

# Solidification and cooling patterns of the slabs during the ISP Thin Casting Process at ARVEDI

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*The idea, conceived in 1976 by Mr Giovanni Arvedi, was to manufacture top quality, ultra-thin gauge, hot rolled strip at competitive prices. This was the basis for the development and patenting of ISP (In-line Strip Production) technology, the original solution of which lies in cast-rolling and having an ultra-thin transfer bar enter the finishing mill (a solution which went against the technical culture of that time).*

**Parole chiave: acciaio, solidificazione, colata continua, collaudi e controlli, processi**

## INTRODUCTION

The ISP process is distinguished by the particular flexibility of use of its machines in terms of the transfer bar thickness and temperature variation. This flexibility of the ISP process has created the conditions for rolling special steels and ultra-thin gauges at maximum width.

The quality results achieved have allowed marketing in sectors reserved until now for cold rolled strip.

The thin slab casting process is one of the most innovative productive systems in the worldwide steelmaking landscape. This casting method can ensure suitable slab sizes, for direct rolling, and energy savings with quality improvements on the final products. For that, some features of ISP-ARVEDI plant are very different from those characterizing the traditional ones.

This paper is about the improvement quality of the products that can be implemented by some fundamental process features:

- the cooling patterns imposed to the slab;
- the liquid core reduction (LCR) and the soft reduction (SR);
- the direct link of the slab from casting to rolling, without the slab be cooled to the room temperature.

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Although these aspects do not represent all the peculiarities of the thin slab casting process and those of the machinery implementing this one, they can show what significant quality improvement can be reached even only by these solutions without any compromising of the high production rate. Particularly, these solutions can ensure improvement on the inner slab quality, avoiding or decreasing the occurrence of micro-segregation events during the strand cooling, while the permanence of the slabs at high temperatures probably permits a more efficient precipitation (in the form of carbides and nitrides) of the micro-alloying elements in the HSLA steels. For the study of these phenomena it is necessary to collect data to insert as inputs on the thermal model that is used to define the cooling patterns of the slab sections.

## BRIEF DESCRIPTION OF THE PLANT LAYOUT

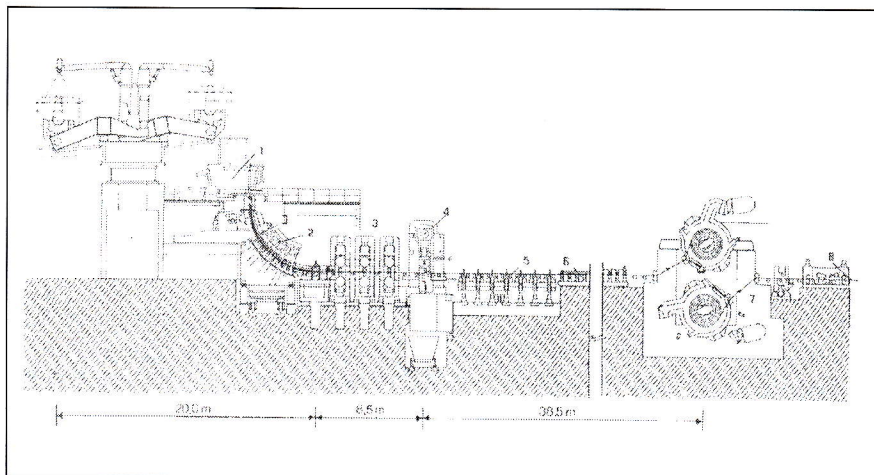
In figure 1 the general layout of the thin slab caster is shown. The steel in the tundish is cast in the so called "Mould System" with some particular features developed by ISP that will be the subject of a future paper concerning the nozzle characteristics and the geometrical shape of the mould. The useful mould length is 0.9m.

