Diamold® design of corners in billet high speed continuous casting

S. Semplici, R. Karan, C. Mapelli

In continuous casting, the heat flow optimization in the mold is a key to improve quality of the product and the savings of production. The heat flow influences and is influenced by several phenomena, of mechanical or metallurgical nature, so its optimization should include them. In particular, the shrinkage of the strand and the solid phase formation are among the most influencing factors affecting the cooling of the solidifying product. Moreover, billet corners are critical during solidification process. For this reason VAI have introduced a new mould with an innovative profile: the DIAMOLD®. This mould has a particular corner profile that produce thermal stress reduction and mechanical benefits on the final product

This paper is about a model implemented by a software tool that can perform the simulation of the shell formation of carbon steel within the mould for rectangular shapes. The validation of this model and the benefits of the DIAMOLD® installation, have been carried out during the revamping of a Continuous Casting Machine in Galtarossa Riva Group Plant.

Key words: steel, solidification, continuous casting, modeling, technologies

INTRODUCTION

Computer aided numerical simulation is nowadays a must to provide an adequate forecasting support to those who design continuous casting plants as well as to those who are responsible of the production management (1,2,3,4,5).

Even if the potentialities of the computational systems and the techniques today available go far beyond the necessities of this kind of simulation, there is not still a reliable tool which could give a precise and comprehensive description of the various phenomena involved in the continuous casting process. The complexity and the number of the involved phenomena and moreover their mutual interactions make the simulation very intricate and time expensive, even limiting the study to specific situations, such as carbon steels and simple shapes (circular and rectangular).

At a macroscopic level it is possible to select as the main aspects (6): heat transfer, stress and strain distributions and their influence on heat exchange, fluid flow during the mold filling and its relation with the mold geometry, the mechanical behaviour of the alloy at casting temperatures, the influence of mold oscillation and the role of the lubricant powders.

In this paper will be introduced the numerical model, its validation and the implementing software for the forecasting of the thermal behaviour of the shell solidified within the mold. Though it does not consider all of the aforementioned factors of influence, it is possible to build a sufficiently complete and at once versatile tool, especially useful for correlating the product's macroscopic quality to various casting parameters controlling the solidification within the mold of carbon steels.

The attention is here focused on heat flow, solid phase formation kinetics and the mechanical behaviour as function of the casting speed, super-heat temperature and the thermal power extracted from the mold.

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The main results to be achieved to reach the fixed targets are:

- temperature distribution inside the solidifying steel;
- thickness of the solidified shell;
- areas of detachment between the shell and the mold;
- plastic deformations undergone by the ingot, as well as the areas of the mold in which they occur;
- well performed mold's contour, in case of curvilinear-contoured molds, with fixed casting parameters;
- optimum combination of casting parameters (casting speed, extracted thermal power, super-heat temperature, carbon content) to grant an acceptable surface quality and a good solidification structure.

As far as rectangular shaped molds are concerned, it was chosen to disregard thermal curvature on the corners of the section and near them, so only the longitudinal deformations have been taken into account.

The program follows a section of the solidifying shell as it passes through the mold.

The validation of the model has been developed on billet casting machine in RIVA GROUP -. GALTAROSSA (Italy) plant, revamped by VOEST-ALPINE IMPIANTI in 2002 and equipped with DIAMOLD® square section and reliable results have turned out.

NUMERICAL MODEL

The numerical model is articulated in three different components, each of which rules a different aspect. The first module is about the thermal flow (7,8) and the enthalpy conservation is governed by the Fourier's differential equation:

$$div(-k \cdot gradT) + \dot{q}(T,x,y,z,t) = \rho(T) \cdot c_p(T) \cdot \frac{\partial T}{\partial t} \quad (1)$$

where the thermal source term is related to the solid phase generation, and because fs does not explicitly depend on time, we can write:

$$\dot{q} = \rho(T) \cdot L \cdot \frac{\partial f_s}{\partial t} = \rho(T) \cdot L \cdot \frac{\partial f_s}{\partial T} \cdot \frac{\partial T}{\partial t}, \quad (2)$$

and consequently, making substitutions and rearrangement,

Quantity	Symbol	Unit
Conductivity	k	W m^{-1} K^{-1}
Specific heat	c_p	J kg^{-1} K^{-1}
Fraction of solid phase	f_s	number
Solidification latent heat	L	272000 J m^{-3}
Heat flow	Φ	W m^{-2}
Density	ρ	kg m^{-3}
Linear thermal expansion	α	10^{-6} K^{-1}
Liquid phase lower temperature	T_l	K
Solid phase upper temperature	T_s	K
Casting temperature	T_c	
Internal action	N	N
Yielding stress	σ_y	Pa
Dimensions of the cells	$\delta x, \delta y, \delta r$	m
Time step	δt	s
Density of water	ρ_{H2O}	1000 kg m^{-3}
Water flow	F	m^3 s^{-1}
Thermal power extracted	ΔQ	W
Specific heat of water	$C_{p,h20}$	4185 J kg^{-1} K^{-1}
Water temperatures	T_{in}, T_{out}	K

Table 1 – Simbology. *Tabella 1 – Simbologia.*

Fourier's equation becomes:

$$div(-k \cdot gradT) = \rho(T) \cdot \left\{ c_p(T) + L \cdot \frac{\partial f_s}{\partial T} \right\} \cdot \frac{\partial T}{\partial t} \quad . \tag{3}$$

