Danieli Universal Endless (DUE) – the evolution of Danieli Thin Slab Casting and Rolling plant

Over the last 25 years the thin slab casting and rolling process has been gaining a major market share in the production of hot rolled strip, progressively eroding the areas previously the exclusive domain of conventional mills. Danieli has progressively developed a new generation of thin slab casting and rolling plant, marking a new phase in the evolution of this process. What makes this new concept different is the ability within one single plant, to perform coil-to-coil, semi-endless and endless rolling modes, making this plant a major technological innovation compared to that of the previous generation.

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The increasing market share taken by the thin slab casting and rolling process is due mainly to the competitiveness of the process over conventional ones, and to the growing ability of this technology to cover the majority of market niches, well beyond the boundaries of the commodity market.

After having significantly contributed to the continuous expansion of this production mode and after an extensive campaign of theoretical research and physical testing in reference plants, Danieli has progressively developed a new generation of thin slab casting and rolling plant, marking a new phase in the evolution of this process.

The new step is epitomised by the name QSP-DUE and this configuration is part of the Quality Strip Production (QSP) family of Danieli's strip-quality-orientated thin slab based plants and has the acronym DUE, which stands for Danieli Universal Endless (US patent no. 8087449, 3 January, 2012).

What makes this new concept different is the ability of one plant, to perform coil-to-coil, semi-endless and endless rolling modes, making this plant a major technological innovation compared to the previous generation. A schematic of the plant layout is shown in *Figure 1*.

This new approach can be seen as the natural evolution of the original, successful Danieli concepts that marked the progress of the thin slab route, namely the application of the vertical curved design thin slab caster and the separation of the rolling stands into high reduction units and finishing units becoming a source of inspiration for most of the recent innovations in the industry.

PLANT LAYOUTS

At present, two different layout concepts have been developed for the thin slab route:

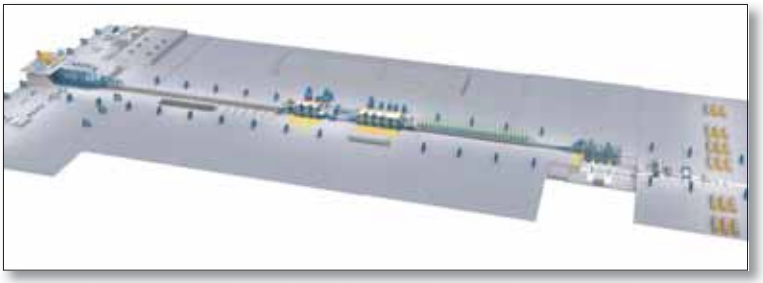

Fig 1 **QSP-DUE plant**

- Plants with one or two casting strands, connected to the rolling mill through long tunnel furnace(s), which have the function of reheating and equalising slab temperature as well as of guaranteeing sufficient buffer time in case of either scheduled stoppages of the mill (eg, work roll change) or unscheduled interruptions of material flow. This is illustrated in *Figure 2*. Danieli has consolidated this layout, reaching world record results, both in productivity and quality.
- In recent years, thanks to a progressive increase in mass flow due to increased casting speeds inherited from the last generation of thin slab casters operating at ultra-high speeds, and in combination with the reliable introduction of induction heating technology in place of tunnel furnaces, it was possible to develop the QSP-E layout (see *Figure 3*): a new generation of extremely compact plants, specifically dedicated to the production of ultra-thin gauges. This is made possible thanks to the application of the endless rolling process (ie, the direct and uninterrupted connection between casting and rolling), to overcome the well-known ▷