At the exit of the mould, the section of the slab is 1250mmX65mm. The successive sections of the casting machine are characterized by a spray cooling zone that extends to 5.56m from the mould exit. This zone could be divided into two zones, pointed out by the following thermal simula-

Fig.1 The layout of the ISP thin slab cast-rolling machine:

1. tundish, 2. secondary cooling zone with LCR and SR, 3. cast-rolling strands, 4. pendulum shear, 5. descaling of the surface oxides, 6. induction re-heating furnace, 7. Cremona furnace, 8. hot rolling finishing strands

Fig.1 Schema generale del processo ISP per la solidificazione in continua e la laminazione di slevi sottili: 1. panierina, 2. zona di raffreddamento secondario con implementazione della LCR (Liquid Core Reduction) e della SR (Soft Reduction), 3. gabbie per il cast-rolling (laminazione in linea immediatamente successiva alla solidificazione), 4. cesoia pendolare, 5. discagliatore, 6. forno di riscaldamento a induzione, 7. forno Cremona, 8. Gabbie per la laminazione a caldo finale



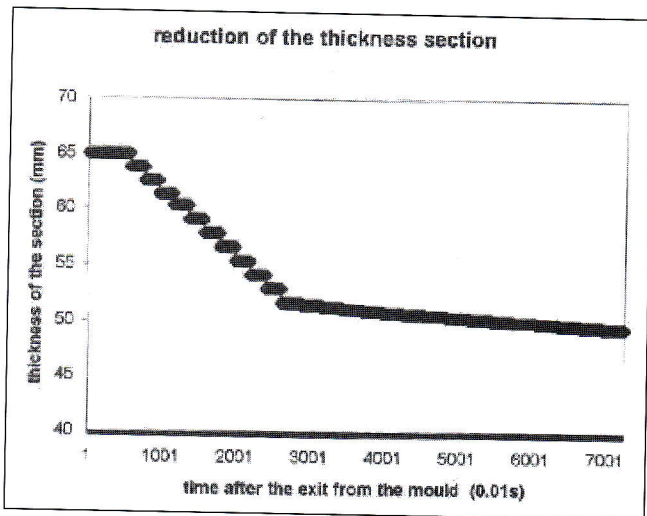


Fig.2 The % rate of the thickness reduction during the passage in the 29 rolls after the exit from the moulds.

Fig.2 Tasso % di diminuzione dello spessore dello slebo durante il passaggio all'interno dei 29 cilindri della colata continua dopo l'uscita dalla lingottiera.

tion. The spray cooling is performed with different cooling densities and with different distribution of the cooling nozzles. The lower boundary of the two main cooling zones are 2.215m, 5.56m from the mould exit respectively. After the rolls N° 2, the slab goes into the first rolls in the so called TTS (Tongue Type Segment) and it undergoes the LCR and SR that produce a progressive reduction of the slab thickness from 65mm to 50mm and this last value is reached at the 29<sup>th</sup> rolls (fig.2).

After the passage under the 29<sup>th</sup> rolls the slab passes through the rolling strands, implementing a process named "cast-rolling", in which the slab always linked to the caster, is plastically deformed and is subject to a further thickness reduction performed in three rolling passes. The leading speed of the bar increases in each strand, because the flow rate of the cast and rolled steel has to be constant.

After these steps the transfer bar goes through the pendulum shear to a refractory tunnel, then to the induction furnace that reheats the bar to a suitable and homogeneous temperature, again to the pairs of "Cremona" coil furnaces, that have the role to buffer the transfer bars and to decouple the rarfing and finishing rolling speeds, and finally to the hot strip that rolls strips down to 1,0 mm gauge.

EXPERIMENTAL

The experimental procedure performed aims at collecting the data to perform thermal computation tasks. The study and simulation are developed for low carbon steels and for HSLA steels. The steels studied were cast at 4.6m/min speed.

The measure of the difference in water temperature at the entry and at the exit of the mould cooling system is fundamental to acquire the input data for determining the heat transfer within the mould. The measures performed for the studied steel grades indicates a nearly constant value 7.5°C with little and not significant oscillations around this value. The cooling water supply within the moulds was fixed at 4800 kg/min for each broad face. The thickness of the cast slab is 65mm at the exit of the mould.

