

ARVEDI ESP PROCESS – AN ULTIMATE TECHNOLOGY CONNECTING CASTING AND ROLLING IN ENDLESS MODE

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ABSTRACT

The conventional continuous casting and rolling route which appeared in the 1950s has undergone a significant evolution due to technical development, high operating costs and new environmental regulations.

First applications of directly charging conventional cast slabs to the hot rolling mill are known from Japan in the 1970s and 80s. These first applications defined the global trend to connect casting and rolling to lower the energy consumption by maintaining the heat of the as cast condition. The avoidance of cooling to room temperature between casting and starting of reheating before rolling significantly reduced the specific energy consumption. Subsequently, high speed Thin Slab Casting and Rolling (TSCR) technology was focused on. The first generation of TSCR technologies uses tunnel furnaces as an interlink between thin slab casting and hot rolling for homogenization of the thin slab with the disadvantage of very long and cost intensive furnace implementations. The required rolling temperature is achieved by homogenisation and/or reheating. High specific investments for the building of two or more casting lines, long tunnel furnaces and huge plant dimensions, characterised by the high total length of up to 500 m, were necessary. Ultimately, directly connecting casting and rolling was seen as inevitable in order to solve the technological, economic and environmental problems. The development of the In-line Strip Production process (Arvedi ISP) became an important milestone on the way to an endless TSCR process. It was characterised by the direct connection of continuous casting with the roughing mill, the tunnel furnace replaced by a very short induction heater with the roughing mill linked to the finishing mill by a compact coil furnace (Cremona furnace).

The Endless Strip Production (Arvedi ESP) line is the first and today only representative of the endless TSCR process, and was put into operation in 2009. Since it was first used, the ESP process has demonstrated stability and high production capacity comparable to that of the TSCR double casting-line process, and has proved to be suitable for producing a wide range of steel grades from low carbon to sour gas resistant line pipe steels. The current work presents results from the production of HSLA steel grades at the Acciaieria Arvedi works in Cremona and draws a conclusion on the potential of the Arvedi ESP process for the production of high quality steel grades.

KEYWORDS: TSCR, Arvedi ESP, quality, material properties

INTRODUCTION

The main driving forces for the development of metallurgical technologies are improvement of product properties, economic efficiency and environmental aspects. Thin Slab Casting and Rolling (TSCR) represents a technology for hot strip production that addresses all three trends. In the past 24 years TSCR technology has been widely applied, and different design concepts have been developed (Fig. 1). The first generations of TSCR plants were designed for batch rolling. A tunnel furnace was used to connect the casting and rolling part. Starting with the Arvedi ISP technology, thin slabs directly entered the first rolling step, to then be batch rolled through the finishing line. The mass flow between HRM and the finishing line was separated by the cutting of the slab after the HRM and intermediate coiling within the Cremona furnace. The direct connection of thin slab caster and roughing mill in the Arvedi ISP process, a first step towards endless rolling, allows energy consumption to be reduced compared to batch rolling designs with intermediate tunnel furnaces by fully exploiting the thermal energy coming from the caster without a comparatively high heat loss in a tunnel furnace.

The latest development, the real endless Arvedi ESP process, features fully coupled mass flow and thus provides the most effective solution in terms of compactness, uniformity of material properties and energy efficiency (Fig. 2).