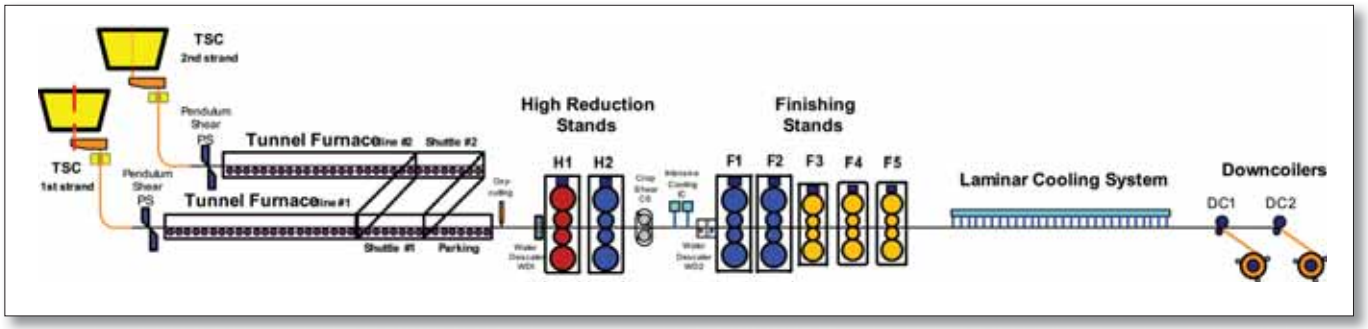

Fig 2 **Quality Strip Production (QSP) configuration**

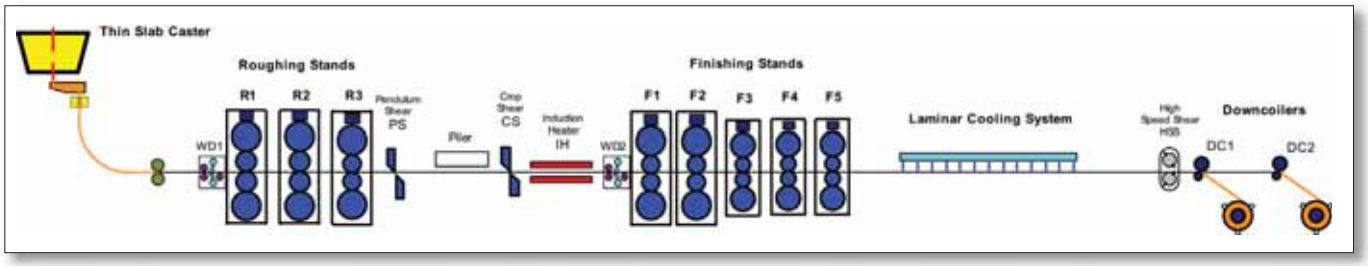

Fig 3 **Quality Strip Production Endless (QSP-E) configuration**

problems of strip threading when producing thin gauges in coil-to-coil mode.

QSP plants have made it possible to widen drastically the mix of thin slab steel grades and to ramp up plant productivity well in excess of 3Mt/yr, also thanks to the possibility of operating with two casting strands. These plants were initially conceived for the application of coil-to-coil rolling and then for the semi-endless process to roll thinner gauges below 1mm.

The QSP-E concept made it possible to optimise the production of ultra-thin gauges in endless mode, but showing little flexibility in the production of more sophisticated grades due to the rigid link between casting and rolling. In the case of endless rolling, the caster is in fact forced to always run at very high casting speeds and this is not possible for all the steel grades for metallurgical reasons.

Moreover, the endless process has proven to be economically competitive only for the production of coils having strip thickness below 1.5mm, but as soon as the strip thickness is increased, the power required by the induction heaters to continue operating becomes excessively high, making it economically necessary to return to coil-to-coil mode.

Since the QSP-E has a compact layout configuration, with slab re-heating provided by the induction heating system, there is no buffer time between caster and mill and this creates significant limitations on the operational flexibility of the entire production line.

Additionally, plant yield and productivity are affected by the absence of a buffer because caster re-stranding has to be synchronised with roll changes in the mill, which are quite frequent in endless mode due to significant wear and thermal deterioration of the rolls in continuous contact with the strip. As a consequence, caster sequencing (ie, plant yield optimisation) is reduced compared to plants operating in coil-to-coil mode, where the sequence length is determined by SEN refractory life and not by roll change scheduling.

Also, the QSP-E layout does not allow the plant's capacity to be doubled by adding a second casting strand, hence limiting the overall productivity to around 2Mt/yr, depending on the product mix – this in spite of significant investment cost, thus making the specific investment per tonne not particularly attractive.

All in all, these factors have negatively influenced the expansion of the endless process, notwithstanding its indisputable advantages, when it comes to ultra-thin gauge production.

THE DANIELI UNIVERSAL ENDLESS (DUE) CONCEPT

In a continuous effort to improve existing processes and technologies and overcome their current limitations, Danieli has developed a new concept in thin slab casting and rolling plants, able to unify in a single production line all the winning features that up to now have been developed using different approaches, while eliminating the limiting factors of each one of them.