The spray plan for the nozzles of the secondary cooling after the moulds were recorded and the overall water flow is within 3600-4000 kg/min. After the 29<sup>th</sup> rolls the thickness of the slab is 50mm and the heat extraction is performed

only by the air convection mechanism, the heat radiation and by the contact with the rolls. The temperature of the slab surface in this zone was measured by optical pyrometers and has a nearly linear decreasing trend from 1170°C at the exit of the 29<sup>th</sup> to 970°C at the end of the cast-rolling area, while from the cast rolling to the entry of the reheating induction furnace the temperature varies linearly from 970°C to 890°C. This last value represents the minimum thermal point of the slab surface before the re-rolling operations.

The cast-rolling set-up implies a progressive reduction and the one chosen for this study is: 1<sup>st</sup> strand 50-32.1mm, 2<sup>nd</sup> strand 32.1-21.2mm, 3<sup>rd</sup> strand 21.2-13.1mm. As the flow rate of the material has to be maintained constant, an increase of the bar speed takes place so that at the exit from the 3<sup>rd</sup> strand it reaches 22 m/min. However, the ISP thin slab cast-rolling machine allows other reduction rates.

To evaluate the mechanical features of the HSLA steels, the S355MC and S420MC (alloyed by Nb) is chosen and mechanical testing samples were taken from two strips 1.25mm and 1.85mm thick for S355MC and S420MC respectively. Six tensile tests were implemented for each steel along the parallel, 45° and perpendicular direction to the rolling one.

THE THERMAL MODEL

A thermal model based on the Fourier equation is developed under the hypothesis that heat flow on the narrow faces of the thin slab is not significant and that the heat extraction is performed only through the two broad faces. The problem to be solved can be considered mono-dimensional. This hypothesis does not make the computation unreliable, because it is yet representative of the 89.6% of the slab. The heat flow in the longitudinal direction is also not considered and the heat is supposed to take place only through the broad faces.

If the function is written including the effect of the latent heat of solidification, the final form is:

$$\frac{\partial}{\partial x} (k_x * \frac{\partial T}{\partial x}) + \rho * L * \frac{dg_s}{dT} * \frac{\partial T}{\partial t} = \rho * c_p * \frac{\partial T}{\partial t}$$

where

$\rho$  = density of the metal (kg/m<sup>3</sup>)

$c_p$  = specific heat (J mol<sup>-1</sup> K<sup>-1</sup>)

$k_x$  = conductivity of the metal (J m<sup>-2</sup> s<sup>-1</sup>)

$L$  = latent heat of solidification (J kg<sup>-1</sup>)

$T_s$  = solidus temperature (K)

$T_l$  = liquidus temperature (K)

and the fraction of solid can be described by:

$$g_s = \begin{cases} 1 & \text{if } T < T_s \\ 0 & \text{if } T > T_l \end{cases}$$

$$g_s = \frac{T_l - T + \frac{2}{3.14} (T_s - T_l) \left\{ 1 - \cos \left[ \frac{3.14}{2} \left( \frac{T - T_l}{T_s - T_l} \right) \right] \right\}}{(T_s - T_l) \left( 1 - \frac{2}{3.14} \right)} \quad \text{if } T_s < T < T_l$$

The heat transfer by the mould [1] is computed by the knowledge of the flow of the cooling water of the mould broad faces and the difference of the temperature of that water between the entry and the exit of the copper plates. The thermal flow is supposed to follow a function that multiply the value  $Q_{mould}$  to consider the not constant value of the specific power exchanged within the mould along the length of the mould itself.

$$Q_{mould} = \dot{q}_{water} * \rho_{water} * c_{p,water} * \Delta T_{water} / A_{mould}$$

where  $\dot{q}_{water}$  is the water flow rate,  $\rho_{water}$  is the water density,  $c_{p,water}$  is the specific heat of the water,  $\Delta T_{water}$  is the difference of the water temperature and  $A_{mould}$  is the area of the

mould walls exchanging heat.