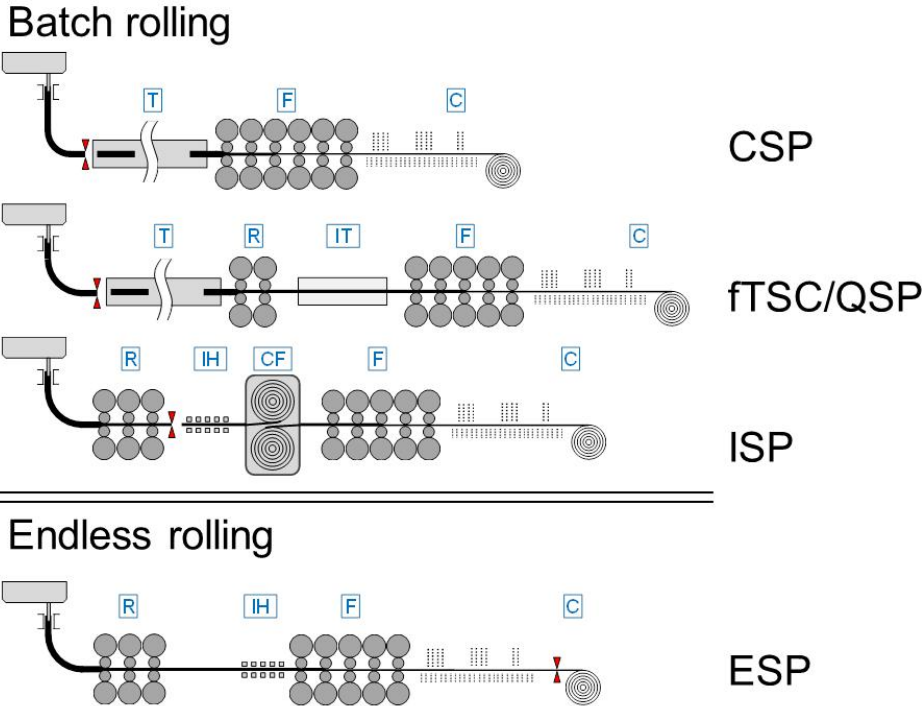


Fig. 1. The evolution of the TSCR technology. The principal elements of the plant are defined as follows: **C** – cooling/coiling; **CF** – Cremona – furnace; **F** – finishing mill; **IH** – inductive heater; **IT** – intermediate treatment (heated transfer table or cooling); **R** – roughing mill; **T** – tunnel furnace.

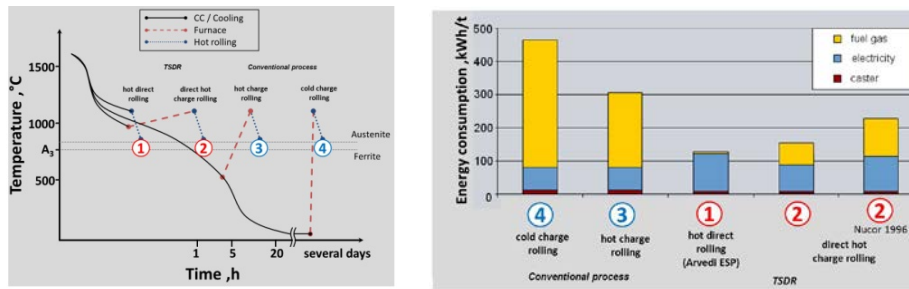


Fig. 2. Energy consumption for hot strip production [1, 2]

The implementation of the endless rolling technology not only provides advantages in overall energy consumption, but also has numerous benefits in daily operation, such as

- unique geometrical strip quality and flatness,
- unique product homogeneity along the strip length (no head / tail ends),
- lowest work roll wear and reduced consumption of consumables overall
- higher availability due to lower cobble rates / caster break outs and
- unique process stability.

The extraordinarily high process stability is a consequence of fewer production interferences and set up changes through all the process steps from the caster down to the laminar cooling section before coiling of the finished hot strip product. The endless production mode serves to ensure higher process controllability and increased homogeneity of final product properties, and maintains stable production windows for all products. In particular, this is reflected in constant product speeds and temperature profiles through all the process steps from casting, and roughing to inductive reheating, finishing rolling and strip cooling. Before coiling, the endless strip is cut into coil portions by a straight cut at the high speed shear located directly in front of the downcoiler area.

An important indication for intrinsic process stability is the start-up curve of a newly installed mill, as it gives an impression of the severity and total number of interruptions.

Fig. 3a provides a comparison of the ramp-up curve for different TSCR processes and the real endless ESP process, indicating that the start-up of the first ESP line already kept up with the most recent ramp up of a TSCR mill installed after decades of development.

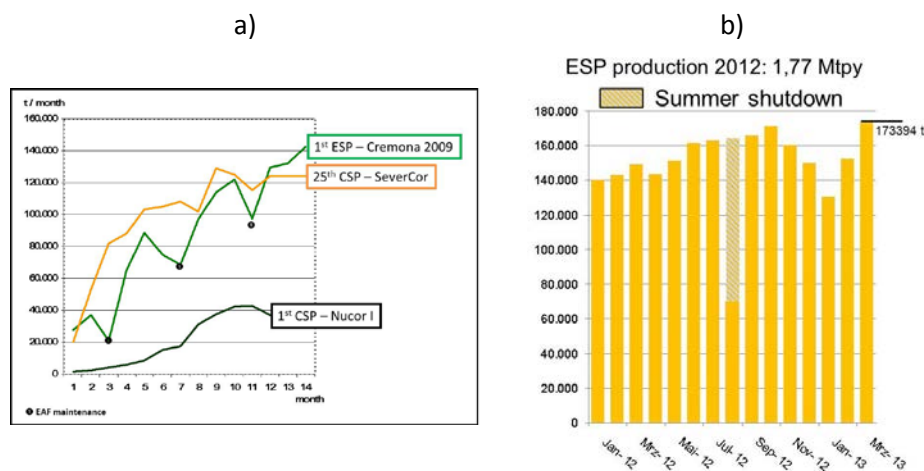


Fig.3: Monthly production per casting strand a) for the ramp-up period and b) for Arvedi ESP in 2012-2013 (production limited by meltshop capacity) [4, 5]

The actual production of Arvedi ESP line is depicted in Fig.3b. The high stability of the production process along the ESP line – production parameters can be kept constant by only minor setup adjustments for approximately eight hours or 3000 tons of produced strip. This permits the possibility of narrowing the processing window, which in turn results in major cost savings compared to TSCR or conventional hot strip mills. The reason for this is that the extraordinary stability lays the basis for aggressive optimisation of alloying concepts and enables the selection of processing parameters very close to plant limits. This advantage becomes especially striking if exploited for advanced high strength steel grades, as demands in terms of process stability, alloying costs and loads are at a maximum for these.