For the present assumptions fs does not depend on time, so the formula n°(3) is formally the same to the Fourier's equation without sources, on condition to consider $c_p(T) + L \cdot \partial f_s / \partial T$ like an Equivalent Specific Heat.
Then the temperature evolution for a generic infinitesimal volume element is described by the following:

$$\frac{\partial T}{\partial t} = \frac{div(-k \cdot gradT)}{\rho(T) \cdot \left\{ c_p(T) + L \cdot \frac{\partial f_s}{\partial T} \right\}} \tag{4}$$

Since heat removal takes place mainly on the lateral surface, the Laplacian can be considered independent from the z variable, corresponding to the on-going casting direction, because some former studies have shown this approximation as a suitable one to be adopted and this simplification is supported by the fact that the micro-structural analysis shows columnar domains perpendicularly oriented to the z axis.
The solution of the Fourier equation has been implemented by the finite difference method, and leads to two slightly different algebraic expressions for the rectangular shape (Fig.1).
The Laplacian takes the form in Cartesian coordinates:

$$\frac{\partial}{\partial x}\left(-k_x(T) \cdot \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y}\left(-k_y(T) \cdot \frac{\partial T}{\partial y} \right)$$

and in the finite differences form:

$$-\left\{ \frac{\Phi_{o,x} - \Phi_{i,x}}{\delta x} + \frac{\Phi_{o,y} - \Phi_{i,y}}{\delta y} \right\},$$

with:

$$\Phi_{o,x} = \frac{k_{x,10} \cdot \{T1(i-1) - T0_x(i-1)\}}{\delta x}, \quad \Phi_{i,x} = \frac{k_{x,21} \cdot \{T2_x(i-1) - T1(i-1)\}}{\delta x}$$
$$\Phi_{o,y} = \frac{k_{y,10} \cdot \{T1(i-1) - T0_y(i-1)\}}{\delta y}, \quad \Phi_{i,y} = \frac{k_{y,21} \cdot \{T2_y(i-1) - T1(i-1)\}}{\delta y}.$$

The thermal conductivity is indexed because it varies with

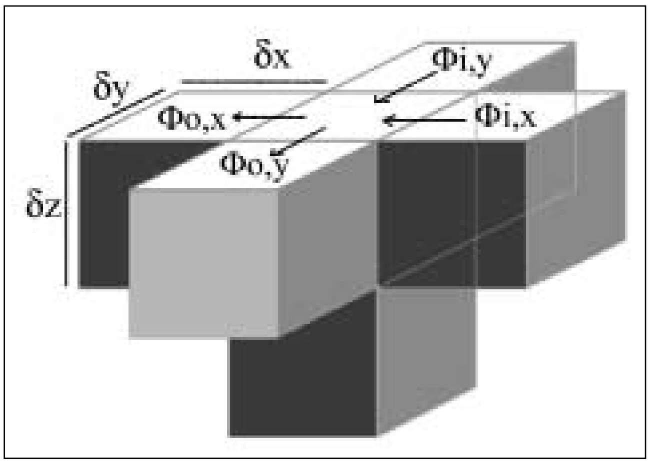

Fig. 1 – Scheme of the cells and heat flows for rectangular ingots.

Fig. 1 – Rappresentazione delle celle e del flusso di calore nel caso rettangolare.

temperature and so it is calculated at each cell interface.
The temperature of the cell with general coordinate (n,m) at the time i is given by:

$$T(i) = T1(i-1) - \frac{\frac{\Phi_{o,x} - \Phi_{i,x}}{\delta x} + \frac{\Phi_{o,y} - \Phi_{i,y}}{\delta y}}{\rho(T1(i-1)) \cdot \left\{ c_p(T1(i-1)) + L \cdot \frac{\partial f_s}{\partial T}(T1(i-1)) \right\}} \cdot \delta t \tag{5}$$

The boundary conditions require:
- initial temperature imposed (tundish temperature),
- heat flow imposed by mold on lateral surfaces,
- no heat flow across the surfaces of symmetry.

The total heat flow from steel in mold to the cooling water is calculated by:

$$q_{ling} = \dot{q}_{H2O} \cdot \rho_{H2O} \cdot c_{p,H2O} \cdot \Delta T_{H2O} / A_{ling} \quad [W/m^2]$$

Along the on-going casting direction the heat flow takes a typical distribution (Fig.2), on the basis of previous and reliable studies (9) dealing with the operating conditions that are similar to the ones encountered in the experimental tasks performed in this analysis. The polynomial curve is a normalized description of the trend that is always respected but shifted up and down as function of the total heat removed by the mold. However, the total heat removed is a constrain condition for the curve, because the total energy exchange cannot overall the total heat extracted by the water. Moreover, the algorithm is able to locally reduce thermal power extraction depending on the presence of an air gap between the mold and the just solidified shell.

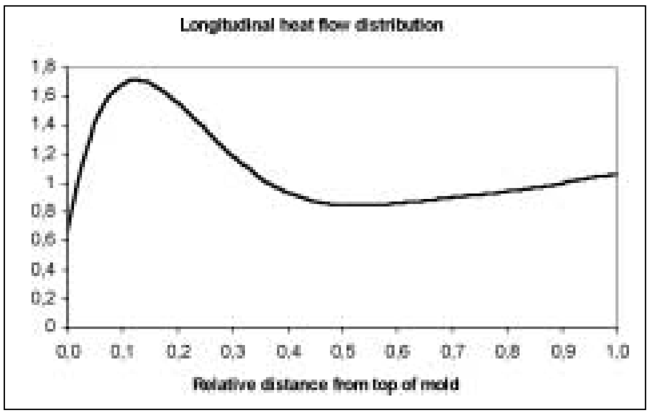

Fig. 2 – Normalized heat flow distribution along casting direction.