The DUE layout features the following:

- High productivity, thanks to an unprecedented combination of slab thickness and speed
- High production flexibility, able to operate in coil-to-coil, semi-endless and endless rolling mode
- High operational flexibility, due to the presence of the tunnel furnace and relevant buffer time
- It covers the full spectrum of steel grades produced for flat products, including the most sophisticated ones rolled via thermo-mechanical rolling (API pipeline grades) or temperature-controlled rolling (multiphase products) as well as the grades which require moderate casting speeds like peritectic, electrical steels and high-carbon grades, being crack-sensitive.
- Covers the full spectrum of geometrical strip dimensions, ranging from 0.8mm ultra-thin gauges, produced in endless mode, up to 25mm thick strips. This, of course, in combination with an unbeatable transformation cost, lower than any other process presently available.

The key features of the plant will now be described.

Thin slab caster This caster is a development of the already consolidated vertical-curved Danieli design. The vertical-curved caster features a 5.5m main radius, designed to operate with a single slab thickness of 110mm after dynamic soft reduction, within the casting speed range of 2.5 to 6.8m/min, depending on steel grade.

Such an unprecedented combination of slab thickness and speed (see *Figure 4*) makes it possible to easily reach the mass flow conditions required for full endless production, particularly when ultra-thin gauges of commercial grades are produced.

Industrial operation at high speed has been extensively experienced since 2008 in Posco CEM minimill, Korea, where the caster usually works in the speed range 6.0 to 7.0m/min with peak of 8.0m/min.

A patented mould and oscillator design, dynamic air-mist secondary cooling and dynamic soft reduction ensure superior slab quality. The combination of the aforementioned slab geometry and caster design features make it possible to obtain mould fluid dynamics similar to a medium slab, resulting in a higher control of the solidification process and in a much easier and more stable operation compared to a conventional thin slab process.

Stability and easiness of operation are key points for endless operation, where repeatability and steadiness of operation are a must.

Danieli, since the beginning of the 1990s, has been the first company to develop and then utilise in an industrial way, dynamic soft reduction as a basic tool in all its thin slab casters, in conjunction with the vertical curved design which provides the best control of internal and surface slab quality in any casting conditions. This enables the mill to be provided with a thicker slab compared to the traditional thin slab approach (see *Figure 5*), with a remarkable increment in the reduction ratio from slab to strip for this kind of plant, which in turn allows the production of a wider product mix.

The possibility of covering the entire production range with one slab thickness, regardless of final product gauge, clearly brings significant operating advantages. The caster can therefore produce up to about 3Mt/yr on a single casting strand, covering a wide range of steel grades including low, medium and high carbon, high strength low alloyed, peritectic, silicon, pipeline and API.

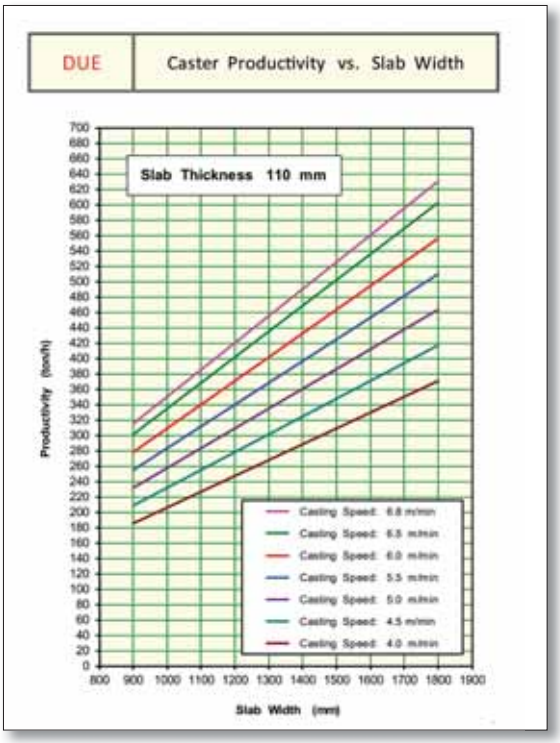

Fig 4 **DUE caster productivity vs slab width**

Fig 5 **Thin slab at caster exit**

Fig 6 **Tunnel furnace**

Fig 7 **Rolling mill configuration**

Fig 8 **Induction heating**

Fig 9 **High-speed shear and high-speed downcoiler area**

The flexibility of the mould design, which guarantees stress/strain-free solidification in the shell, makes it possible to perform continuous slab width adjustment during casting, so improving flexibility and profitability.

The mould's narrow faces are designed with a special profile, and an on-board mould width adjustment system provides the ability to dynamically change mould narrow side taper to suit changing conditions, ie, steel grade, casting speed, sticking detection, providing consistent strand support in all production modes, including endless. Moreover, a dynamic secondary cooling system, complete with width adjustment, makes it possible to optimise the temperature of the slab edges, eliminating corner cracks even for the most crack-sensitive grades such as HSLA and high carbon.