In the zone of the water spray cooling the thermal flow removed from the steel surface is determined through the sum of the heat removed by water and that removed by radiation towards the environment:

$$Q_{\text{watercooling}} = h_s \cdot (T - T_{\text{water}}) + \sigma \cdot \epsilon \cdot (T^4 - T_{\text{air}}^4)$$

where  $T$ ,  $T_{\text{water}}$ ,  $T_{\text{air}}$  are the surface temperature of the steel, the water temperature and the air temperature respectively,  $\sigma$  is Stefan-Boltzmann constant,  $\epsilon$  is the radiation factor of 0.8,  $h_s$  is taken according to the indications contained in another analogous study [2]:

$$h_s = 1570W^{0.55} [1 - 0.0075(T_w - 273)] / C_m$$

where  $T_w$  is the sprayed water temperature,  $W$  is the water supply taken by the steel surface during its going down,  $C_m$  is a constant typical of the different spray cooling zone of the machine. The form of this expression is designed to include Leidenfrost effect that produces a layer of steam that shields the steel surface from the on-coming water.

The boundary conditions imposed in the cooling zone performed by the air convection are the data provided by the optical pyrometer measurements.

The model was solved by a finite differences method, in which the time step is chosen as 0.01s and the spatial one varies from 1mm to 0.534mm in order to include the effect of the LCR.

In table I the physical parameters used for the running of the model are shown.

Liquidus temp	1536°C
Solidus temp	1514°C
Latent heat	270000 J K <sup>-1</sup>
Density	7000 kg m <sup>-3</sup>
C <sub>p</sub>	620 J kg <sup>-1</sup> K <sup>-1</sup>
k	30 W m <sup>-1</sup> K <sup>-1</sup>

Table I - Physical parameters used in the simulation task.

Tabella I - Parametri fisici usati per la simulazione termica.

RESULTS AND DISCUSSION

The solidification pattern of the steel within the mould is not the main object of this study, but an approximated solution of this condition has been implemented because it is needed to integrate the system on the successive casting steps of interest: the secondary spray cooling period and the period from the cast rolling to the reheating.

The  $C_m$  of the machine is not a single value, but by the interpolation of the thermal value computed at the end of the mould, the temperature data measured after 29<sup>th</sup> rolls and the recorded water supplies it has been possible to define 2 different characteristic coefficients (Table II). These values are very different from that of a traditional continuous casting machine.

C <sub>m</sub>	Rolls
0,5	1-13
1	14-29

Table II

Tabella II

The different values are due to the variations of the conditions for water supply in different positions of the thin slab caster.

The thickness of the shell computed at the exit of the mould is between 0.9-1mm that agrees with the experiences on this

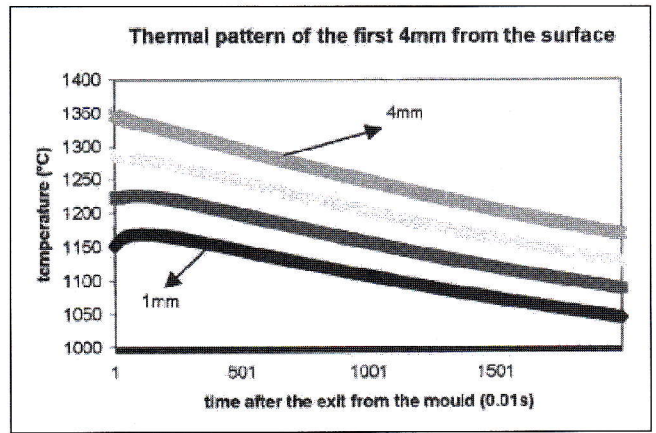


Fig.3 The computed thermal state of the layers within the first 4mm from the surface after the exit from the mould.

Fig.3 Lo stato termico calcolato per le regioni dello slebo contenute nei primi 4mm dalla superficie.

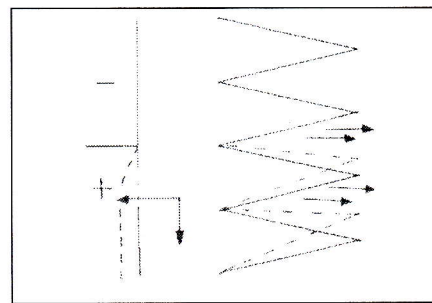


Fig.4 Enrichment of interdendritic liquid for the thermal expansion of the outer layer of the shell due to an inversion of the longitudinal thermal on the surface and on the layer just below.