Fig. 2 – Flusso termico normalizzato lungo la direzione di colata.

When the air gap occurs, the modality of the heat extraction changes from the conductive to the convective one and the constant of the heat conduction decreases.
The heat flow along the casting direction is given by the product $q_{ling} \cdot f$ and then the boundary conditions are:

- $\Phi_{o,x} = \dot{q}_{ling} \cdot f_{(zi-l)}$ for $x = X_{ling} / 2$, that is on the edge
- $\Phi_{o,y} = \dot{q}_{ling} \cdot f_{(zi-l)}$ for $y = Y_{ling} / 2$
- $\Phi_{i,x} = 0$ for $x = 0$, that is on the core
- $\Phi_{i,y} = 0$ for $y = 0$

while the initial temperature is put equal to the casting temperature: $T(0) = T_c$ homogeneous on the overall cross section.
A work by B. Rogberg (11) is useful to calculate the solid phase fraction related to the temperature:

$$f_s = \frac{T_l - T + \frac{2}{\pi}\cdot(T_s - T_l)\cdot\left\{1-\cos\left[\frac{\pi\cdot(T-T_l)}{2\cdot(T_s-T_l)}\right]\right\}}{(T_l - T_s)\cdot\left(1-\frac{2}{\pi}\right)}.$$

Thus, the term $\partial f_s(T) / \partial T$ in Fourier's equation is easily obtained:

$$\frac{\partial f_s}{\partial T} = \frac{\sin\left[\frac{\pi\cdot(T-T_l)}{2\cdot(T_s-T_l)}\right]-1}{(T_l - T_s)\cdot\left(1-\frac{2}{\pi}\right)}$$

PHYSICAL PROPERTIES OF THE MATERIAL

Density of solid at high temperature is taken constant to 7200 kg/m^3 with good precision, while that of Liquidus is described by the relation 8523-0.8358*T (kg/m^3).
In the biphasic shield a weighted average is made as a function of the solid fraction.
An empirical method, often used in continuous casting, has been adopted to evaluate the thermal conductivity: a value K=120[W/m·K] is used for high turbulence in liquid steel, while K=30[W/m·K] is the optimum for calm steel. Some functions have been written for values in the previous interval, considering the growing of the solidification seeds:

- per $T \geq T_{liq} \rightarrow K = 120$ [W/m·K]
- per $T < T_{liq}$ $f_s \leq 0{,}3 \rightarrow K = 120$
  $0{,}3 < f_s \leq 0{,}6 \rightarrow K = (1 - f_{vl}) \cdot (0.0116 \cdot T + 15.24) + f_{vl} \cdot 60$
  $0.6 < f_s \leq 1 \rightarrow K = (1 - f_{vl}) \cdot (0.0116 \cdot T + 15.24) + f_{vl} \cdot 30$
- per $1273 \leq T \leq T_{sol} \rightarrow K = -0.0116 \cdot T + 15.24$
- per $T < 1273 \rightarrow K = -0.0556 \cdot T + 89.65$

where f_{vl} is the fraction of liquid volume calculated as
$\rho_s \cdot (1-f_s) / (\rho_s \cdot (1-f_s) + f_s \cdot \rho_l)$.
For the specific heat parameter we used standard data with the distributions as shown in the following pictures (Fig.3-4).

EDGE DETACHMENT CONDITIONS

The cell on the edge is involved in a bidirectional heat flow, while on the boundary unidirectional model is applicable (Fig.5). For this reason we developed 4 functions (reduced to 3 because of the symmetry) that calculate the cells' temperature depending on which position they have.

Function 1

Is the only one cell that feels the heat transfer on both sides. It must be imposed: $\Phi_{o,x} = \Phi_{o,y} = \dot{q}_{ling}$, while $\Phi_{i,x}$ and $\Phi_{i,y}$ are calculated as seen before.

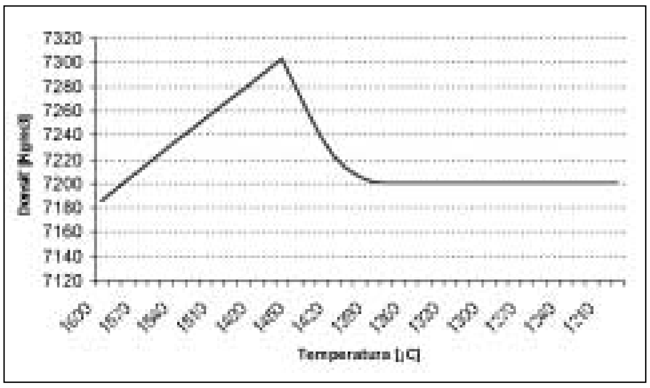

Fig. 3 – Density - temperature correlation.

Fig. 3 – Relazione densità/temperatura.

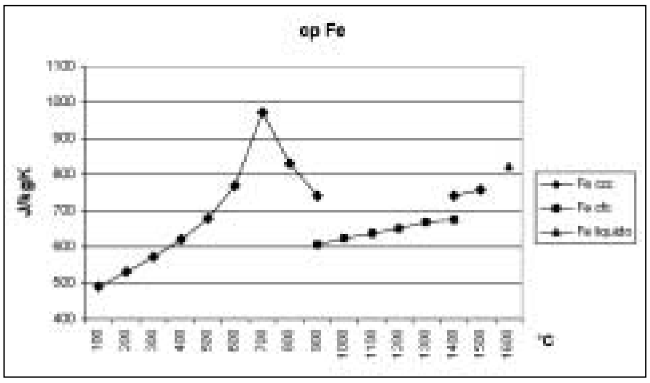

Fig. 4 – Iron specific heat.

