STEELMAKING PRACTICE FOR NIOBIUM CONTAINING STEELS

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Summary

Niobium, which is widely used as a microalloying element in steel to improve mechanical properties, in some cases, can cause problems during processing.

In this paper, we discuss difficulties enountered at USINOR, especially during continuous casting and also some problems studied in a more fundamental way in close cooperation with IRSID.

Niobium microalloying itself does not lead to any difficulties. Problems arise when specification requirements concerning low sulphur levels and spheroidization of the sulfides are to be met, as the procedures used for this purpose can increase nitrogen content. In this case, Steelmaking and continuous casting must be carefully controlled, as high niobium and nitrogen content may in some cases give rise to surface and internal defects.

We describe in this paper a general method for choosing a steelmaking, casting and cooling strategy, based on a study of defects and their causes, and on an experimental heat transfer study of the efficiency of secondary cooling.

Background

USINOR has, in its Dunkirk plant, five two-strand curved-mold continuous casting machines which are used for more than 90 percent of the steels produced. Niobium containing plate grade production is concentrated on the 2 machines built by Fives-Cail-Babcock in the No. 1 steelshop. These machines have a 12 meter radius of curvature (1). To date, more than five million tons of niobium microalloyed steels have been produced at this plant. The Solmer plant at Fos-sur-Mer has a one-strand caster and produces similar steels, but mainly for coil production on a continuous hot rolling mill.

The production of niobium-microalloyed plates at Dunkirk (500,000 tons/year) may be classified as follows:

1. 380,000 tons/year of plates for pipes (controlled rolled).

   300,000 tons rolled on a four high stand mill.
   80,000 tons rolled on a continuous hot rolling mill.

2. Other plate steels.

   35,000 tons/year

3. Hot rolled strip.

   70,000 tons/year

4. Plates directly quenched after rolling and then tempered (USIRAC process).

   1,500 tons/month in 1981.

Table 1 gives details of these steels (other alloying elements, slab reheating conditions, etc.).

The range of niobium contents is from 0.01 to 0.08 percent. Specific ranges are as follows:

Plates for pipes rolled on a plate mill	: 0.03 to 0.04 %
Plates for pipes rolled on a continuous hot rolling mill	: 0.01 to 0.06 %
Plate HSLA	: 0.03 to 0.04 %
Coil HSLA	: 0.01 to 0.08 %
Plates O and T	: 0.15 to 0.035 %

Procedures For Niobium Alloying

During steelmaking, the sequence of alloy additions is as follows:

1. Ferrosilicon is added to the empty ladle,
2. During casting, further ladle additions are made in the following sequence:

Table I. Nb - Steels Produced at Dunkirk.

Steel Type	Grade	Application	Composition	As Delivered Product	Slab Soaking Temperature
Pipeline Plate	X 52 to X 80	- gas transportation - oil transportation	Nb Nb V Nb Mo Nb V Mo	controlled rolled	1100 to 1180 C
High strength Plate	USITEN 355 to 460 and equivalents: in particular grades > E 36 (ex : ASTM A 131)	- pressure vessels - off-shore - bridges - shipbuilding - railroad rolling stock - roof strusses - cranes	Mo Ni-Nb (Ni) Nb V	normalized or possibly controlled rolled	1180 to 1250 C
High strength coils and sheets	NORMECA 275 to 590 and equivalent SAE 945 to 980 ...	- structural parts for automobiles - tanks, containers - welded pipes	Nb NB V Nb Ti	. hot rolled tempered	1200 to
Ouenched & tempered plates	USIRAC 460 to 690 and equivalents (ex: ASTM A 537 A 724)	- earth moving equipment - off shore - miscellaneous structures	Nb Nb - B	tempered	1180 to 1250 C
	USIRAC 320 AR	- abrasion resistant plates	Nb-B-Mo	as quenched	

- Aluminum
- Ferromanganese
- Ferrovanadium
- Ferroniobium (62% Nb)
- Ferromanganese again, if the total content required exceeds the volume of the feed hoppers.