Fig.4 Arricchimento di liquido interdendritico per l'espansione termica degli strati più esterni della frazione solida, a causa dell'inversione del gradiente termico della regione superficiale e di quelli immediatamente sottostanti in direzione longitudinale.

process. The thermal profile of the section at the exit of the mould (fig.3) is subject to a little and not significant inversion of the thermal gradient in the longitudinal direction only on the surface. The nearly complete absence of the inversion of the thermal gradient due to the change of the heat transmission modality permits to avoid the phenomenon that has been already pointed out [3], that is these inversions can become dangerous in certain situations for the possibility that a micro-segregation phenomena can arise, because of the mechanical effect of a new thermal expansion (fig.4). The dilatation of the external layer may produce an inflection of the solidified shell, which pulls the dendritic inner arms that pump the interdendritic liquid on the tips regions, creating an enrichment of the segregating elements, whose contents can overall the solubility product generating undesired precipitation of non-metallic compounds. On the other hand, the only inversion of the longitudinal thermal gradient that is indicated by the thermal simulation task is due to the change of the  $C_m$  that corresponds to the 14<sup>th</sup> rolls of the machine. But the occurrence of the inversion of the thermal gradient interests only the first 9mm from the outer surface, whereas there is other 10mm completely solidified before the mushy zone. The inner 10mm completely solidified between the outer layer and the mushy zone can avoid the pulling effect of the outer 9mm subject to thermal inversion, that otherwise can interact with the movement of the mushy zone itself.

The LCR and SR take place by the passage of the slab in a conic alignment of the rolls with traction toward the upper region. The LCR and in a more little measure the SR produce a stirring effect which generates a relative movement between the liquid and the solidifying shell in the dendritic

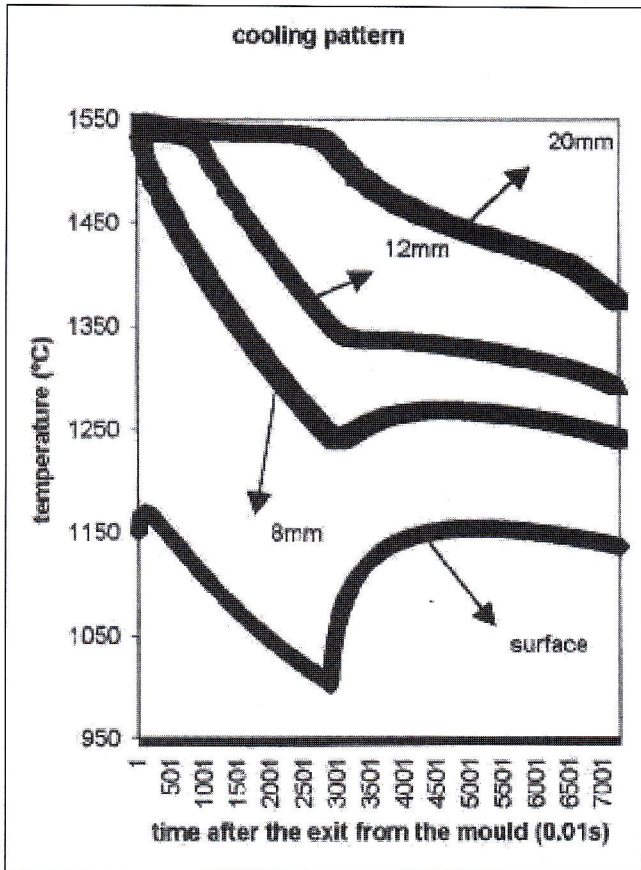


Fig. 5 The cooling pattern of several points (surface and 8mm, 12mm, 20mm from the surface) of the slab section from the exit of the mould to the 29<sup>th</sup> rolls.