Tunnel furnace The tunnel furnace, designed and manufactured by Danieli Centro Combustion (see *Figure 6*) was conceived to operate in three modes: coil-to-coil mode as in conventional thin slab rolling plants, semi-endless mode, able to accommodate long mother slabs that are the equivalent of several coils, and in full endless mode.

This unit provides a fundamental buffer function that increases plant flexibility and provides the possibility of performing work-roll changing as a background task, without affecting the operation of caster and meltshop, 'switching' from endless to coil-to-coil operating mode during roll changes, which in any case does not reduce plant productivity.

Rolling mill The DUE mill is the natural evolution of Danieli's QSP concept, which features the well-known and already successfully proven configuration with separation of the mill stands into high reduction units and finishing units in order to perform dual step rolling (see *Figure 7*).

This configuration includes:

- A dedicated high-pressure descaling unit at finishing mill entry (in addition to the one at high reduction stand entry), to limit imprinting scale phenomena on the bar, thus significantly improving the surface quality of the final coil
- An intensive cooling system, incorporated into the descaler box at finishing mill entry, used when producing Thermo-Mechanically Rolled (TMR) and/or API grades in order to guarantee the correct bar temperature profile and proper control of grain growth that are essential features of the thermo-mechanical rolling process
- A crop shear, beneficial for thin gauge production, used to cut the transfer bar head and/or tail end, in order to have smoother threading into the finishing mill as well as reducing tail chew-up

Induction heating An induction heating system (*Figure 8*), designed and manufactured by Danieli Automation is installed for consistent production of thin and ultra-thin gauges in endless mode. Induction heaters are individually mounted on a retractable frame so they can be transferred offline for maintenance purposes or when they are not being used (ie, during coil-to-coil production mode).

Temperature control using induction heaters provides increased heating efficiency. The new unique design is based on a fully digital control of the heating power and a smart circuit diagram that have made it possible to obtain high heating efficiency while simplifying power pack serviceability.

The number and size of mill stands are designed to cover a wide range of strip thickness, from 25mm down to 0.8mm, starting from 110mm-thick slabs, guaranteeing superb geometrical and mechanical properties.

The stands are equipped with state-of-the-art features for utmost strip crown and profile control, bearing in mind that these control functions also have to be operational under load conditions as required by the endless rolling process.

The line is complete with a laminar cooling system and a coiling area comprising a high-speed shear (used to cut the coil to length when working in endless or semi-endless mode), threading devices, pinch rolls and downcoilers, already fully tested and presently in operation at the Arvedi plant, Italy (see *Figure 9*).

Fig 10 **3Q typical display**

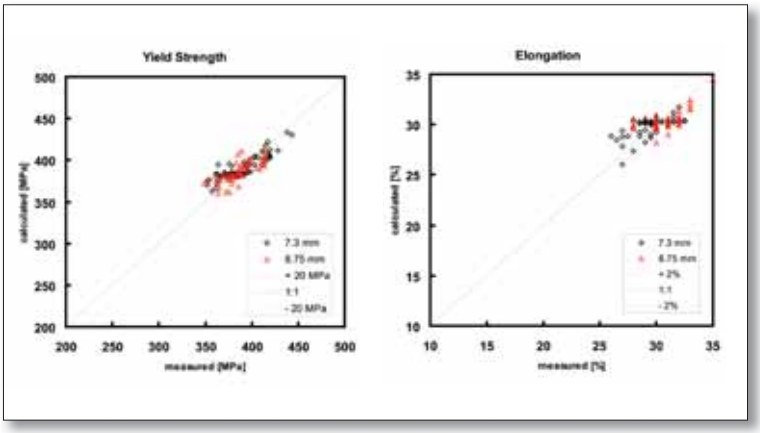

Fig 11 **Coil Quality Estimator (CQE) results**

Automation Using the original 3Q technology developed by Danieli Automation it was possible to overcome the challenges the DUE process posed for the automation system. In fact, not only is the automation system required to control the process, but it also has to assist operators in properly running the process, providing the necessary experience to develop an innovative process.