The implementation of new grades is also facilitated by the endless concept, as process variations are kept to a minimum by construction. As a result, well-defined conditions along the whole strip ease the identification of causal relationships between processing parameters and final product properties.

The facilitated development of steel products backing on this stable process is also reflected by the fast diversification of the product range covered by the Arvedi ESP Masterplant, located in Cremona. At the end of 4 years of production it reached a variety compared to TSCR process-based mills after decades of development on several different line implementations. After it started up, several products of different demanding steel groups were produced within industrial sized trial production or even already implemented for every day production, providing Arvedi’s customers with the benefits of the advanced product characteristics inherent to strip produced in fully endless mode.

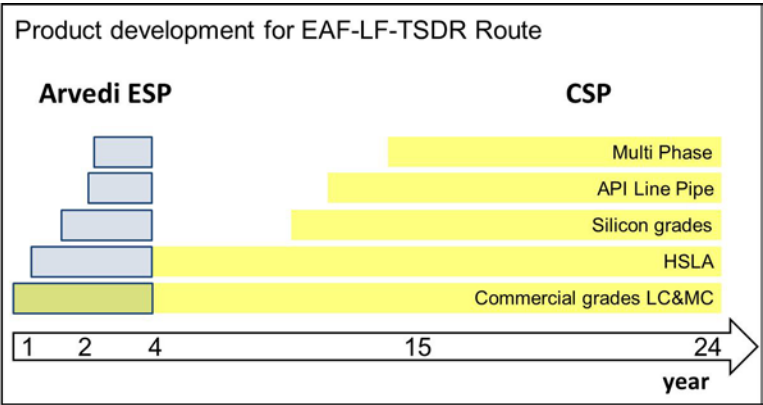


Fig.4: Comparison of time-to-market for products produced on Arvedi ESP and CSP lines [3]

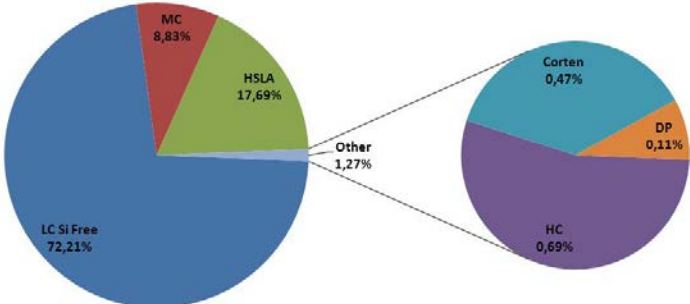


Fig. 5: Arvedi ESP product mix 2012

Another advantage for product diversity is the selected line basic parameters of the ESP process, as the strand thickness lies between 70 and 120 mm in contrast to 45-65 mm at classical TSCR plants. Moreover, the two-step rolling concept including the inductive heater not only leads to a high quality of the final product geometry but also facilitates control of the target microstructure, which is critical for achieving suitable mechanical properties of the finished strip. This patented solution is the key to the wide product range that can be produced at the Arvedi ESP line, ranging from ultra-thin hot rolled strip to advanced high strength steels [6].

1. POTENTIAL OF THE ARVEDI ESP PROCESS FOR THE PRODUCTION OF HIGH QUALITY STEEL GRADES

The indisputable ecological and economic advantages of TSCR technologies for the production of commodity steel grades are further multiplied by an increasing share of high quality steel grades in the production mix. As depicted in Fig. 4 and 5, HSLA steels, medium and high carbon steels as well as dual phase steels already have a share of more than 25% of the annual Arvedi ESP production in Cremona. TSCR processes in general and the Arvedi ESP process in particular have a high potential for the production of quality demanding steel grades like electrical steel, complex phase steel grades and line pipe steels (API grades).

In a quality pyramid for typical hot rolled strip steel grades (Fig. 6), low carbon steels (LC) form the basis: they are relatively easy to cast at a high casting speed and the quality demands are limited to homogeneous mechanical properties and a homogeneous microstructure as well as a sound surface.