Fig. 5 Percorso termico di solidificazione e/o raffreddamento per diverse regioni (superficie, 8mm, 12mm, 20mm dalla superficie) della sezione dello slebo dall'uscita della lingottiera fino ai 29<sup>mi</sup> cilindri della macchina di colata continua.

form. Thus, the LCR and SR can improve the inner slab quality compensating also the detrimental effect that would otherwise rise for the effect of the high casting speed that is reached to maintain a good productivity rate. The calibration of the cooling system shows a good performance in eliminating the inversion of the thermal gradient, especially at the exit from the mould, when the pulling effect of the outer layers can become evident and very detrimental on the micro-segregation structure and the stirring effect of LCR and SR cooperate to improve this aspect (fig. 5).

LCR allows to make the thickness of the slab independent from that of the mould and it permits a larger available volume within the mould to contain the long lasting refractory materials. These materials can be maintained far enough from the walls so not to have problems of quality and it can allow the presence of liquid sections large enough to reduce the speed of the eddy generated by the re-circulating flow of metal.

The thermal pattern results are also joined with thermodynamic model developed by Inoue et al [4] and applied on two typical HSLA steels produced by the thin caster of ISP Arvedi (Table III), to evaluate how suitable is this process to the production of these types of steels.

The main aim for the steelmaking unities involved in HSLA production is to promote a correct precipitation of carbides, nitrides and carbo-nitrides which can take part to the re-pinning effect on the austenite grain size that are functions of the precipitate volume and of their dimensions according to the relations of Zener and Gladman [5]. The optimum conditions would be that featured by a great quantity of precipitates of little dimensions, because the coarsening effect of the precipitated can produce also a coarse austenite grain.

The lower is the temperature, more critical is the precipitation phenomena due to the increase of the solubility products of non-metallic compounds, the steels studied are checked within the lowest thermal range measured over the observed thin casting process before the final hot rolling deformation.

This range is reached just after the cast rolling within the refractory tunnel leading to the induction furnace. In this area where the measured surface temperature varies between 970°C and 890°C the thermal status of the 13,5mm slab is computed (fig. 6).

The hot shortness of these steels begins in a range between 1000°C and 950°C where the used thermodynamics model forecasts the start of the NbN precipitation that according to other authors [6] marks the starting point of the hot shortness phenomenon. However, when the thin slab reaches this temperature the curve of the machine is terminated, so that the possibility of unbending surface cracks are minimized. The only solubility product that is exceeded by the chemical composition is that of NbN (Table IV), while that of NbC,

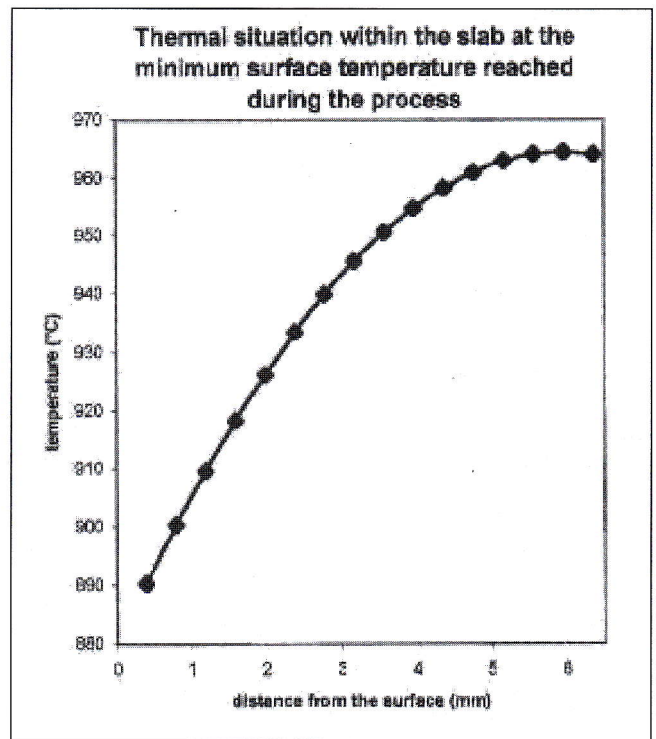


Fig. 6 The thermal profile computed on the half of the slab thickness at the point of the lowest temperature reached by the slab surface during the cast-rolling process.

