Modernization of Continuous Casting Machines in the Era of Intelligent Manufacturing

Digital technologies are transforming industry at all levels. Steel has the opportunity to lead all heavy industries as an early adopter of specific digital technologies to improve our sustainability and competitiveness. This column is part of AIST’s strategy to become the epicenter for steel’s digital transformation, by providing a variety of platforms to showcase and disseminate Industry 4.0 knowledge specific for steel manufacturing, from big-picture concepts to specific processes.

Modernizing the modeling process of continuous casting is a complex activity, as it involves advanced mathematical and statistical models. In order to simulate the physical process, considering the variables involved and the computational phenomenon to the required accuracy, the appropriate selection of model is important. The multi-dimensional complexity such as heat transfer, thermal stress, solidification, segregation effects, shrinkage and bulging, to name a few, cannot be captured simultaneously during the process and presented in a single, comprehensive model. A reliable transformation of essential process parameters to the boundary conditions of a mathematical model is required in order to develop a technological solution resulting in the increase of steel product quality, elimination of defects and increase in the final product quantity.

Empirical focus is on selecting a more complex or intelligent model to avoid non-synchronizing; the complexity with the intelligence of the model, i.e., verification of model parameters; and their correlation with process data. Hence a division on each area of influence is applied and a selected process is tuned to improve the overall phenomenon. The natural division thus applied in continuous casting process modeling is related to an attempt at identifying the ensuing problem during actual steel casting, or focusing on a selected section of the process in order to improve the existing technology. The optimization of process modeling affects the functional and technical improvement of each selected section process, resulting in smart or intelligent manufacturing with the goal of obtaining production efficiency, product quality and providing excellent service.

As a result of extensive research and analysis, various technological packages for continuous casting machines were designed, developed and deployed, focusing on improvements in process modeling, passing through the development of a complete simulation environment for flexible and intuitive casting practice tuning, including monitoring of equipment conditions.

Technological packages Q-MAP, Q-LEVEL+, Q-COOL, Q-CORE and Q-PULSE focus on the concept of manufacturing with the purpose of optimizing production by using advanced technological solutions with the goal of attaining a 3Q paradigm (Quality-Quantity-Quickness) through intelligent or smart manufacturing. The ability of these technological packages to be stand-alone products provides an added advantage so that the client can focus on the existing structure and can gain the time-cost factor for the installation and maintenance.

DIGI&MET Intelligent Manufacturing in the Context of Industry 4.0

Danieli’s new cross-functional business unit, DIGI&MET, provides customers digital innovation under new business models. The statement “From a Plant to a Smart Plant” can summarize the DIGI&MET vision: the smart plant is a safe, flexible, efficient and environmentally friendly concept of manufacturing founded on the extensive digitalization of processes, the deep integration of cyber and physical worlds, and the strong interconnection between intelligent systems and humans. In a smart plant, systems and equipment autonomously execute complex tasks and support
humans in complex decision-making or even provide decision automation.\textsuperscript{1}

Intelligent manufacturing or smart manufacturing in the context of Industry 4.0 is a broad concept of manufacturing with the purpose of optimizing production and product transactions by making full use of advanced information and manufacturing technologies.\textsuperscript{2} It is regarded as a new manufacturing model based on intelligent science and technology that greatly upgrades the design, production, management and integration of the whole life cycle of a typical product. The entire product life cycle can be facilitated using various smart sensors, adaptive decision-making models, advanced materials, intelligent devices and data analytics.\textsuperscript{3} Production efficiency, product quality and service level will be improved.\textsuperscript{3}

The fundamental measurements for the advancement of manufacturing system technology are quality, productivity and cost. Productivity and efficiency are focal points for manufacturing technology advancement; quality and cost form the constraints. Enhancement in the area of productivity and efficiency and the flexibility in the manufacturing systems are the byproducts of advances in information technology.

In order to refer to a system as intelligent, it should possess the predictable nature (sense) and the capability to take decision (decision-making) and act on it. Due to the increasing complexity in modern manufacturing systems, process-based decision-making has become a daunting task. The need to leverage vast data coming from various systems and the ability to use cutting-edge computing techniques in order to make intelligent decisions is exponentially increasing.

The challenge lies in processing information and knowledge in order to make the correct decision in real time with minimal or no human intervention. Big data analytics, cloud computing and machine learning are the potential sources for intelligent manufacturing. Advances in analytics technologies have a significant impact on intelligent manufacturing implementation.