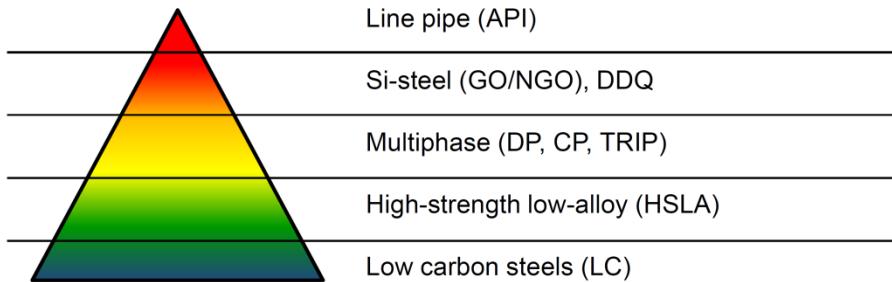
The quality demands for microalloyed LC steel grades (HSLA steel grades) are somewhat higher but still moderate: internal soundness becomes more important as the formation of coarse primary nitrides and carbo-nitrides in segregations has to be avoided. Microalloying elements might in addition cause a pronounced second ductility trough. In conventional continuous casting of slabs this is a common reason for the formation of surface defects. The higher casting speed in TSCR results in a shorter time of the strand surface at elevated temperature and thus suppresses the precipitation of nitrides, carbides or carbon-nitrides along grain boundaries. For the Arvedi ESP process, the absence of a tunnel furnace shortens the time between meniscus and recrystallisation in the first stand of the high reduction mill to less than 4 minutes. The premature precipitation of Nb(C,N) is suppressed [7]. The efficiency of microalloying elements is thus higher than that of other TSCR processes. Moreover, the use of Ti for the control of grain growth is unnecessary, which is an additional advantage with respect to the castability of steels.

A further interesting field of application of the Arvedi ESP technology is high-strength or ultra-high-strength multi-phase steels. In contrast with the ferritic microstructure of LC steels and microalloyed LC steels, multiphase steel consists of either ferrite/martensite mixtures (dual phase steels), a ferrite/martensite/retained austenite microstructure (TRIP steels) or ferritic/bainitic/martensitic structures (complex phase steels). Multi-phase steel grades have a higher carbon content and commonly also higher manganese and silicon content. In high-speed continuous casting the hypo-peritectic range is generally avoided, whereas hyper-

peritectic (medium carbon) steels proved to be suitable for the TSCR process. For multi-phase steels, homogeneity is of major importance. All types of meso- and macrosegregation, like centre segregations and hot tear segregations proved to be harmful. In the Arvedi ESP process, the bow-type caster with funnel-shaped mould provides stable operating conditions. Additional features like the innovative strand support system and the dynamic control of secondary cooling and liquid core reduction promote the favourable development of the strand centre regarding centre segregation and prevent the formation of hot tear segregations. The high degree of deformation due to two-step rolling in the high reduction mill and finishing mill in the Arvedi ESP process provides excellent conditions for the homogenisation of the microstructure in the hot rolled strip [8].

One of the most demanding flat products is line pipe steel for sour gas applications. The low content of residuals and tramp elements together with highest demands on the homogeneity of the product additionally challenges steel plants and rolling mills. The advantages of the Arvedi ESP technology regarding homogeneity and the precise adjustment of the mechanical properties have recently been reported [9].

In the following section, several characteristic quality features will identified and discussed based on the examples of HSLA and API grades produced by the Arvedi ESP production line.



	Quality attributes						
	Cleanliness	Internal quality				Surface quality	
		Centre segregation	Hot tearing	Homogeneous mec. properties	Homogeneous microstructure	Defects*)	Surface Decarburizing
Relevance of process step for quality attribute							
Steel making	▲▲▲	(▲)				(▲)	
Continuous Casting	▲▲	▲▲▲	▲▲▲	▲	▲	▲▲▲	▲
Hot rolling	(▲)	(▲)	(▲)	▲▲▲	▲▲▲	▲▲▲	▲▲▲
Relevance of quality characteristics for product demands							
LC				▲		▲	
HSLA	▲	▲	▲	▲	▲	▲▲	▲
MP	▲▲	▲▲▲	▲▲	▲▲▲	▲▲▲	▲▲	▲▲▲
Si-steel, DDQ	▲▲▲	▲	▲	▲▲▲	▲▲▲	▲▲▲	
API	▲▲▲	▲▲▲	▲▲▲	▲▲▲	▲▲▲	▲▲▲	▲▲▲

*) cracks, oscillation marks, slag gripping, pinholes, blowholes

Fig. 6: Quality pyramid for typical hot rolled strip steel grades

2. QUALITY FEATURES RELATED TO THE ARVEDI ESP THIN SLAB CASTER

Fig. 6 depicts the influence of the process steps steelmaking, casting and rolling on the most important quality attributes of the final product. The main quality characteristics of continuously cast semis are steel cleanness, internal soundness and surface quality [10].