Since DUE is a highly integrated process, encompassing casting, reheating, rolling, cooling and coiling, a single virtual pulpit solution was selected. This means that all operators can easily communicate either verbally or visually, consolidating the concept of 'one crew' running the plant. Moreover the operators are assisted in managing the plant by a new operator interface concept covering multiple hierarchical levels, each one of which orientated to a specific operational function. A typical screen display is shown in *Figure 10*.

Changing the strip thickness during rolling requires a very accurate tracking system and a set of smart strategies to simultaneously achieve the required thickness variation while minimising the transition length. The same concept applies to width changing during casting. Both technologies significantly improve plant utilisation, adapting 'in-line' production to orders, and reducing the number of coil widths kept in inventory.

To obtain the required mechanical properties of the rolled strip in all operating modes, the transfer bar and strip cooling are controlled by an integrated set of sophisticated cooling models that combine physical equations with an advanced adaptation system.

Synchronising the caster and rolling mill is one of the enabling technologies for endless rolling. A new control algorithm has been developed to provide a smooth, reliable link between caster and rolling mill in all operating conditions, while continuing to produce top quality strip.

Crown, flatness and wear control in endless plants is paramount. Danieli has developed a complete set of online mathematical models to achieve the target crown, flatness and edge drop on the final strip. Control strategies are changed dynamically according to the actual rolling mode, the expected rolling campaign and in order to use the most effective actuator in each section of the plant. Online assessment of internal quality parameters for both slab and coil is achieved thanks to the advanced inhouse-developed slab Quality Control System and Coil Quality Estimator.

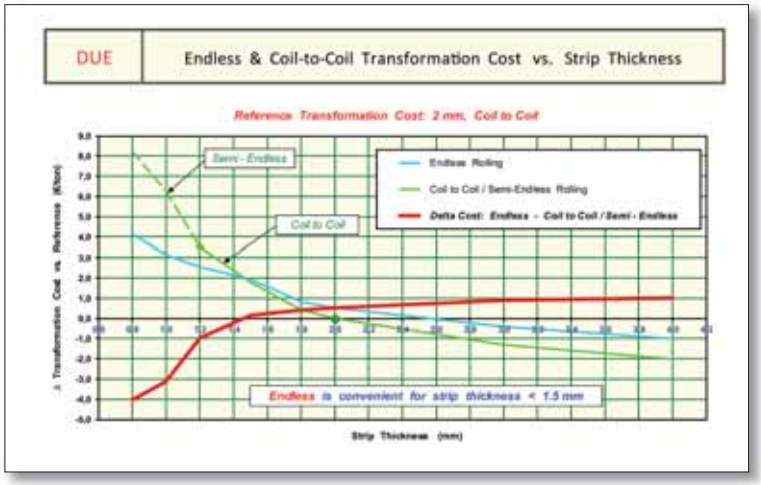

Fig 12 **DUE – transformation costs vs strip thickness**

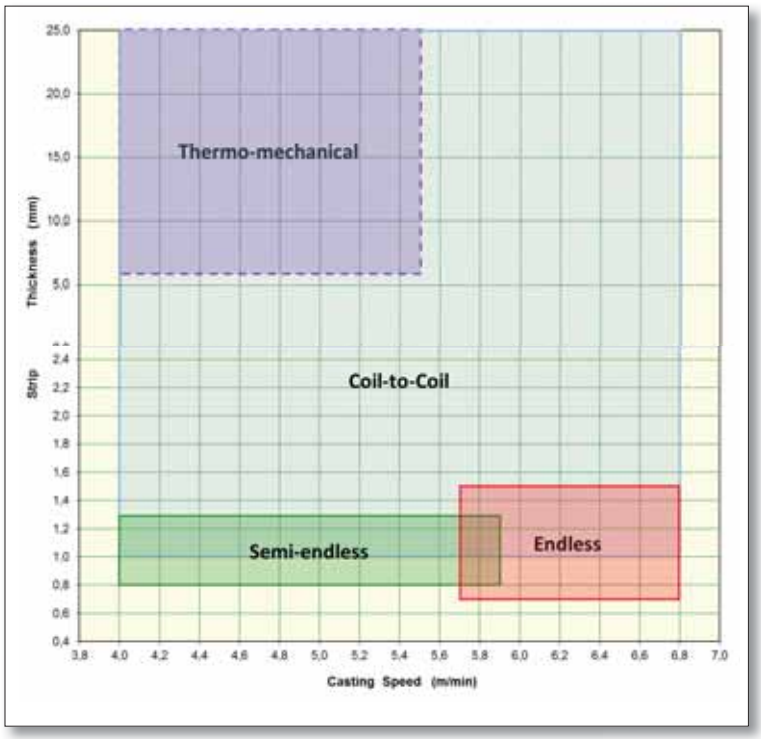

Fig 13 **DUE – optimum rolling mode vs casting speed and strip thickness**

The Coil Quality Estimator (CQE) is able to calculate the mechanical properties of the coils in real time thus allowing timely corrective action. Examples of strength and ductility prediction are shown in *Figure 11*. Surface quality is checked online thanks to dedicated cameras installed in key positions throughout the plant. Root cause analysis is performed to access the cause of surface defects.