Model-Based Technological Packages for Continuous Casting

In the DIGI&MET approach, the technological packages for the casting machine must cover all the critical aspects in production, from planning and scheduling to management and control of energy, maintenance and process. All together they form the Q-CAST platform,\textsuperscript{2} a comprehensive solution dedicated both to long products (billet, blooms, beam blanks) and flat products (slabs, thin slabs) casting machines. Each package typically is supplied with two different application modes: an online version, for process control/monitoring, and an off-line version, to perform process simulation with the aim of practice optimization and scheduling support. Sharing the same model kernel assures alignment between simulated and real results in compliance with the digital twin concept. The modular architecture allows a customized configuration suitable for the specific requirements, an important feature in particular for brownfield and revamping situations.

All packages are built on top of a tracking supervisor with the task of performing event recording (ladle open/close, strands start/stop, semi-product cut/weight/sample), data recording, estimation of the remaining process time, temperature tracking and superheat calculation, coordination of the process-related packages, and equipment life tracking in order to properly assign quality levels on-line. An integrated and flexible script-based process simulation package is provided to support model tuning, practices definition, data analysis and troubleshooting.

Q-MAP

Q-MAP is a new system for mold phenomena detection and analysis. It provides a complete scenario of mold thermal distribution, lubrication and solidification phenomena, as well as a detailed guide to the process and operation. This package provides a wide spectrum of thermal monitoring functions to identify several phenomena in the mold, such as longitudinal cracks — both on wide and narrow faces, slag entrapment, and irregular powder behavior such as the sudden detachment of the permanent layer of mold powder from the mold Cu plate, and slag washing. It identifies the warning signs of sticking, such as the occurrence of a progressively colder meniscus along the mold perimeter. The system here provides a sticking prediction system that is able to forecast the sticking condition and avoid its actual occurrence. The mold friction analysis can also be viewed online, which in turn allows the operator to determine if there are any deviations from the usual trends that may indicate a malfunction in the mold lubrication process. When the mold is equipped with a grid of temperature sensors (K-type thermocouples) on each side, typically for slab and thin-slab casters, analysis of the signal can be performed to detect sticking, breakout and cold-tooth events.\textsuperscript{6} The package detects the pre-conditions of this event and takes appropriate actions in order to permit the healing of the skin of the slab before unrecoverable damage. This package jointly executes the functions of thermal map acquisition, detection and visualization, and activates all the necessary healing sequences.

Results — The combination of the decrease in meniscus temperature and the increase in mold level standard deviation produces an alarm for the sticking detection (Fig. 1). Thus the Q-MAP triggers the message to decrease the casting speed, resulting in the prevention of sticking with a consecutive increase in the meniscus
temperature and a decrease in mold level standard deviation.

In Fig. 2, the mold plates are shown during cold sticking condition on the left and in the hot sticking condition on the right, which illustrates the thermal condition after the speed is reduced. In this case, the limited speed slowdown (from 5.4 m/minute to 5.2 m/minute) prevents sticking. Q-MAP predicts this harmful condition and triggers an alarm or message to the operator to reduce the casting speed before sticking occurs. During mold level fluctuation, the molten fluxes are progressively consumed since they are brushed onto the Cu plates, where a thicker and thicker permanent layer is built up. This thicker powder layer reduces the thermal exchange between the steel and the Cu plates, hence the meniscus temperature is reduced as well as the heat flux. The shortage of molten fluxes is therefore responsible for sticking due to a lack of lubrication.

A dedicated algorithm in the Q-MAP system also identifies the longitudinal face crack as shown in Fig. 3, allowing the activation of the healing cycle.

**Q-LEVEL+**

Q-LEVEL+ is specifically developed for monitoring and controlling mold level, coupled with both radioactive and electromagnetic sensors in order to improve meniscus stability. The system is composed of different modules and submodules, with a specific and dedicated functionality. The system receives the setup parameters and control signals from the process control station (PCS) (Fig. 4) and the process signals from field sensors. From the internal estimated status of the process and after an in-depth analysis, the system counteracts any sort of anomalies.

The package has three different modules:

- Supervision and control strategies.
- Filters system.
- Optimal controller.

The supervision module is always active during casting operations...
and it decides the best strategies to keep the target level and fix the anomalies. The module checks the mold level anomalies during casting, such as bulging, standing waves or rolls eccentricity, and applies the typical strategies like special filtering, hiding specific frequency, or changing the optimal controller setup. Thus the filters module is composed of special filters and counteracts phenomena like bulging waves, roll eccentricity waves or standing waves. When the supervision module detects an abnormal condition, due to known phenomena, the filters are called into action to contrast the perturbation and recover the normal situation.

An optimal controller is composed of mainly two different parts: linear quadratic estimator (LQE) and linear quadratic regulator (LQR). The LQE is a special module used to estimate the real-time process data. It has a mathematical model of the mold level process. The model gets tuned, caster by caster, and the optimal parameters have been found from post-processing analysis data. The benefit of the LQE application is to have the estimated process variables without noise and/or delay time due to sensors. The updating time for collecting data is a trade-off in order to have a good process estimation speed and robust control loop. The LQR matrix is a proportional vector from estimated states to actuator reference. By varying the matrix values, one can change the mode of the controller in order to increase or decrease the speed response.