The microscopic steel cleanness is mainly determined by the secondary metallurgical treatment. Neglecting re-oxidation as a potential source for the formation of small inclusions, the importance of casting processes for microscopic steel cleanness is only minor. Sources for meso- and macroscopic inclusions are mainly entrapped ladle slag, refractories and mould slag [11], but clogging and the agglomeration of inclusions at the steel/mould flux interface also have a negative influence on steel cleanness. The prevention of clogging and a stable meniscus are thus important requirements for the operation of casting machines. In the Arvedi ESP process, the funnel-shaped mould with a thickness of 90 – 110 mm assures stable meniscus conditions with a low breakout rate and beneficial conditions for macroscopic steel cleanness.

The internal soundness of cast thin slabs is mainly determined by segregations and the existence of hot tear segregations. Several factors like intensive mould cooling with internal heat transfer of up to 4 MW/m², the design of the strand guiding system and secondary cooling together with liquid core reduction and the low solidification time of less than 2 minutes result in favourable conditions for less pronounced centre segregations compared to conventional slab casting. Fig. 7 depicts micrographs for the strand centre for a low carbon steel on the left-hand side and a medium carbon steel on the right-hand side, both cast at 5 m/min. The centre of the thin slabs is virtually free from porosities, and the enrichment of segregating elements is moderate. This is an important prerequisite for a homogeneous formation of microstructure in the final product but also for the prevention of the formation of large primary nitrides and carbides in the casting of microalloyed steels.

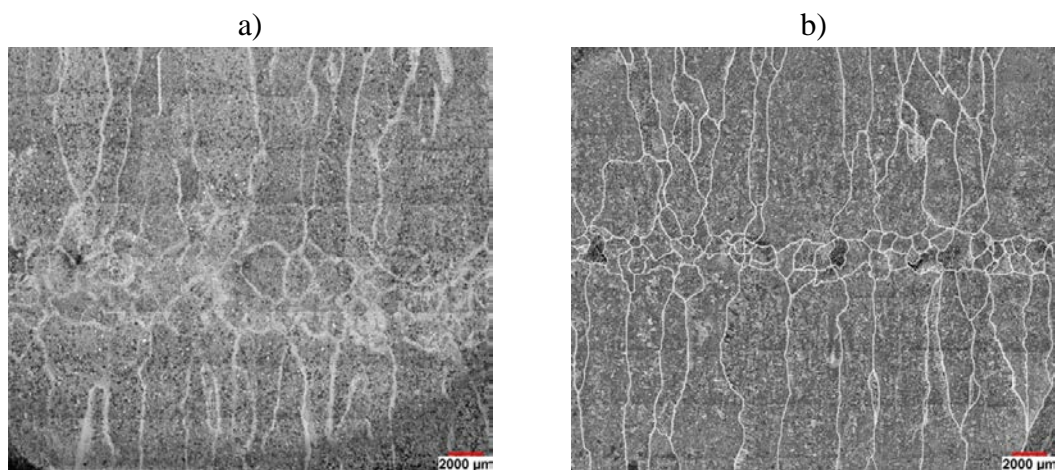


Fig. 7: Arvedi ESP thin slab: 80mm a) low carbon steel b) medium carbon steel

An overcritical straining of the solid/liquid columnar zone during casting results in the formation of hot tear segregations (HTS) and hot tears [12, 13]. Within hot tear segregations, large sulphides form even for the lowest sulphur content, and unfavourable brittle phases may form after hot rolling. Thus, HTS represent a serious quality problem for line pipe steels but

also for most medium and high carbon steel grades. Today, strain accumulation models are commonly used to predict HTS formation in casting processes [12]. Fig. 8 shows the calculated accumulated strain for the casting of API X100 for the casting speed of a 120 mm thick medium slab with 3 m/min and an 80 mm thick slab (after LCR) with between 4 and 6 m/min. Under the assumed conditions, the maximum accumulated strain is far from critical limits, which range – depending on the quality demands on the final product – from 0.8 to 1.6 % for this type of steel.

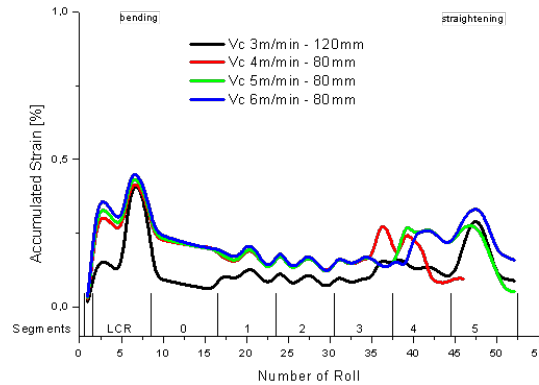


Fig. 8: Calculated accumulated strain for API X100

A frequent problem in conventional slab casting is the formation of transversal cracks due to the precipitation of carbo-nitrides and nitrides during the casting process. Mainly Nb(C,N) but also AlN are known as very critical precipitates [14]. In thin slab casting, the short time in the secondary cooling zone is not sufficient for the precipitation of a considerable volume fraction of harmful precipitates [7]. The comparatively lower Nb content in HSLA steels for the Arvedi ESP route further enhances the sensitivity towards transversal surface cracks.