Rolling modes Thanks to its layout configuration, DUE is able to work in coil-to-coil, semi-endless and endless rolling modes, selecting the most suitable production mode according to final product specification Endless mode is economically convenient for strip thickness ≤1.5mm) and an example is shown in *Figure 12*.

Selecting the optimum rolling mode is possible with the DUE layout, in accordance with casting speed and final strip thickness; this is shown in *Figure 13*.

COIL-TO-COIL ROLLING MODE

The slab generated in the caster is cut to length by the pendulum shear at caster exit, so each cut slab generates a single coil. In this mode, caster and mill operate with different mass flows so that each one can be optimised according to the specific needs of each unit, in order to guarantee the best product quality.

This process is advisable for the production of strip thicknesses ≥1.4mm. However, as intermediate bar reheating with the induction heating system it is also possible to have a more stable and reliable rolling condition for the production of thin gauges down to 1mm without having to speed up the bar, once the coiling operation starts, in order to limit temperature losses. *Figure 14* illustrates some typical temperature profiles.

Semi-endless rolling mode The mother slab generated in the caster (corresponding in length to approximately five coils) is cut to length by the pendulum shear at caster exit: after rolling, coils are cut to length by the high speed shear at coiling area entry.

In semi-endless mode the caster and mill operate with different mass flows – as in coil-to-coil production mode – however, in this case there is less material loss, since there are fewer head and tail end crops at the crop shear at finishing mill entry, due to the smaller number of slabs being threaded into the mill.

Furthermore, it is possible to reduce the minimum strip thickness rolled in the mill, since for the coil generated from the central portion of the mother slab, even when the rolling speed is increased, there is no risk of 'flying head' on the runout table, as the strip is already under tension between mill stands and downcoiler.

In the DUE layout the semi-endless process is applied mainly for the production of thin strips if the endless process

cannot be applied due to insufficient mass flow, ie, in the case of medium carbon, high carbon or high- strength low-alloy steels (HSLA), or in the case of liquid steel shortages.

With the DUE configuration, even during production in semi-endless rolling mode, it is possible to have a more stable and reliable rolling condition for the production of thin gauges, thanks to the induction heating system, without having to speed up the bar when the coiling operation starts, in order to limit temperature losses, as illustrated in *Figure 15*.

Please note that without the semi-endless process, the DUE layout can be even more compact, since for coil-to-coil and endless mode, the length of the tunnel furnace alone can be shortened to less than 100m, thus further reducing Capex and Opex.

Endless rolling mode Danieli's developments in ultra-high casting speed mean that the thin slab caster can now generate sufficient mass flow for a full endless process. The slab generated in the caster is continuously rolled in the mill in endless mode and coils are cut to length by the high speed shear at coiling area entry. The endless rolling mode is used mainly for high tonnage production of thin and ultra-thin strips, overcoming the difficulties implied by other production mode as well as with higher plant yield.

With a rolling speed in excess of 6m/min endless rolling, coupled with induction heating allows stable production of ultra-thin gauges down to 0.8mm from the 110mm slab with strip temperature at finishing mill exit in the area of 850°C. *Figure 16* illustrates some examples.

Thermo-mechanical rolling mode The installation of an intensive cooling system between the high reduction stands and finishing mill stands allows production of high added value pipeline grades, such as API and arctic applications down to -60°C. The cooling system is applied in coil-to-coil mode and, when in use, the induction heating system is put offline. It is an essential tool for applying a real thermo-mechanical rolling process as it cools the transfer bar below the non-recrystallisation temperature as illustrated in *Figure 17*. In this way the risk of partial recrystallisation in the finishing mill and the consequent non-uniform microstructure is prevented.

With a 110mm thick starting slab, the reduction ratio that can be obtained with the DUE configuration from slab to transfer bar and from transfer bar to the final strip can be higher than in other thin slab route plants, allowing the production of API grades in greater thicknesses and making it possible to apply spiral welded pipes in high pressure large diameter gas transportation lines.