Fig. 4 – Andamento del calore specifico dell'acciaio.

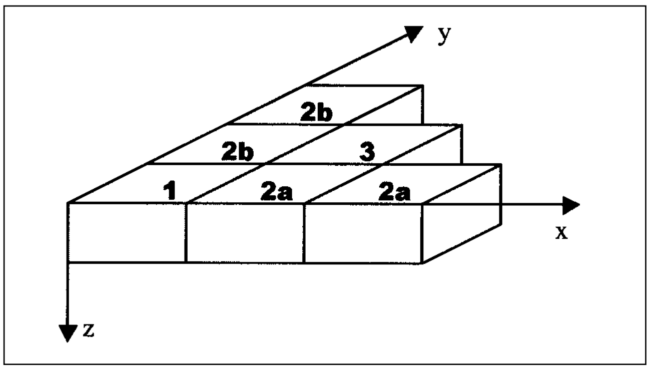

Fig. 5 – Cells and functions distribution.

Fig. 5 – Distribuzione delle celle e delle funzioni di calcolo.

Function 2a

This cell has a heat exchange only along y-axis: $\Phi_{o,y} = \dot{q}_{ling}$ and $\Phi_{o,x}$ $\Phi_{i,x}$ and $\Phi_{i,y}$ are calculated with respective formulas. Function 2b is equivalent to the Function 2a with inverted indexes because of the symmetry.

Function 3

There are no boundary conditions to impose on these cells because they are internal, and their temperature can be calculated with formula (5).
The idea is to become to detach the edge of the mold as soon as the strength of the shell is higher than metallostatic pressure of the liquid core. The shell temperature has been taken as control parameter, because the strength of the shell is dependent on the temperature.
The following hypotheses allow a safety model.

- the metallostatic pressure is calculated considering the overall cross section as liquid steel along all the casting direction. With this assumption the value of the pressure is maximized. Then we can write:

$P = \rho(T) \cdot g \cdot z \cdot 10^{-3}$ [MPa]

- the density value is considered constant and the maximum assumed in $T_{col} \div T_{liq}$ interval.
- the strength limit is:

$\sigma_{sn} = k \cdot P$ [MPa]

with k safety factor variable at pleasure.
Common formulas have been used to calculate the temperature that gives a certain value of strength to the steel. Then, for each cross section of the mold, the maximum temperature for the steel to resist at the metallostatic pressure is given.
The detachment temperature is assumed equal to the lower temperature calculated before, because of the reheating of the shell. This phenomenon is due by the loss of solidification latent heat from the liquid core to the new shell formed, and by the formation of an air gap, after detach, that compromise the heat transfer.
It is important to choose the right detach temperature also to avoid temperature oscillations near 950°C, because of the loss of ductility.
The detachment is simulated by the annihilation of the heat flow. This condition is applied to the cells which temperature lowers below the detachment temperature.
This hypothesis is made considering not relevant the radiation heat flow within the air gap for thickness of higher than 1 millimeter, because of the low air density.

PROGRAM FOR SIMULATIONS

The program needs as inputs the main casting parameters (casting temperature, speed, flow and ΔT of the primary cooling water, etc) and the data to identify the steel grade (carbon percentage, liquidus temperature, etc).
The taper of the mold is not considered to make the calculation easier and reduce the elaboration time.
The program works on a quarter of the cross section, divided in 1000 meshes by 50x50 cells each, and find the solution for iteration with a step dependent on the casting speed: calling δz the distance between two meshes, the step is (11):

$$\Delta t = \frac{\delta z[mm]}{\dfrac{v_c[m/\min]}{60}}$$

The outputs consist of:
- 100 maps for the temperature distribution,
- 100 maps for the growing of the solid shell,
- 1 mold contour.

Each map is representative of one time. The higher the number of maps the better the accuracy to evaluate the evolution of the quantities.
The contour of the mold has the edge detached. The maximum detachment is fixed in one third of the width to avoid bulging phenomena.

RESULTS AND DISCUSSION

The simulations have been done considering real values collected during 4 performance tests executed on a revamped plant with DIAMOLD® installed. This is a particular mold, patented by VOEST-ALPINE, that applies this concept of edges detachment.
Every simulation is related to a specific heat and steel grade. For each one will be attached:
- 1 temperature map at mold outlet
- 1 solid shell map at mold outlet;
- 1 mold contour.

CASTING PARAMETER		HEAT NUMBER 17153L5	26393L3	17667L2	26910L2
C %	%	0,798	0,078	0,759	0,849
Casting Temperature	°C	1521	1554	1533	1504
Liquidus Temperature	°C	1463	1513	1467	1459
Solidus Temperature	°C	1350	1501	1360	1350
Casting Speed	m/min	2,24	2,24	2,15	2,48
Mold width	m	0,14	0,14	0,14	0,14
Mold length	m	0,85	0,85	0,85	0,85
H_2O flow	m^3/h	85	84	84	88
H_2O inlet temperature	°C	28	27	32	30
H_2O outlet temperature	°C	38	37	41	39
Heat flow	kW	988629,1	976998,2	879298,3	921169,7
Number of mesh		1000	1000	1000	1000
Delta x =	mm	0,0014	0,0014	0,0014	0,0014
Delta y =	mm	0,0014	0,0014	0,0014	0,0014
Delta z =	mm	0,00085	0,00085	0,00085	0,00085
Delta t =	s	0,022768	0,022768	0,023721	0,020565

Table 2 – Casting parameters. *Taella 2 – Parametri di colata.*

HEAT N°17153 L5 (Fig.6-7)

The solid shell thickness calculated is 8.4 mm.
It can be seen by the graph (Fig.6) how the edge is hotter than the rest of the lateral surface: this is because of the transmission of latent heat from the cells backward, while the transmission with mold is annihilated.
Using a traditional mold with the same casting parameters values, the edge would be colder than the contour. With our assumption the edge temperature is always higher than 1000°C, permitting to avoid the transition in the low hot ductility zone close to 950°C.
It can be seen which part is involved in the detachment: it begins when the temperature is rising.