To sum up, the Arvedi ESP process offers favourable conditions for the production of HSLA steels but also for other higher quality steel grades like API grades or complex phase steel grades.

3. QUALITY FEATURES RELATED TO THE ARVEDI ESP ROLLING CONCEPT

Besides its stability, a major advantage of the Arvedi ESP layout is its two-step rolling concept as it allows for precise control of the microstructure in the final product.

The main purpose of the high reduction mill (HRM) directly placed behind the caster exit is the complete elimination of the as-cast microstructure. The as-cast slab has an inverse temperature profile compared to that at the exit of a reheating furnace. Moreover, the temperature difference between undercooled slab surface and centre can reach as much as 200°C for an 80mm thick slab; see Fig.9a. for a comparison. As a consequence, the hot core of the slab is significantly softer than the undercooled surface. Hence, deformation in the centre of the slab compared to the near-surface area is higher than when the slab is rolled with a temperature profile as arising after a conventional reheating or tunnel furnace. This results in a more homogeneous recrystallised microstructure at the exit of the high reduction mill. Accordingly, rolling schedules take into account the inhomogeneous temperature profile (see Fig. 9b.) along the thickness direction and are designed accordingly to take maximum advantage of the homogenisation effect.

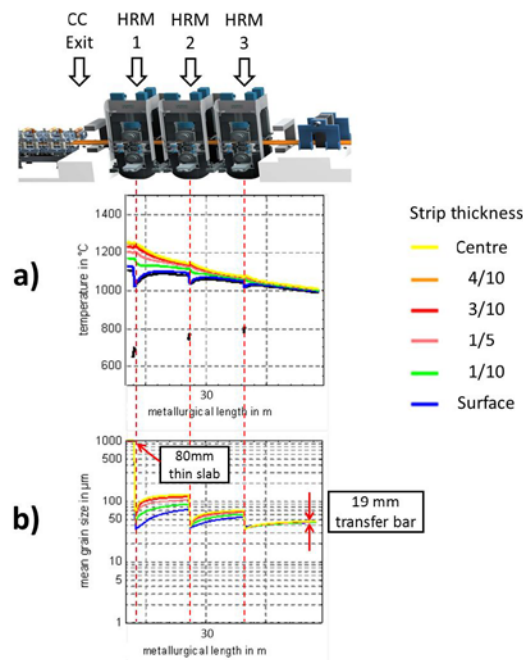


Fig. 9: a) Through-thickness temperature profile and b) through-thickness austenite grain size evolution along the HRM area of the Arvedi ESP plant [15]

In comparison to one-step rolling, the microstructure at finishing train entry is already refined and homogenised. As is common for all TSCR processes, microalloying elements except Ti remain in a solid solution before finishing rolling. Due to the short time spent in the induction heater, alloying with Ti to limit grain growth is not necessary. The direct linking of induction heater and finishing mill train in conjunction with a properly chosen cooling strategy permits precise microstructure engineering for micro alloyed steels. The start of rolling in the non-recrystallisation regime can be shifted between the 2nd and 5th rolling step by a corresponding adjustment of induction heater power and pass schedule setup (see Fig. 10 for a comparison).

A processing model including a solidification model in the caster area as well as microstructure evolution coupled with a precipitation model has been developed for the ESP plant. This model is used to simulate the production of microalloyed steels, like HSLA or line pipe steels, and to predict the properties of the finished hot strip.

Moreover, precise online control accounts for changes in rolling speed, for instance forced by shortages of liquid steel in the melt shop to avoid early stopping of a casting sequence, strip gauge change or changes in chemical composition.