Results — The result from Fig. 5 indicates the trend on the first part as controlled by proportional–integral–derivative (PID) controller algorithm and for the second part as seen by Q-LEVEL+. Using the mold level standard deviation as the evaluation index, the average for the PID zone is 1.51 mm and with Q-LEVEL+ it is 1.17 mm; thus with the advanced version of Q-LEVEL+, an improvement of 23% was achieved.

The result from Fig. 6 indicates the trend on the first part as controlled by PID controller algorithm and for the second part as seen by Q-LEVEL+. Using the mold level standard deviation as the evaluation index, the average for the PID zone is 1.12 mm and with Q-LEVEL+ it is 0.51 mm; thus an improvement of 54% was achieved.

The result from Fig. 7 indicates the trend on the first part as controlled by the PID controller algorithm and for the second part as corrected by the stopper feedforward correction by Q-LEVEL+. Using the mold level standard deviation as the evaluation index, the average for the PID zone is 1.74 mm and with Q-LEVEL+ it is 1.01 mm; this represents a 42% improvement.
The results in Fig. 8 indicate the trend on the first part as controlled by PID controller algorithm and for the second part as corrected by the bulging rejection system by Q-LEVEL+. Using the mold level standard deviation as the evaluation index, the average for the PID zone is 1.37 mm and with Q-LEVEL+ it is 0.97 mm; thus an improvement of 29% was achieved.

**Results** — The Q-PULSE system provides feedback from the strand, having an intensity of the signal linked to the solidification thickness of the slab in the section where the physical testing is performed. In fact, the peak of the frequency is reduced when pulsation is applied closer to the end of solidification point (Fig. 9a) and it is flatter for the sections where the solidification has been completed. The sketch in Fig. 9b of the slab profile is provided during solidification and it does match with the calculation provided by the mathematical model for temperature and solidification.

As far as quality assessment is concerned, the application of Q-PULSE allows for fine tuning of the machine setup to be carried out, as well as tuning of the mathematical model, with the target of improving the internal quality of slabs produced (Fig. 10).

The system has been effective in detecting the liquid sump and the end of the solidification point. The self-tuning accuracy is an appreciable aspect for soft reduction and factors such as slab thickness width or casting speed do not affect the functionality of the system. The system can be used under any circumstances, without disturbing the quality or operation process.

**Q-PULSE**

Q-PULSE detects with maximum precision the position of the liquid pool end, both for conventional and thin-slab casting. Q-PULSE can perform automatically at any time during casting a test on the segment close to the predicted solidification endpoint. The test consists of a light oscillation of the upper segment frame that generates a pressure wave in the liquid pool and the measurement is based on the frequency analysis of the meniscus level in the mold following a periodic oscillating impulse applied to the cast product by the rolls along the casting line. Since the liquid is incompressible, the wave propagates along the liquid pool in the mold. Here, the mold level control, through fast Fourier transform (FFT) analysis, detects the frequency and assesses whether a liquid core is present. Whenever dynamic soft reduction is applied in continuous casting, the Q-PULSE system is a useful tool that allows the internal soundness to be optimized in terms of minimum centerline segregation and porosity. The endpoint of solidification can be confirmed anytime during casting, since the method permits on-line identification in very short time while casting. The soft reduction profile is then set at the best profile to obtain all the related benefits.

**Q-COOL**

Q-COOL is a real-time temperature control capable of maintaining the strand surface temperature at the required target to guarantee the surface quality irrespective of the casting speed and/or superheat variation. The surface temperature uniformity is guaranteed in longitudinal, transversal and thickness directions avoiding hot and cold, which are vital and detrimental to the final product quality. The model calculates the estimated product temperature profile and communicates the data to the spray water control system, which, in turn, checks the estimated temperature of the liquid process control (LPC) against the optimal ones as defined in the database for the product. The temperature difference is used as feedback to adjust the spray water flowrate.

The model is based on a dynamic 3D solidification model that implements an advanced meshless method to solve the Fourier heat transmission equation in real time.
time for the material from the meniscus down to the cutting torch. It employs multi-nozzle layouts across the slab width to provide even water distribution and heat transfer. The nozzle layouts are offset in alternative roll pitches to ensure spray overlaps do not line up along the length of the caster. To limit overcooling of the slab corners (especially for microalloy grades), the outer wide-side nozzles can have the water turned off dynamically. The estimation of the mushy and the liquid pool length permits the adequate real-time updating of the roll gap configuration for the Q-CORE soft reduction control.