Additionally, the use of a powered cooling system on the runout table allows further grain refinement and transformation hardening, taking advantage of the potential of acicular ferrite and bainitic microstructures. In this way it is possible to save on the cost of expensive alloying additions and increasing the strength of the produced coils.

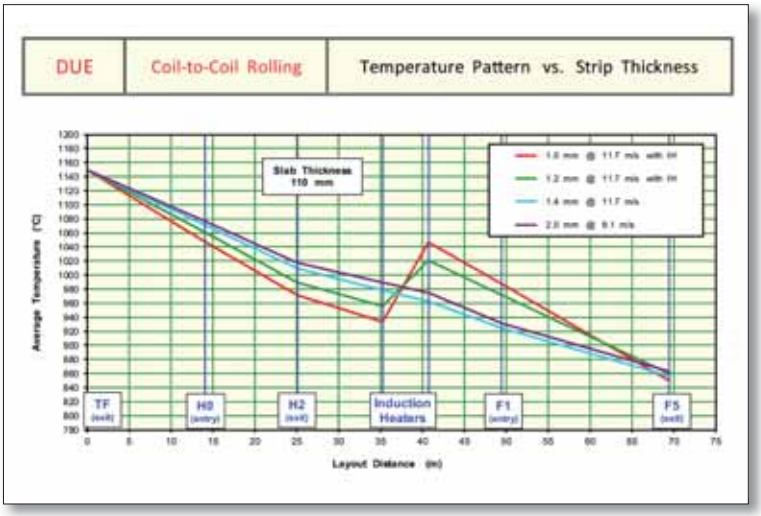

Fig 14 **Coil-to-coil rolling – temperature pattern vs strip thickness**

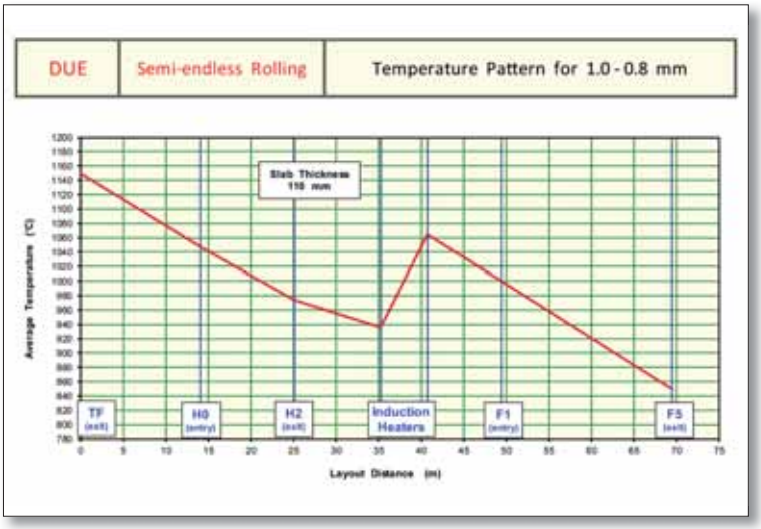

Fig 15 **Semi-endless rolling – temperature pattern for 0.8-1.0mm strip**

MODULAR DESIGN

Depending on specific needs (such as liquid steel availability, market situation, product mix and Capex) the DUE configuration can also be implemented in steps, starting with a classic QSP layout (see *Figure 18*).

For instance, depending on liquid steel availability, phase 1 of the project could focus on limited production of hot rolled coil, rolling thin gauges on seven stands, down to a 1mm strip thickness in coil-to-coil mode, starting from a 70mm slab.