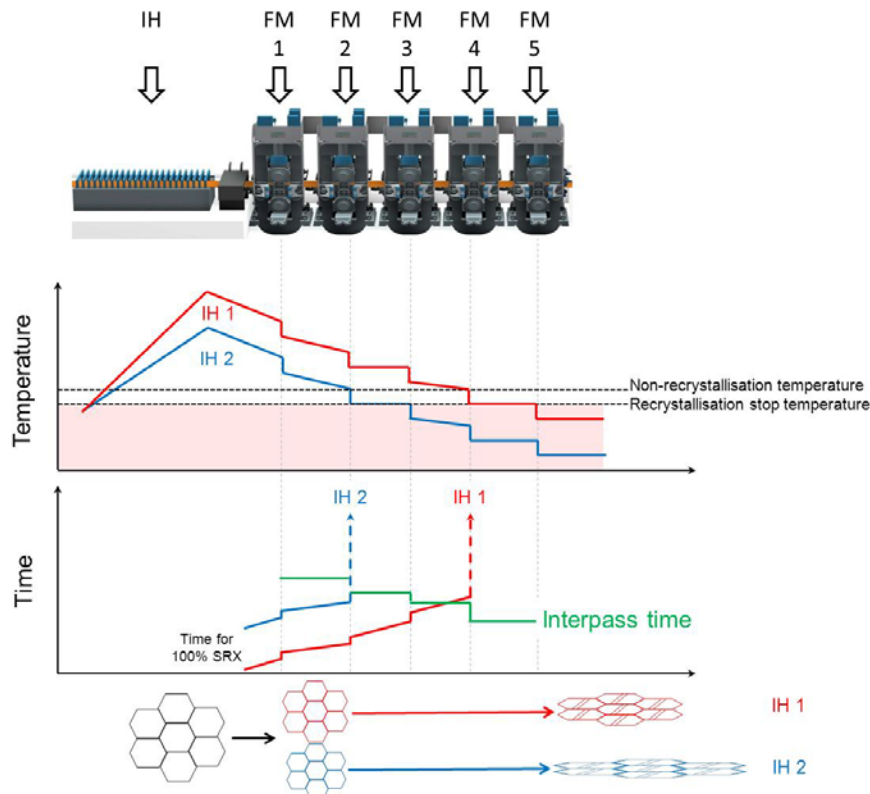


Fig. 10: Temperature and microstructure evolution in the induction heater and finishing train area of Arvedi ESP plant: by properly choosing the IH exit temperature and pass schedule, precise microstructure engineering for micro alloyed steels is accomplished

Fig. 11 shows the results of microstructure modelling for Nb-bearing HSLA steels with the chemical composition given in Table 1. Different simulations were carried out for strip thickness ranging between 2 and 3mm. The austenite grain size at the caster exit reached $1400\mu\text{m}$ at $\frac{1}{4}$ slab thickness, which was significantly refined during the high reduction mill. Between high reduction and finishing mill austenite grains are observed, especially during inductive heating. The first Nb(C,N) and AlN start to precipitate on austenite grain boundaries at the minimum temperature before inductive heating. Rolling in the finishing mill partially occurs below the non-recrystallisation temperature, and, as a consequence, the recrystallisation fraction is less than 20% after the fifth stand. The representative austenite grain size is about $20\mu\text{m}$ after the last pass. The final ferrite grain size is $5,06\mu\text{m}$ (s. Fig. 12). The dislocation density reaches its maximum value in the finishing mill, which, in combination with decreasing temperature, leads to the onset of strain-induced precipitation and stops recrystallisation. The major part of NbC precipitates in the ferrite region by nucleating at dislocations. The size of these precipitates is $<10\text{nm}$. Hence, their influence on the strength of the final product is significant.

Table 1: Chemical composition of HSLA steel

Wt.%					
C	Mn	Si	Nb	Al	N
0,05-0,06	0,3-0,5	0,02-0,17	0,02	0,03-0,04	0,005

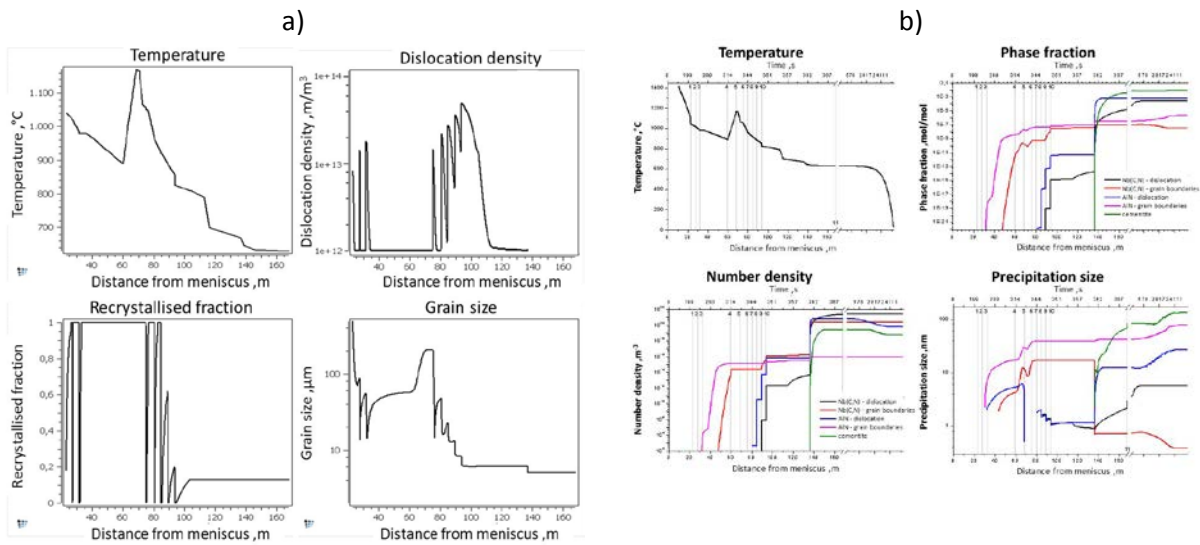


Fig. 11: Simulation of microstructural quantities for a 2mm final strip thickness gauge with chemical composition according to Table 1: a) microstructure evolution; b) nucleation and growth of precipitates along the ESP line