Results — This model can be easily installed on existing slab casters and can control the strand surface temperature through the critical unbending zone in excess of 950°C. It helps in avoiding scarfing of the corners by maintaining the optimum required temperatures at slab corners and edges at the critical point of unbending or straightening. The internal quality of the product also has seen a significant improvement because of the even cooling across the slab width avoiding the “W” slump or “dog bone.”

As shown in Fig. 11, with the application of the technological package Q-COOL, the quality has certainly improved with the reduction of corner cracks percentage. As demonstrated in the graph for the 674 slabs inspected and the 42 slabs inspected with the dry corner tests, the percentage of level less than or equal to was 24% and that of 2–6 was 76%. On the other hand, for dry corner tests, those observed for less than or equal to 2 were 84% and those in the range of 2–6 were 16%.

Q-CORE

Q-CORE controls the dynamic application of mechanical soft reduction. This solution is applied to slab casters and to the last generation of long products caster, both on rectangular and on round blooms, whenever the mechanical installation has provision for the application of soft reduction. Soft reduction practices can be prepared according to the experience of the metallurgist, or in some special cases using advanced numerical tools; multi-physics thermomechanical models supply the necessary information about the relationship between applied force and the resulting thickness reduction according to different machine setup and steel grade characteristics and the stresses and strains applied on the product.

Real-time soft reduction control is then managed using the information on the evolution of internal strand solidification supplied by the on-line solidification model and applying the correct reduction according to designed practice. The optimization of soft reduction allows the best quality to be obtained also during transient casting conditions, such as sequence start-up, fly tundish and steel grade change.

A complete simulation environment is provided by Q-CORE in order to check the behavior of the model and to test new practices off-line.

Results — To be really effective, soft reduction has to be applied at the correct position as well as with the proper amount of rate. In conventional slab casters, the
Digital Transformations

Figure 11

Performance results (a) and human machine interface system (b).

reduction is normally applied between 0.4 and 0.7/0.8 fraction solid (Fs). If soft reduction is applied too early, there is a limiting effect on reducing centerline segregation. If applied too late, there is a danger of internal cracking. In thin-slab casters, soft reduction is applied starting from segment 0 up to the final solidification point.

The solute elements (Mn, S in particular or also known as segregates) are moved into the bulk liquid core (back up the strand) and dispersed. Normally, the roll gaps are set to follow the strand contraction – line taper. With soft reduction at the appropriate location the roll gap is increased to “squeeze” the strand.

However, as the strand bulges between the rolls, an effect is created between the liquid pool and the mushy zone where the liquid containing the segregate is sucked back toward the slab centerline. If allowed to remain there, centerline defects will result. One can overcome this effect by applying soft reduction in the correct place and in the correct amount. Q-CORE will adapt the segments’ position in order to apply the soft reduction in the proper way and guarantee the quality of the product.

Conclusions

The objective of installing the technological packages is to improve the performance, availability and reliability of the slab casters by replacing the obsolete automation system with state-of-the-art equipment and functionalities. The new automation system integrates with the existing machines, improving control functionalities with minimal modifications. The significant added advantage of these technological packages can be installed as “stand-alone” without interrupting the existing architecture or framework.

Plant A (Kazakhstan) has decided to modernize the automation system of level 1 and level 2. The modernization started in the second week of August 2018 and by the end of November the provisional acceptance certificate was obtained. The pre-erection activities for the both the CCM took about 3 weeks. Dismantling and erection of the new equipment, erection checking and cold commissioning, first cast operations and hot commissioning, completion of industrial commissioning, and final acceptance and performance tests each took a couple of weeks. Thus, in 4 months’ time, the target was achieved with the plant production halted only for 2 weeks.

In Plant B (Italy), the technological packages Q-COOL and Q-MAP were installed. Previously, the caster did not have any secondary cooling control model. With the installation, now the plant can execute practical operations with ease and can perform simulations to understand and improve the cooling profile over various steel types.

In Plant C (USA), the technological packages Q-CORE, Q-LEVEL+ and Q-PULSE were installed. The existing plant had a solution provided by a third party without soft reduction. With the installation of Q-CORE, the reduction of central segregation was achieved and thanks to other two technological packages, Q-LEVEL+ and Q-PULSE, endpoint solidification verification and optimal control of mold level can be achieved.

Figure 12

Macroetch print showing uniform centerline solidification across the slab length.
The qualitative and quantitative results of each of the technological packages at various steel plants during the last year have been reported. The operative results for each plant with the respective packages have been illustrated, providing an overview of the significance of modernization and imparting intelligent features.

References


Table 1

<table>
<thead>
<tr>
<th>Plant Location</th>
<th>Q-MAP</th>
<th>Q-CORE</th>
<th>Q-LEVEL+</th>
<th>Q-PULSE</th>
<th>Q-COOL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant A (KZ)</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Plant B (IT)</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Plant C (US)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
</tbody>
</table>

Equiaxial zone obtained in the slab centerline.