The evolution of thin slab casters: from first pioneering experiences to ultra-high speed casting

Thin slab casting and rolling was originally developed as a low cost alternative to a conventional casting and rolling process route. However, due to the technological restrictions of the first generation plants, only limited quality and productivity goals could be achieved, questioning its further application to more advanced applications.

This paper describes the original contributions that Danieli has made to the development of thin slab casting, from first generation plants to the present front-running applications, and production of high added-value steel grades.

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The thin slab casting and rolling process which, for the first time, considered the full integration of the casting and rolling processes previously seen as ‘separate worlds’, was a fundamental contribution to the progress of the steel industry.

It is well known that the original idea was to establish a viable economical alternative to the conventional process route, with the target to limit both capital investment and operational costs associated with the huge conventional complexes that historically had been the only way to produce hot rolled coils.

This concept was applied successfully to ‘first generation plants’, however, due to technological limitations, there were also some substantial limitations in its application, namely:
- A limited range of grades could be produced because of market requirements
- There was limited productivity, mainly due to the limitation of caster productivity.

For these first generation plants, a commercial and regional market could be served, but without the advantages of mass production or the high added-value product margins, the coil total cost could not be economically sustained in a sophisticated marketplace.

Starting from this recognised standpoint, Danieli has been constantly developing its own approach to the design of the thin slab caster to enlarge the application range of this technology to achieve increased productivity and product quality.

To achieve these goals, the new generation of thin slab casting machine has to address the following issues:
- Optimisation of mould fluid dynamics
- Mould level stability
- Uniform solidification in the mould
- Prevention of dynamic bulging
- Strand temperature control.

The fluid dynamics of the mould have been modelled to identify the most suitable SEN design to match the increased productivity, while ensuring the stability of the meniscus. Danieli has performed detailed Finite Element Modelling (FEM) analysis and tests using water models to confirm the performance of the chosen design for the latest generation of ultra-high speed thin slab casters.

Mould level control has been enhanced with a new online predictive model, allowing a higher gain for the controller and, at the same time, several diagnostic features for the level signal have been provided to closely control the process. The Bulging Rejection System (BRS), a feed-forward function to suppress bulging, has been implemented and has been found effective in reducing the level standard deviation in case of light bulging appearance.

Casting powder has been designed, which is fundamental to guarantee proper lubrication and to prevent possible crack formation in the mould due to the higher heat flux associated with higher casting speeds. This had led to the development of improved higher basicity powders.

The Mould Breakout Prevention System has also been enhanced to a new Q-Map system with new algorithms that allow detection of possible sticking and longitudinal face crack phenomena, as well as reducing the number of false alarms. An additional algorithm has been developed to guide the operator to evaluate the behaviour of powder during casting. Thermocouple sensors with faster response time have also been introduced.
To eliminate the dynamic bulging that historically has been the main factor in limiting productivity (by restricting casting speed), a new OPTIMUM segment design has been developed, having tighter roll pitches and new secondary cooling spray nozzles with higher efficiency. Moreover, strand support and spray cooling capacity has been improved.

In recent years, a new concept of sprays nozzle has been developed with increased cooling capacity thanks to reduced distance from the slab and a larger footprint. The result is more uniform cooling and an increased overall Heat Transfer Coefficient (HTC).

OPTIMISATION OF MOULD FLUID DYNAMICS

The development of the SEN design in the thin slab caster is fundamental to guarantee a stable casting condition. In fact, good meniscus stability in terms of mould level waviness and meniscus velocity is required, both for proper lubrication and surface quality.

Each SEN assures good performance in a given working range. Whenever the range needs to be enlarged, the design needs to be checked to establish whether the parameters for good performance are still in range.

Having had extensive experience in designing and supplying slab casting machines, Danieli has defined a methodology to classify the SEN design. At first, the SEN is modelled using FEM analysis to study the velocity contours as well as the meniscus waviness (see Figure 1).

Then the SEN design is verified over its full operating range using a 1:1 physical model that is installed on Danieli’s water model stands to cross-check the expected performance (see Figure 2).

Through the use of both the FEM analysis and water modelling, the SEN is designed to ensure:

- Meniscus velocity average value shall not exceed 0.3m/s, with an additional limitation considered including the Root Mean Squared (RMS) of the meniscus velocity
- Meniscus waviness span both time average and max instantaneous below a given value.

The working field where the above conditions are fulfilled is then identified and can be compared with the productivity of the machine. In Figure 3, the working range of two SENs is indicated, as well as the productivity limit of the caster. SEN A is not fulfilling all the criteria, while SEN B is.