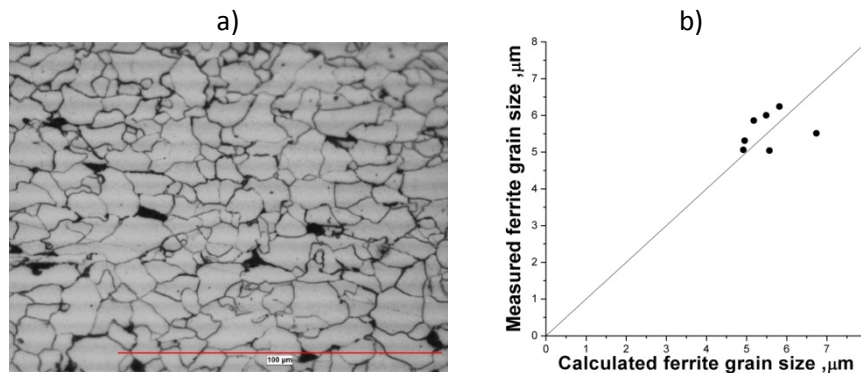


Fig. 12: Comparison between simulation and actual production results at Arvedi ESP: a) typical microstructure obtained; b) comparison of measured and calculated ferrite grain size

Taking into account major strengthening mechanisms in the simulation approach provides an insight into the contribution of each mechanism to the yield strength of the final product. These mechanisms include grain size effects (Hall-Petch relation), precipitation strengthening by means of the Ashby-Orowan model as well as empirical equations describing solid solution and base strength effects[9]. Fig. 13a shows the contributions arising from the different strengthening mechanisms as well as their sum, which corresponds to the yield strength. The precipitation strengthening of NbC is about 10%, and other strengthening mechanisms (solid solution and base strength) amount to 36%. The fine ferrite grains make up about 54% of the total yield strength.

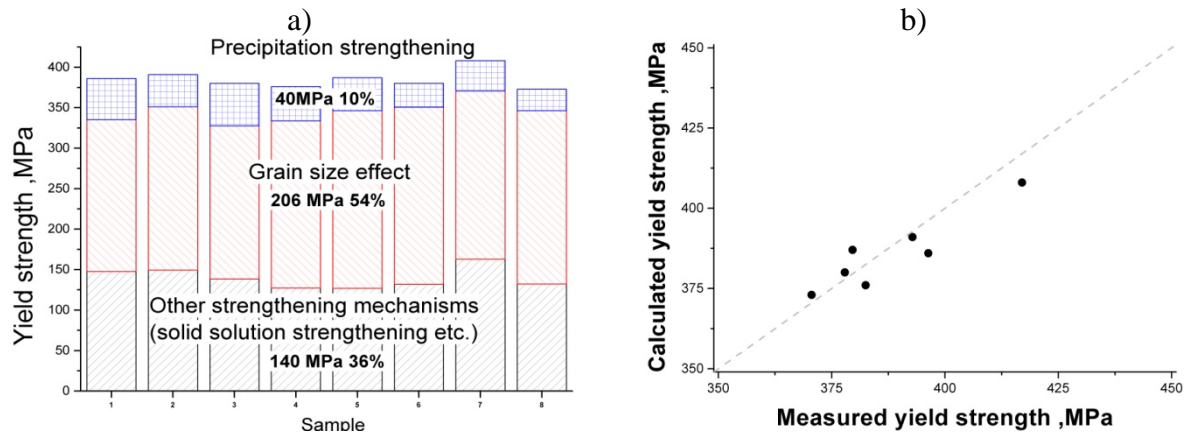


Fig. 13: a) Results of mechanical properties calculated and contribution of different strengthening mechanisms b) comparison of calculated and measured yield strength

CONCLUSIONS

After less than four years of operation, the production mix of the Arvedi ESP masterplant at the Acciaieria Arvedi works in Cremona comprises a share of more than 25% of HSLA steels, medium carbon steels and high carbon steels. Dual phase steels, line pipe applications and Si steels have been successfully produced for experimental purposes.

The Arvedi ESP process offers the best possibilities for a particularly economical and environmentally compatible production of thinnest strip at highest quality standards.

The advantages of the Arvedi ESP process with respect to the quality demands of high quality steel grades were illustrated using the example of HSLA steels and API steel grades. The excellent homogeneity of the final product, the associated precise adjustment of the material properties and the potential for saving micro-alloying elements have to be emphasised.

The potential of Arvedi ESP for a further extension of the product mix towards high quality steels grades like multi-phase steels, high strength API grades or electrical steels will be realised in the future development of the process.

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