Using this procedure, 96 percent of the niobium is retained in the finished product.

In most cases, in order to meet requirements for high touphness and high ductility, niobium steels are produced with a low sulphur level and spheroidization of the remaining sulfide inclusions. This is achieved by:

- desulfurization of pip iron prior to steelmaking using a special mixture containing mainly Mg (USIMAG process)
- spheroidization of sulfides by injection of a calcium alloy into the liquid steel after steelmaking.

The industrial practice concerning these ladle treatments was described in detail in a paper presented at the Scaninject II meetinp held in Lulea in June, 1980 (2) to which the reader may refer for details concerning:

- a description of the plant
- the treatment method and the corrections to be applied as a function of temperature and chemical analysis
- the metallurgical results obtained for the liquid metal
- the metallurgical results obtained on plates.

This ladle procedure induces secondary metallurgical effects, which may cause difficulties. Among these may be cited:

1. An increase of nitrogen content between the converter and the ladle, as a consequence of the higher casting temperature required (the mean value of this N_2 increase is 36 ppm).

2. An increase of nitrogen content during the desulfurizing and spheroidizing treatments (nitrogen increase : 10 to 30 ppm). It should be noted that an Argon treatment makes it possible to decrease this renitridinp.

3. An increase of hydrogen content, which is a consequence of the use of lime in the slag to improve desulfurization.

4. A risk of rephosphorization, consequence of the high casting temperature and of the larpe amount of slag.

Although the internal and external cleanliness of slabs is improved by these ladle treatments, the resulting nitrogen increase causes bearinp grades to be more sensitive to the occurrence of transverse cracks during the straightening operation in the continuous caster. This sensitivity is made worse because the increase in nitrogen content also increases the aluminum nitride precipitation which is the primary cause of cracking during continuous casting.

In the second part of this paper, this cracking phenomenon is examined in detail, but it should be mentioned here that the tendency to cracking is also aggravated *as* the slab thickness is increased. As an amplification, Figure 1 gives temperatures at which straightening is carried out for a metallurgical length approximately equal to 19.5 meters. For similar liquid pool lengths

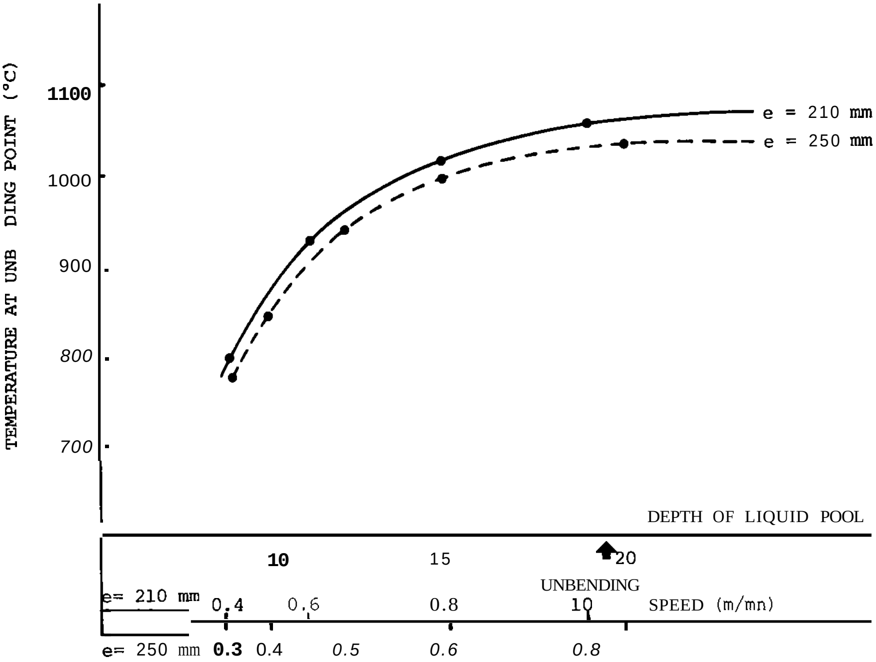

Figure 1. Temperature at unbending point.