HEAT N°26393 L3 (Fig.8-9)

This is a Low Carbon steel grade. The solid shell thickness value is 11.2 mm, a quite high because of a strong hard cooling due to the fact that the water flow was kept constant for every heat. Also the high solidus temperature increases this phenomenon.
Set different flow rates for different steel grades should be a way to obtain homogeneous results.

HEAT N°17667 L2 (Fig.10-11)

In this case the temperature is more homogeneous between edge and surface.
The edge temperature is quite the same between heat n° 17153 and 17667, but the lower temperature of the surface for heat n° 17667 is due to a higher cooling water flow rate and delta T.
The mold contour has a more restrict detach zone, because of the higher temperature of the surface. So the detachment conditions are realized less quickly.

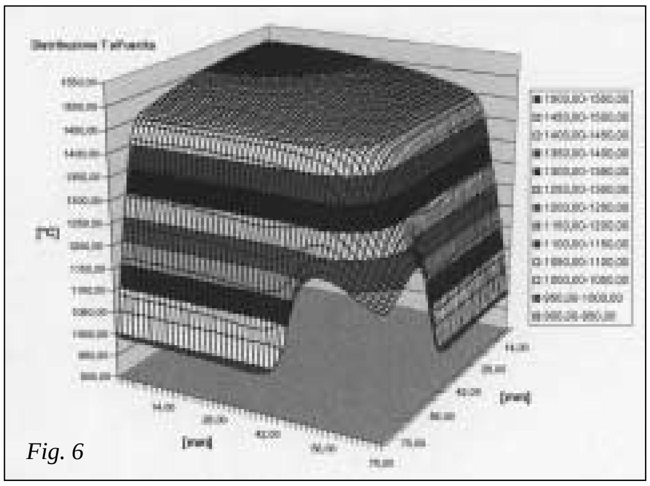

Fig. 6

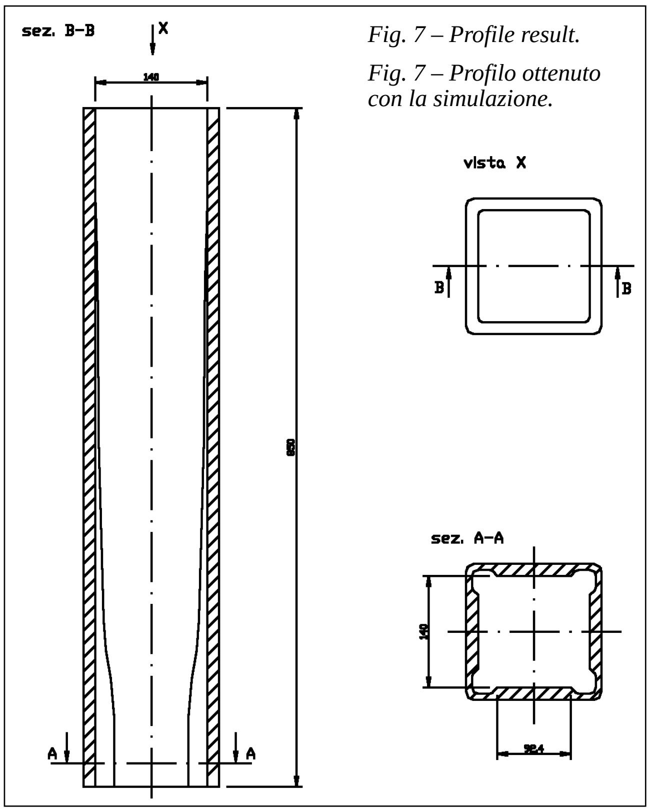

Fig. 7 – Profile result.

Fig. 7 – Profilo ottenuto con la simulazione.