Fig. 6 Profilo termico calcolato su metà spessore dello slebo in corrispondenza del punto di temperatura minima raggiunto dalla superficie dello slebo durante il processo di cast-rolling

	%C	%Si	%Mn	%Al	%Nb	N(ppm)	P	S
S 355 MC		0.06	0.021	0.4	0.036	0.02	65	< 0.01 < 0.005
S 420 MC		0.06	0.065	0.4	0.05	0.025	85	< 0.01 < 0.005

Table III  
Tabella III

VC and VN are not reached in this temperature range. The Nb(C<sub>x</sub>N<sub>(1-x)</sub>) is the only compound that precipitates and the little amount of NbC is in solution within the other precipitates. The x stoichiometric coefficient at 915°C is 0.14 and 0.11 for S355MC and S420MC respectively.

On the basis of the thermodynamics results, it is possible to use the method of the solubility product to compute the NbC that would have precipitated within the non-metallic compound at the different temperature. The results indicate that a great part of the Nb contained in the steel would precipitate (88% for S355MC and 94% for S420MC), but the dimensions of the precipitates have the possibility to remain very small, because of the temperature effect on the precipitate dimension according to Lifshitz and Slyozov' expression:

$$r_t^3 = r_n^3 + \frac{8D\sigma V^2 C}{9RT} t$$

where

r<sub>t</sub>= final radius of the equivalent sphere with the same volume of the precipitate (m)

r<sub>0</sub>= initial radius of the equivalent sphere with the same volume of the precipitate (m)

D= A exp (-Q/RT) (m<sup>2</sup> s<sup>-1</sup>)

σ= the interaction energy between the precipitates and the iron matrix (J m<sup>-2</sup>)

V= the mole volume of the non-metallic compound (m<sup>3</sup>mol<sup>-1</sup>)

C= is the solute concentration in the matrix which is in equilibrium with the particle of average radius (mol m<sup>-3</sup>)

R= gas universal constant (8.3145 J mol<sup>-1</sup>K<sup>-1</sup>)

T= temperature (K)

t= time (s)

Temperature (°C)	970	950	915
Solubility product of NbN ([mass%Nb][mass%N])	3.4*10 <sup>-5</sup>	2.37*10 <sup>-5</sup>	1.23*10 <sup>-5</sup>

Table IV

Tabella IV

The permanence at high temperature may promote the formation of a coarser distribution, but the time factor may play a balancing effect, because the high speed reached in this process by the thin slab after the cast-rolling plays a favourable role, actually the slab speed is roughly 22m/min, decreasing the processing time which contributes to increase the precipitate size. On the other hand, the permanence above the 890°C permits to maintain in solution the great part of the other eventual micro-alloying elements.

This is a marked difference between this situation and that of the traditional casting method, because the most frequent situation implies a complete or nearly complete cooling of the steel to the environment temperature, so that the precipitation phenomena can be explicated at least one time before the reheating, so that the r<sub>0</sub> of the former expression will have a greater value than if the first complete cooling does not take place.

These are favourable conditions to obtain a significant efficiency of the action of the micro-alloying element.

Actually, the experimental measurements performed have pointed out that the mechanical features of the steels tested reach high value (table V, table VI), although the micro-alloying elements are in the lowest range of the value imposed by EN 10149. This increasing in the tensile performances are associated with a significant value of the percentage elongation to the fracture, which minimum limit is 19% for S355MC and 16% for S420MC.

The thermodynamics forecasting method used is applied also to a S500MC (alloyed by Nb and V: C <0.06, Mn =0.70-0.90, Si =0.20-0.35, P=0.010, S=0.005, Al=0.02-0.040,

S355MC	Rel	Rm	A%
av.transv	464	517	24,2
st.dev.	21,5	21	0,1

Table V. Mechanical tensile features

Rel yield strength, Rm ultimate fracture strength,

A% %elongation to fracture, av. transv. are the data on the direction perpendicular to the rolling one.

Tabella V. Caratteristiche meccaniche?