MOULD LEVEL STABILITY

It is well-known that mould level control plays a key role in guaranteeing stability of casting, as well as the good quality of the product. At high casting speeds, however, level control can become even more critical as any disturbance of the casting process can be wrongly amplified by an incorrect action performed by the mould level controller.
Thus, the importance of having a mould level control model that can estimate the casting process becomes fundamental, for the following reasons:

- To provide a deep diagnostic system for all the different variables and disturbances affecting the mould level real time while casting
- To enact the proper corrective action and to calibrate properly the gain of control loop avoiding any possible amplification of fluctuation.

Danieli has developed a mould level controller, with the brand name Q-Level+, to fulfill both of these requirements and minimise the mould level standard deviation at high casting speeds. Furthermore, the controller is equipped with BRS, a feed-forward function, able to perform the following actions:

- Identify the dynamic bulging phenomenon by an online fast fourier transformation analysis and estimate frequency and amplitude
- Implement corrective action through the stopper rod in phase opposition in order to neutralise the fluctuation.

The BRS, in the case of light bulging (ie, low amplitude in oscillation), has demonstrated effective reduction of the mould level standard deviation in several Danieli reference plants, taking corrective action in phase opposition. In contrast, conventional controllers are not able to identify the bulging phenomenon and with a standard feedback controller they can amplify the hunting of the mould level instead of reducing it. Q-Level+ automatically identifies the onset of bulging and its amplitude and activates the feed forward action whenever the bulging phenomenon appears (see Figure 4).

**UNIFORM SOLIDIFICATION IN THE MOULD**

At high casting speeds, the thickness of the solidifying steel shell in the mould decreases, shell temperature increases, and hence the fracture strength of the shell decreases. The combination of the higher frictional force and the decreased shell strength makes it more difficult to prevent the formation of surface cracks and breakouts at higher casting speeds, hence the support to the solidifying shell is critical.

The exclusive design of the Danieli H2 long funnel mould (see Figure 5) has been developed to counteract the above phenomenon, with the following features:

- An upper zone characterised by a progressive reduction of the section perimeter to compensate the shell shrinkage due to solidification and freezing
- A lower zone characterised by vertical walls (cambered in the central part and parallel in the external parts) to avoid dummy bar extraction problems
- A rounded edge connection between the upper zone (tapered) and the lower one (vertical) of each broad face to assure mould-shell contact and to avoid gap formation.
Mild cooling during the initial solidification has been considered an effective countermeasure against crack formation. Local heat flux and solidification rate can be decreased in the mould by crystallisation of the mould powder, due to the reduction of the thermal radiation mechanism.

Moreover, an increase in casting speed makes the air gap thinner, so the reduction of radiation by crystallisation of mould flux becomes more important in high-speed casting. Figure 6 compares the heat flux of a crystallised mould powder with a standard glassy type mould powder. The higher thermal shielding of the crystallised powder is confirmed by the lower average thermal flux compared to that of the glassy type powder in the same casting conditions.

As well as addressing the fundamental design of the mould Danieli has developed an innovative mould oscillator to enable optimum performance at ultra-high casting speeds, both in terms of safety and quality. The design is based on the principles of the patented INMO (INtegrated MOtion) mould system, developed to provide both a very precise guide for the oscillating mould and wide flexibility of operation in terms of the applied stroke, frequency and waveform. This gives new options for the best oscillation condition for both good mould lubrication and good surface quality, through the whole range of casting speeds.

The main features of the INMO mould design are the guidance system between the stationary and the oscillating structures and the hydraulic cylinder acting directly on the oscillating mass. The mould assembly is located on an oscillating frame, which moves within a stationary structure and is guided by 'rolling elements' (see Figure 7).

This system incorporates the following features:

- Virtually no friction, which means maintenance-free equipment
- Extremely tight guiding tolerances for a higher slab surface quality.

As a result, the H2 mould can achieve the following benefits:

- Greater hot liquid steel surface for powder melting purposes (better lubrication)
- Less turbulence in the liquid steel bath with greater meniscus stability
- No shell washing and re-melting (reducing the risk of breakout)
- Greater mould-submerged nozzle spacing (no bridge formations)
- Sound liquid steel temperature pattern and homogeneous solidification structure on all the slab width.