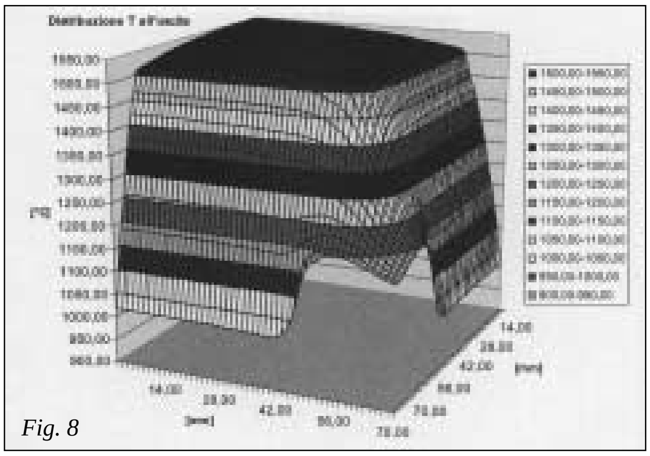

Fig. 8

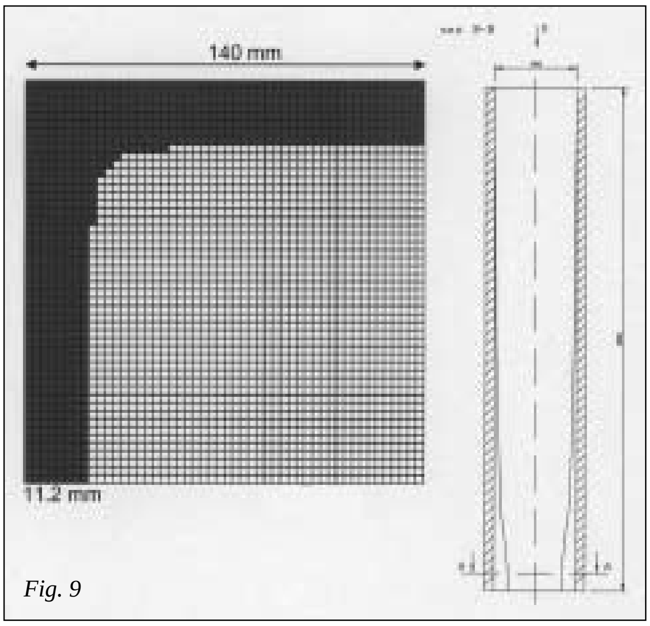

Fig. 9

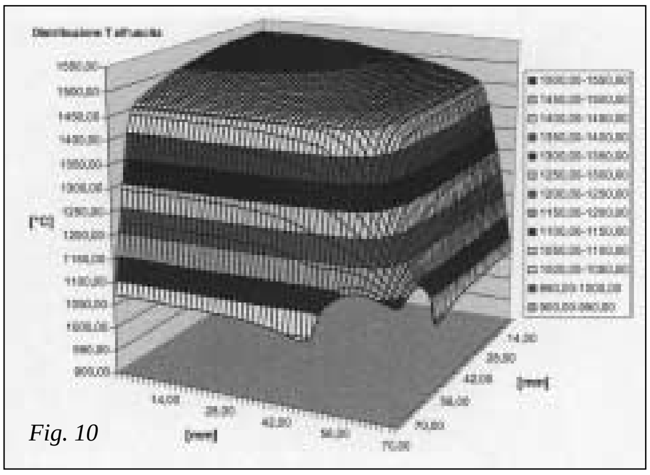

Fig. 10

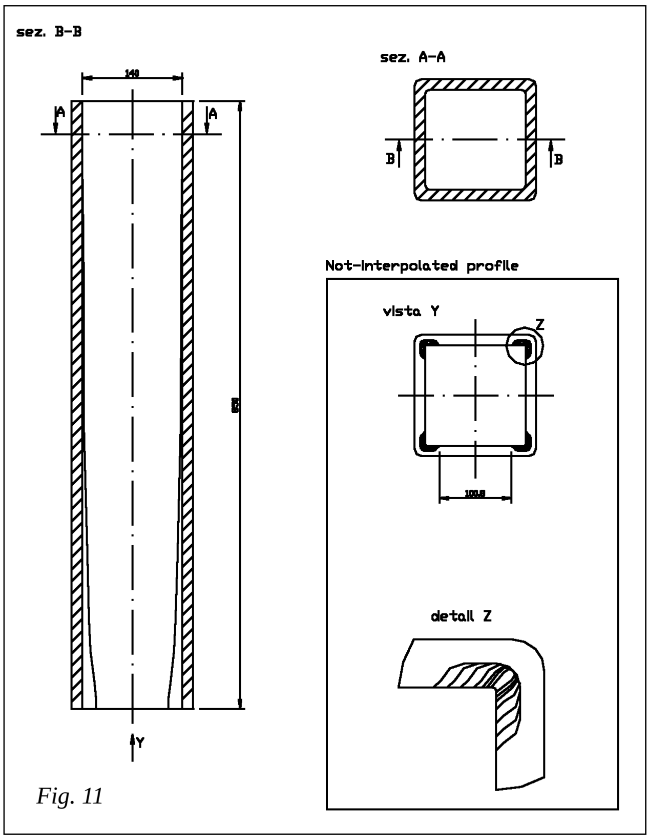

Fig. 11

HEAT N°26910 L2 (Fig.12-13)

The solid shell thickness is 7 mm.
The contour temperature is more homogeneous than other cases, and never below 1000°C.
Casting speed, higher than others, influences on calculated detachment, which grows to the maximum only at the bottom of the mold.
A comparison between billet cast before the revamping and after, using DIAMOLD® high speed mold, highlights the enhanced billets quality (Fig.14).
Billet shape has been clearly improved and the edges are smooth and cracks-free (Fig.15).