Rel sforzo di snervamento, Rm sforzo alla frattura,

A% allungamento % alla frattura, av. transv. Sono dati realtivi ai provini prelevati in direzione perpendicolare rispetto a quella di laminazione.

S420MC	Rel	Rm	A%
av.transv	469	520	25,8
st.dev.	14,1	9,5	0,1

Table VI. Rel yield strength, Rm ultimate fracture strength, A%

%elongation to fracture, av. transv. are the data on the direction perpendicular to the rolling one

Tabella VI. Rel sforzo di snervamento, Rm sforzo alla frattura, A%

allungamento % alla frattura, av. transv. Sono dati realtivo ai provini prelevati in direzione perpendicolare rispetto a quella di laminazione.

Nb=0.040-.060, V=0.02-0.03, N=0.008). Nearly all the V content is stored in solution within the austenite matrix (in which the solubility product is larger than in the austenite [6]) to precipitate during the rolling operations. Thus, this process would give a good perspective also for the production of the V-Nb steels, too. Actually, the VN and VC solubility product reach a value that allows the precipitation of this compounds within the S500MC only in the ferrite field. The simulation for the Ti micro-alloyed steels are not performed during this study.

## CONCLUSIONS AND DEVELOPMENTS

The thin slab casting process has some innovative features that has to be considered to understand the potential of this method in increasing the production rate and the inner quality of the slabs. This paper is focused only on two particular but significant aspects related to the thermal pattern of solidification and cooling of the slabs:

- the characteristic coefficients that govern the secondary cooling were determined;
- the calibration of the secondary cooling avoids the occurrence of the longitudinal thermal gradient inversion, forbidding the micro-segregation due to the dendrite movement in the mushy zone;
- the LCR coupled with SR produce a stirring effect that can allow to avoid some micro-segregation phenomena in the inner regions areas of the slab just in front of the mushy zone;
- LCR allows to make the thickness of the slab independent from that of the mould and it permits a larger available volume within the mould to contain the long lasting refractory materials;
- LCR makes the thickness of the slab not dependent on the mould thickness;
- The permanence at high temperature can permit to decrease the content of the micro-alloying element within the steels, because of a more efficient use of their properties, avoiding the precipitation of coarse precipitates or the for-

mation of nucleation sites that can catalyse the successive growth of coarser precipitates during the reheating period.

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**A B S T R A C T**

**SOLIDIFICAZIONE E RAFFREDDAMENTO DI SLEBI DURANTE IL PROCESSO DI COLATA CONTINUA IN SOTTILE PRESSO L'ACCIAIERIA DI ISP ARVEDI**

*La presente memoria tratta alcuni aspetti fondamentali relativi all'impianto per la produzione in sottile di slebi in funzione presso l'acciaieria di ISP Arvedi di Cremona. Questo impianto fu concepito per volontà del Cav. Giovanni Arvedi nel 1976 e costituisce uno degli esempi di maggiore innovazione per la produzione di nastri a caldo.*

*Questo processo per la produzione e la laminazione in linea di slebi colati in sottile presenta caratteristiche tali rendere particolarmente competitiva la produzione di alcuni manufatti che sono sempre stati di pertinenza dell'acciaieria a ciclo integrale, mentre con questo processo hanno potuto conseguire prestazioni meccaniche considerevoli anche a parti-*

*re da acciai prodotti al forno elettrico. E' il caso degli acciai micro-legati (tabelle V-VI) che presentano elevate caratteristiche meccaniche, pur se i tenori dei microleganti presenti si attestano nella fascia inferiore della forcilla prevista dalla normativa.*

*Tali risultati possono essere conseguiti in virtù della particolare configurazione del processo e delle modalità di solidificazione e laminazione.*

*Per definire il percorso termico delle regioni dello slebo è stata sviluppata un'analisi del processo di solidificazione attraverso un programma di simulazione costruito dagli autori e che ha permesso di definire alcuni parametri caratteristici del raffreddamento secondario. E' stata discussa attraverso l'impiego di modelli termodinamici e cinetici la possibilità di ottenere precipitazioni fini dei composti prodotti dai microleganti.*