the application of advanced strategies Industry 4.0 are strongly followed including:

- application of innovative on-line monitoring systems and defect detection
- Application of digital twin strategies with on-line solidification process simulation
- Integrate on-line detection systems with simulation approach to reach advanced capabilities of solidifica-tion understanding as support to availability of advanced alerts and decision support

These applications and strategies are also the conditions to improve product quality as support to further development of production of special steel as in industrial strategy of Acciaierie di Calvisano.

For this reason, improvements and adaptations on continuous casting machine are on-going to implement further plant sections and devices able to realize and control the solidification process in adapted way as necessary for each steel grade.

To reach these targets Acciaierie di Calvisano follows R&D projects and collaborations with technology ad research partner to be supported with a high level of technical contributions in a continuous route of develop-ment starting by technological devices availability, process management and simulation/controls.

In this way, also the collaborations with research partners as Politecnico di Milano and Visiorobotics has been useful support to realize the mathematical model for solidification simulation used to define optimal process configurations for internal quality improvement while the collaboration with BFI is running for surface defect monitoring.

Furthermore, the partnership with a technology developer as Ergolines, Visiorobotics, and Automazioni Industriali Capitanio enabled developments of innovative systems for defect detection on billets during casting.

The mentioned developments have been realized in the R&D project "Support Cast" supported by the EU funding scheme Research Fund for Coal and Steel and in the R&D project "SteelPro4.0" supported by the funding scheme "Accordi per l'Innovatività" promoted by Regione Lombardia.

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