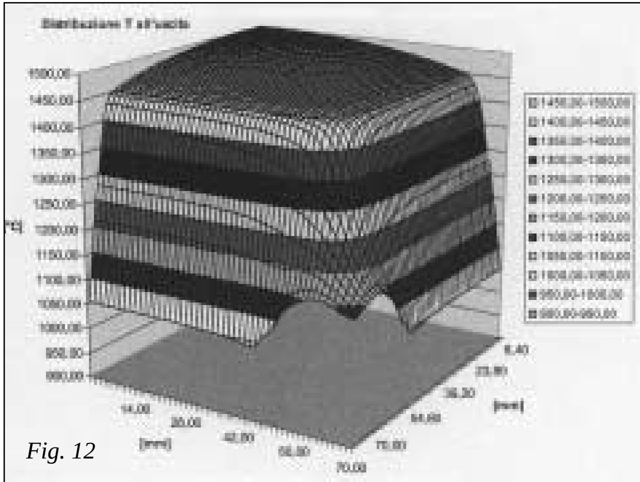

Fig. 12

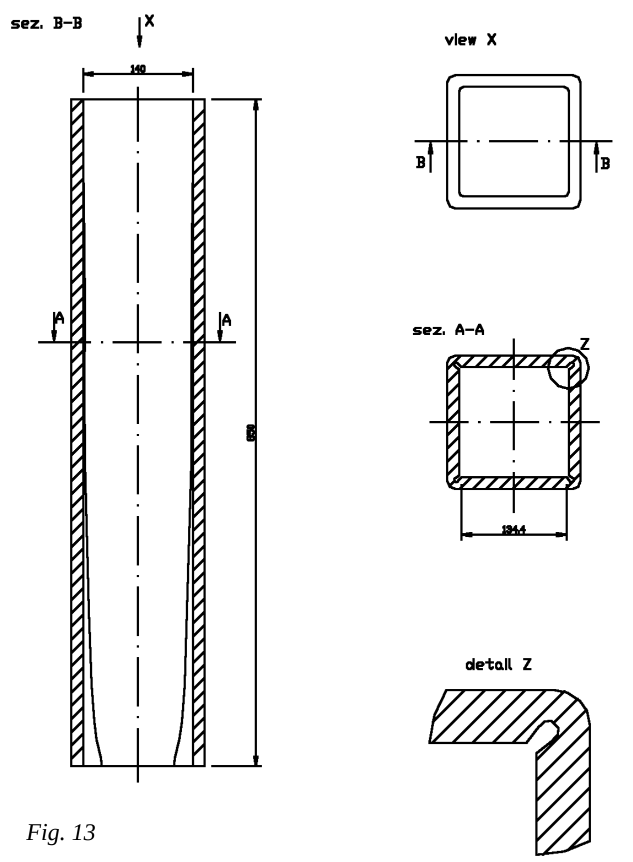

Fig. 13

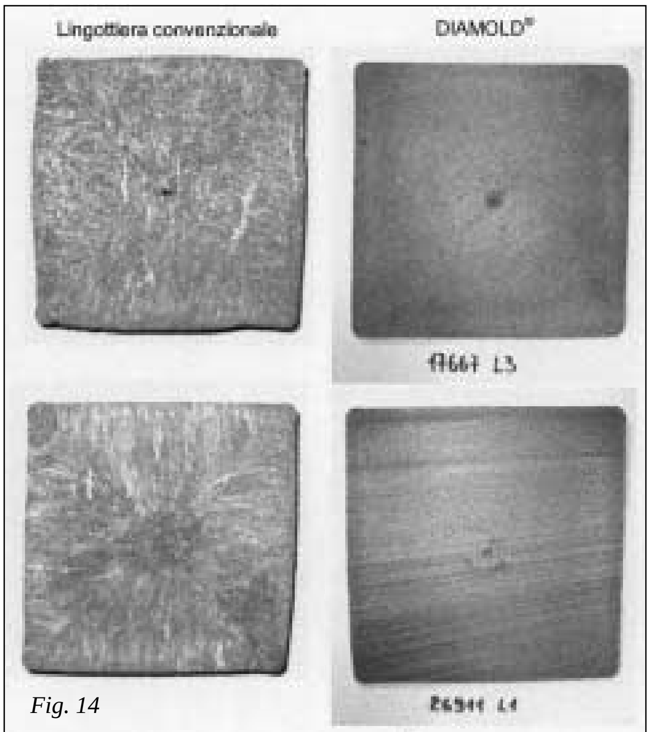

Fig. 14

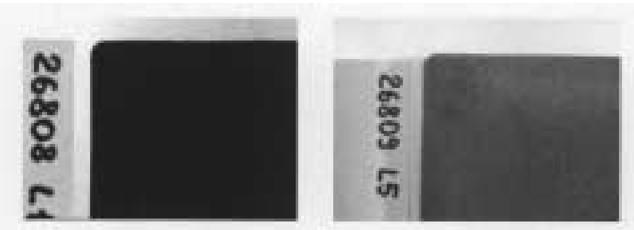

Fig. 15

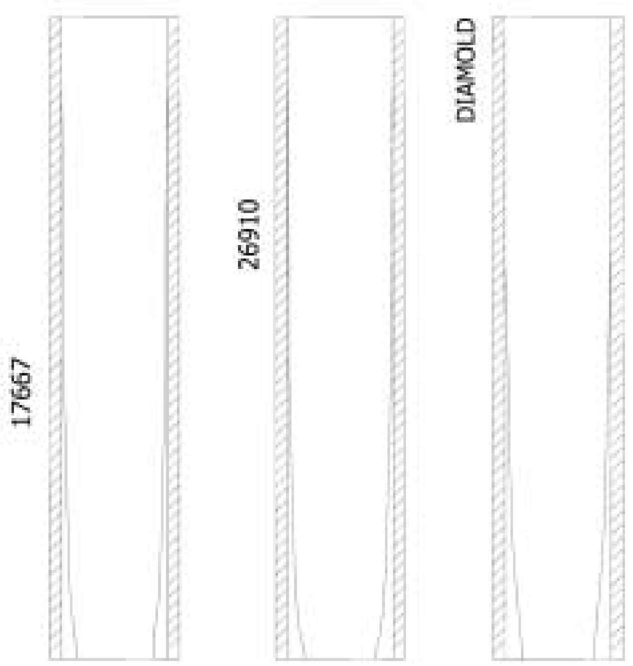

Fig. 16

CONCLUSIONS

Continuous Casting Process has a huge importance in the Steel making Industry. The increase of production obtained using CCP has to be followed by an increase of the quality level, having the costumer satisfaction. These goals can be fulfilled by the development of new technologies and optimization of casting parameters. Our approach demonstrates that the improvements made with the installation of the DIAMOLD® high speed billet mold are reliable. The mold profi-