(17 to 18 meters) and for slab unbending at 19.5 meters, the surface temperature of a 210 mm thickness slab is about 30 C higher than the temperature of a 250 mm thickness slab. The 210 mm slab can thus be made less sensitive to transverse cracking if "hot" secondary cooling is used (unbending temperature $\geq$ 900 C).

The above remarks show clearly the importance of the effect of chemical analysis on surface cracking sensitivity during continuous casting. Let us now consider the evolution which has taken place in the choice of the best compromise for chemical analysis/mechanical properties in the case of pipe steels.

1. Before the use of a controlled rolling practice, it was necessary to use high carbon content (with or without normalizing) and X60 was the highest strength level available.

2. Controlled rolling made it possible to manufacture higher strength (X60/X70) grades with lower carbon equivalents and better toughness. Niobium made a major contribution to this evolution (smaller grain size, precipitation hardening).

3. The more recent evolution of specifications requiring X70 and above yield strength with greater wall thickness, lower carbon equivalent and better toughness makes it now necessary to

- decrease the rolling temperature in the austenite region
- increase the niobium content and use molybdenum or vanadium additions
- decrease temperature at the end of rolling with finish rolling in the $\gamma + \alpha$ region. This practice is generally associated with a low slab reheating temperature and a low niobium content, in order to achieve a good yield strength/toughness compromise.

For high strength plates other than pipe plates, a similar evolution has taken place concerning carbon equivalent. For coils (NORMECA trade mark) a niobium addition is used, niobium content being a function of the required yield strength.

Without entering into the detailed metallurgy of the effects of niobium during transformation, let us emphasize that the choice of chemical analysis must not be made simply on the basis of the rolling conditions. A compromise has to be found for each step of the steel making process, in particular:

- between casting and ladle additions (or tundish additions),
- during secondary cooling,
- in the process of rolling, to obtain the required mechanical properties.

The overall compromise thus covers much more than the simple choice of niobium content.

Parameters which have an influence on the occurrence of defects during continuous casting (angle, star, longitudinal and transverse cracks) are given in Table II.

A policy of systematic scarfing depends on the importance of surface cracks in the end product and is influenced by the following liquid metal parameters:

Table 11. Parameters Having an Influence on Surface Cracks.

		Angle	Star	Longitudinal	Transverse
Steel grade	Sensitivity for high grades (ductility trough)	**	**		***
Mold adjustment	Conicity GF PF	?	**	*	
Nature of copper	Recrystallization, deformation, melting		*		
Mold lining	Avoid slab - copper contact		***		
Mold wear	Striation, plastic deformation		*		
Oscillation cycle	Frequency amplitude	**	*		*
Slag cover	Suction, ripple formation	*		***	*
Slab width	Slab - mold rubbing rupture of slab film		*	*	
Nozzle	Thermal attack of solidified, part	*		**	
Extraction speed	Increasing+ increase in: - force - temperature of the copper - temperature at the unbending point	?	*	*	***
Secondary cooling	Quantity; repartition, homogeneity Influence on slab temperature	**		**	***
Geometrical state of caster	Alignment, separation state of rolls		**		***
Temperature at the unbending point	Ductility trough	**			***

- niobium content
- carbon content
- spheroidization treatment of inclusions (via its influence on nitrogen content)
- casting temperature.

Scarfing may be, in most cases, limited to the topside of the slab.

In the first part of this paper, we have underlined problems arising from high niobum or nitrogen contents, relatinp to steelmaking practice or chemical composition and their effects on surface quality.

In the second part, we describe a strategy in continuous casting which enables a compromise to be found between surface quality and internal quality i.e. a compromise between cracking sensitivity and slab bulging. In both cases control of secondary cooling has a major effect.

We shall not take into account in this paper parameters which have an influence upon axial segregation and other defects; in this context, however, studies are currently being carried out by USINOR, IRSID and CEM in the field of electromagnetic stirring during secondary cooling.