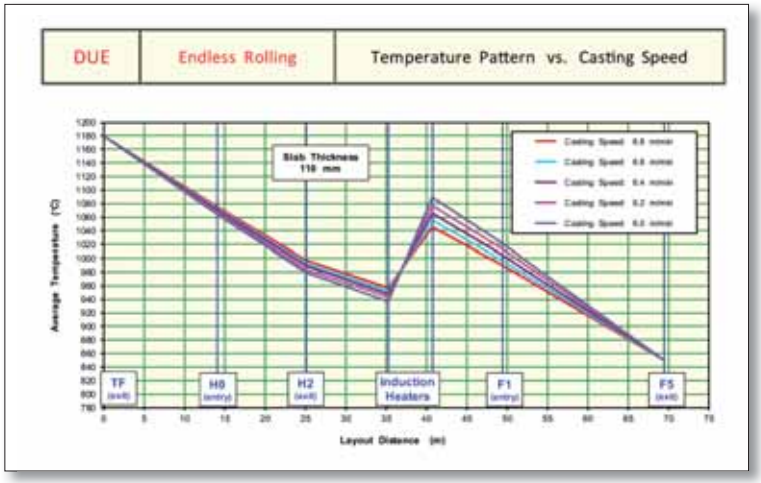

Fig 16 **Endless rolling – temperature pattern vs casting speed**

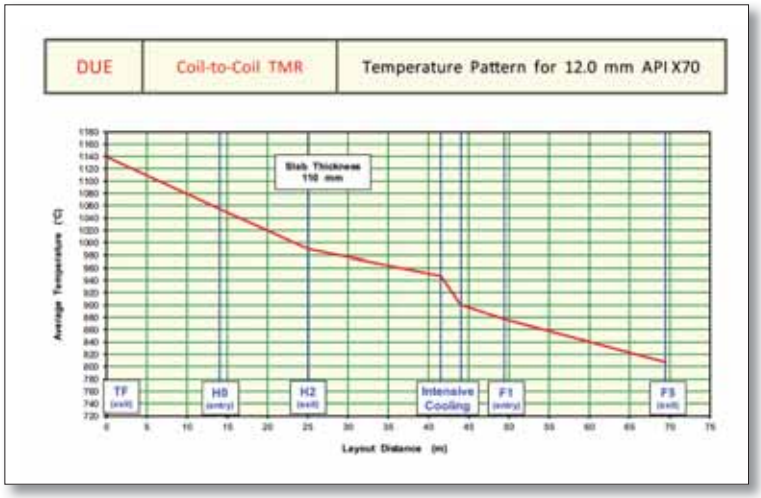

Fig 17 **Coil-to-coil thermo-mechanical rolling – temperature pattern for 12 mm API X70**

At a later stage, when additional liquid steel is available, phase 2 could see a boost in production by increasing slab thickness to 110mm, and adding the necessary caster segments as well as one more rolling stand in order to continue producing 1mm strip thickness in coil-to-coil mode.

The last stage could be the implementation of the 'endless package', by installing an induction heating system and a high-speed shear in order to produce ultra-thin gauges down to 0.8mm strip thickness in full endless mode.

CONCLUSIONS

DUE (Danieli Universal Endless) is Danieli's solution to the existing limitations of current thin slab casting and rolling configurations, and constitutes a universal tool able to reach all the production niches of the flat products market, by applying the process that is best suited to each steel grade and product.

Thanks to the combination of slab thickness and casting speed, never-before-seen production rates are possible – up to 3Mt/yr on a single casting strand, making the Capex investment per tonne extremely attractive.

The layout configuration, together with an effective combination of thermal energy (gas-fired tunnel furnace) and induction heating, optimises energy consumption, making DUE a very 'green' plant, while also reducing Opex by about 15-20% compared to the current benchmark thin slab-based plants.

Coil-to-coil and endless, thermo-mechanical and multi-phase, ultra-thin and thick products are now all possible in a single production line.

This makes both niche products with high-added value and the mass production commodities segment within reach of this new plant, which today represents the most extensive application of Danieli's concept of flexibility. **MS**

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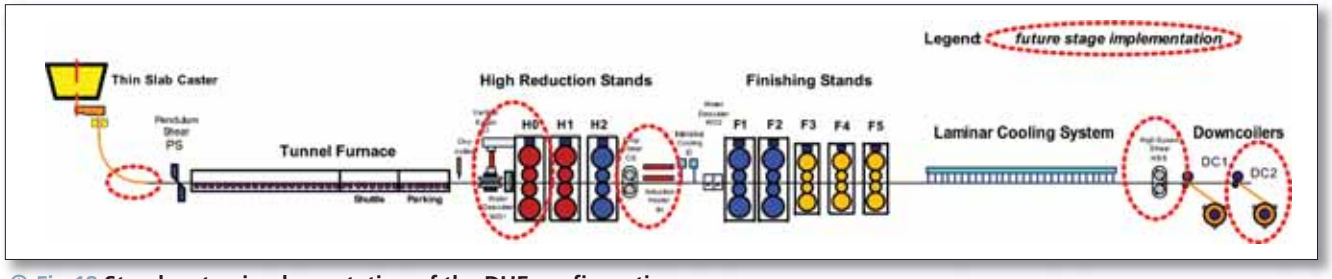

Fig 18 **Step-by-step implementation of the DUE configuration**