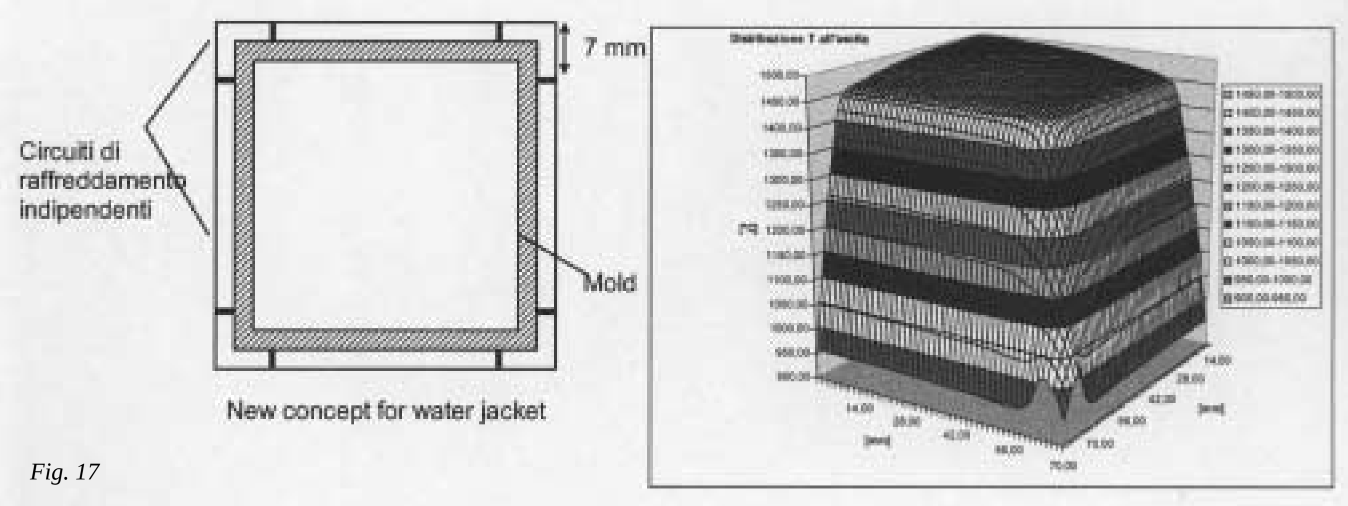

Fig. 17

les obtained with our model are supported by the DIAMOLD® casting results, besides the DIAMOLD® profile itself (Fig.16). This program could be a powerful instrument to improve both aspects, because the contours obtained are quite similar to DIAMOLD® one. On the other side we have to consider that is not possible to use a specific mold for each steel grade, so an optimization of mold geometry is necessary to cast a large range of steel grades. A possible solution should be the adoption of a “differential cooling system” instead of the edge detachment. It consists in a special water jacket with separated conduits for surfaces and edges: in this manner it is possible to use different flow rates to obtain different cooling intensities (Fig.17). With this solution the boundary conditions in our model change: the heat flow is no more annihilated but only reduced and it has repercussions in an even more homogeneous shell temperature, from the surface to the edges, as shown in the picture. To realize this system the closed water-cooling circuit has to be more complicated than usual, but all the system will be even more flexible.

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11. Voest Alpine Industrieanlagenbau – Conti Cast Calculator

ABSTRACT

LINGOTTIERA DIAMOLD® PER IL COLAGGIO IN CONTINUO DI BILLETTE QUADRE AD ALTA VELOCITÀ

PAROLE CHIAVE: acciaio, solidificazione, colata continua, modellazione, tecnologie

L’ottimizzazione dei flussi di calore in lingottiera nel processo di colata continua dell’acciaio è di fondamentale importanza per migliorare la qualità del prodotto e per ottimizzare i costi di produzione. Lo scambio termico influenza ed è influenzato da fattori di natura sia metallurgica sia meccanica, fattori che devono necessariamente comparire nel processo di ottimizzazione. In particolare, la formazione della fase solida ed il ritiro della billetta durante la solidificazione sono sicuramente i fattori principali che influenzano il raffreddamento durante la colata. Inoltre gli angoli delle billette risultano essere zone particolarmente stressate sia termicamente sia meccanicamente. Per queste ragioni VAI ha introdotto sul mercato una lingottiera dal profilo innovativo, il cui nome brevettato è DIAMOLD®. Questa lingottiera ha un particolare design che riduce drasticamente le sollecitazioni termo-meccanche sugli spigoli delle billette e che porta ad un miglioramento della qualità del prodotto colato. Questa memoria descrive l’implementazione di un modello matematico di solidificazione dell’acciaio attraverso l’uso di un software appositamente sviluppato, che consente di svolgere simulazioni relative alla solidificazione dell’acciaio in lingottiera per billette di sezione quadrata. In base alla classe di acciaio prodotto ed ai parametri di colata, il programma è in grado di elaborare le distribuzioni di temperatura sulle varie sezioni della lingottiera e di definire il corretto profilo dello spigolo per incrementarne le caratteristiche meccaniche e la qualità. Il modello è stato validato attraverso prove di performance svolte sulla macchina di colata continua revampata da VAI nello stabilimento del Gruppo RIVA di Galtarossa – Verona, Italy.