Control of Secondary Cooling in Continuous Casting of Plates

In order to define an operating strategy for a continuous caster, an analysis of the metallurgical requirements for manufacturing defect-free products had to be developed, along with an assessment of machine capabilities in terms of heat transfer. Two concepts were defined on this basis: metallurgical criteria and technological constraints, the presentation of which constitutes the fist two parts of this chapter.

Metallurgical cooling criteria

A metallurgical cooling criterion expresses, in terms of heat transfer, the metallurgical requirements which have to be met in order to produce defect-free products, i.e. slabs devoid of surface or internal cracks, of centerline segregation and cast with a minimum breakout rate. The list of the main cooling criteria is presented here and the influence of niobium is indicated.

Reliability of the casting operation. Breakouts - the most dreaded incident on a continuous caster - are caused by an insufficient or an irregular solidification in the mold, which is often related to faulty lubrication between slab and mold.

Breakout rate, for otherwise constant operating conditions (mold length, steel grade, casting temperature, nozzle geometry, etc.) is a rapidly increasing function of casting speed (3) due to the decrease in the solidified shell thickness at the mold exit. The influence of casting speed and casting temperature on this thickness has been investigated by IRSID (4), and it has been shown that a 0.1 m/min increase is speed or a 10 C increase in superheat lead to a 1 mm decrease in shell thickness at the mold exit.

The first metallurgical criterion therefore states that casting speed should be maintained below a maximum value, possibly indexed to the superheat, in order to ensure a safe casting operation. Niobium content has no influence upon breakouts.

Internal cracks due to hot shortness of steel at very high temperatures. Hot shortness of steel in the vicinity of its solidus temperature can be responsible for segregation cracks if strain at the solidification front becomes greater than the fracture strain. For plate grades these defects should be avoided. Therefore any deformation of the CC product should be prevented while solidification is proceeding. This leads to limitations on the length of the liquid pool, the details of which depend on the type of caster.

In Dunkirk, where neither compressive casting (3) nor progressive unbending (5) are used, this second criterion is expressed as a limitation of solidification at the tangent point.

Niobium may have some effect on the hot shortness of steel near the solidus temperature, but its effect is not very clear.

Surface temperature uniformity. Improper secondary cooling can result in cracks either internal or superficial.

a. Surface reheating

Reheating of the surface of the CC product establishes a tensile state of stress at the solidification front. Stress and strain levels increase with the amount of reheating. Brimacombe et al (6) have shown that a surface temperature increase of more than 100 C leads to internal crack formation in CC billets.

IRSID has investigated different situations where reheating can also be detrimental to quality. Plant evidence seemed to show that if reheating takes place just after complete solidification, a centerline crack can form in the presence of a segregated centerline. An elastoplastic stress analysis was performed, which demonstrated that 200 C reheating could indeed open up the segregated centerline and lead to the formation of a so-called "double-slab".

For the case of plate grades it therefore appears to be necessary to set a limitation on surface temperature reheating along the caster. This third criterion applies whether solidification is in progress or is already completed.

Because steel is viscoplastic at these elevated temperatures, it seems preferable to express this metallurgical criterion in terms of a reheating rate. Based on the above-mentioned results, the maximum tolerable reheating rate was chosen to be 100 C/m.

b. Surface cooling

Surface cooling of the CC product establishes a tensile state of stress at the surface, which can sometimes open up previously initiated cracks (7, 8) or create new cracks if the steel has a low ductility at the temperature involved. A limitation of surface cooling to 200 C/m was chosen as the expression of the fourth metallurgical criterion.

Niobium does not seem to have any influence on the occurence of these internal cracks.

Absence of deformation of the shell in the low ductility region. A most common surface defect on CC slabs for plates is the fine transverse crack generally located at the bottom of the oscillation marks. In Dunkirk, when this defect appears, it is concentrated on the inside radius side of the slab. There seems, therefore, to be a strong relationship between this type of crack and the unbending operation on the continuous caster.