It has been well-documented that mould flux plays a very important role in continuous casting in terms of lubrication and heat transfer and that high casting speeds result in decreased mould powder consumption, causing higher frictional force at the shell/mould interface. Therefore, as well as addressing the fundamental design of the mould, Danieli has also developed specific mould fluxes for high casting speeds.

Heat flux increases with casting speed and cracking becomes pronounced when the heat flux exceeds a certain critical value.
Because there are no bearings or springs within the rolling element design, very accurate mould guidance can be achieved, which can be maintained over time as very little wear actually occurs (see Figure 8).

The oscillation motion is transferred to the mould by two servo-controlled hydraulically actuated cylinders, one located on each side of the mould. The hydraulic oscillating system gives the maximum flexibility in the choice of the oscillation parameters: stroke, frequency and wave shape can all be adjusted independently improving lubrication efficiency and reducing oscillation mark depth.

To achieve the fast response times required for high-speed oscillation, the two servo-assisted hydraulic cylinders are controlled independently. Within the software, a self-check facility permanently monitors and guarantees the perfect synchronisation of these cylinders at any time.

PREVENTION OF DYNAMIC BULGING

Considering the mechanical design of the thin slab caster, the main issue preventing high casting speed is the initiation of dynamic bulging. In fact, in the worst case scenario such phenomena can lead to mould level fluctuations so severe that they can jeopardise the mould lubrication with a corresponding dramatic deterioration in the surface and internal quality of the slab.

Dynamic bulging originates in the secondary support zone of the machine and is due mainly to a lack of support of the solidified shell, which then bulges or collapses in between the roll pitches, and causing the first drop in steel level (see Figure 9).

When the bulged portion is ‘pushed back’ by the following roll, while extracting the slab, an ‘inner’ pulse of liquid is created, resulting in a mould level overshoot.

In order to overcome the bulging phenomena Danieli has progressively developed the roll geometry of the thin slab caster with smaller roll diameters and pitches. At the same time, recent engineering solutions have allowed the reduced roll diameter to maintain the proper load capability and thereby provide proper functionality.

It is believed that there is a minimum roll pitch of 6-8mm below which there is no significant influence on bulging, so this is the aim roll pitch to use.

In order to maximise shell support, roll design has been conceived with a minimum width for the bearing support, that also somehow contributes to eliminate the bulging. Figure 10 compares first generation and the latest ultra-high speed roll geometries.

STRAND TEMPERATURE CONTROL

It is well-known that the most sensitive area of the machine to bulging is the upper part, where the solidified shell is thinner and therefore has lower strength. At the same time, because the solidified shell is thinner here,
this is also the zone where any increment of the spray cooling capacity is more effective at growing the shell. Consequently, Danieli has developed a higher efficiency secondary cooling spray nozzle. This new spray nozzle type has an increased cooling capacity thanks to the reduced distance from the slab and larger footprint. The result is a more uniform cooling and an increased overall HTC, as confirmed by laboratory tests. This extra cooling capacity is also contributing to a reduction in the bulging, allowing a more rapid shell growth.

CONCLUSIONS
In the past 20 years, Danieli has been developing a suite of original technological solutions for the thin slab caster with a strongly diversified approach from other available solutions, dramatically enlarging the applications of the first generation plants with the following results:

Productivity: from an original 0.8Mt/yr per casting strand, today, 2Mt/yr per casting strand is already a consolidated result, as seen at POSCO where a world record casting speed of 8m/min was achieved and where daily average speeds are in excess of 7.0m/min (see Figure 11).

Thanks to the experiences of ultra-high speed casting, it is possible to conceive a thin slab casting and rolling plant, with two casting strands with a productivity of 4 Mt/yr, i.e., the same as a conventional thick slab hot strip mill plant.

Quality: at present, ‘conquest’ of the flat product market by thin slab casting is almost complete (see Figure 12), as demonstrated by the production of quality steel grades at numerous Danieli reference plants, including Essar Algoma (HSLA grades like the so-called DSPC700, having yield strength of 700MPa); Benxi Iron and Steel Company (electrical steels with a Si content up to 3.2%), and OMK (conceived for the production of top quality pipe grades, like API X70 and X80 for arctic applications).

Only specific areas are still fundamentally excluded, such as where metallurgy imposes very high reduction ratios in rolling, or where process temperatures are not compatible with an uninterrupted process.

Hence, niche high added-value products or mass-production commodities are both markets that can be served by the Danieli thin slab caster and rolling line, which has enhanced and expanded one of Danieli’s cornerstone concepts, that of flexibility. MS

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