This defect has been extensively investigated at IRSID and its formation correlated to the low ductility that many steel qualities exhibit in the vicinity of the $\gamma \rightarrow \alpha$ transformation (9).

Hot ductility is determined using a hot tensile RPI machine (Gleeble machine). The experimental procedure consists of pulling a cylindrical specimen of as-cast material in tension at constant temperature and at a constant and small strain rate ($10^{-3} s^{-1}$) until fracture occurs. The reduction in area is measured and taken as the ductility parameter. Before being tested, the specimens are heated to 1300 C for 15 sec. and then cooled at a rate that follows a typical cooling cycle for a spot on the surface of a CC slab. A hot ductility curve was plotted from experimental data obtained at decreasing testing temperatures: such a curve is given in Figure 2. Steel grades for plates exhibited a trough in their ductility curves in a temperature zone that depends strongly on chemical composition. The minimum ductility is generally attained at a temperature between 700 and 750 C, which corresponds to the $\gamma \rightarrow \alpha$ transformation range. The upper limit of the ductility trough lies between 900 and 1100 C and marks the transition between transgranular fracture and fracture at grain boundaries. Precipitates enhance the brittleness of the austenite grain boundaries.

Aluminum, nitrogen and niobium were found to increase the temperature range of the low ductility trough as shown in Figures 3 and 4. This correlates with the operator's experience that grades containing high concentrations of these elements are more prone to exhibiting transverse cracks.

CHEMICAL COMPOSITION (10^{-3} %)

C	Mn	S	P	Si	N	Al	Nb
162	1390	9	21	325	6	55	26

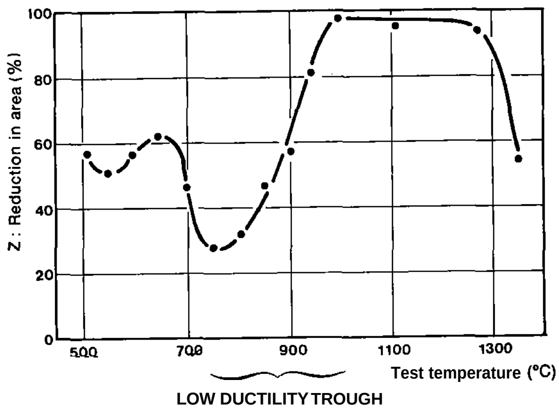

Figure 2. Hot ductility curve for an AFNOR 18 M 5 (AISI 1518) steel.

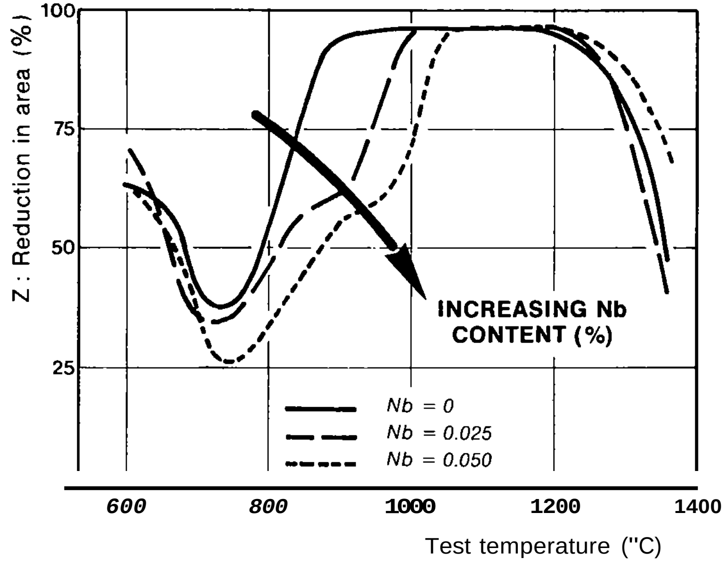

Figure 3. Influence of niobium on hot dutility (AFNOR 18 M 5 grade - AISI 1518).

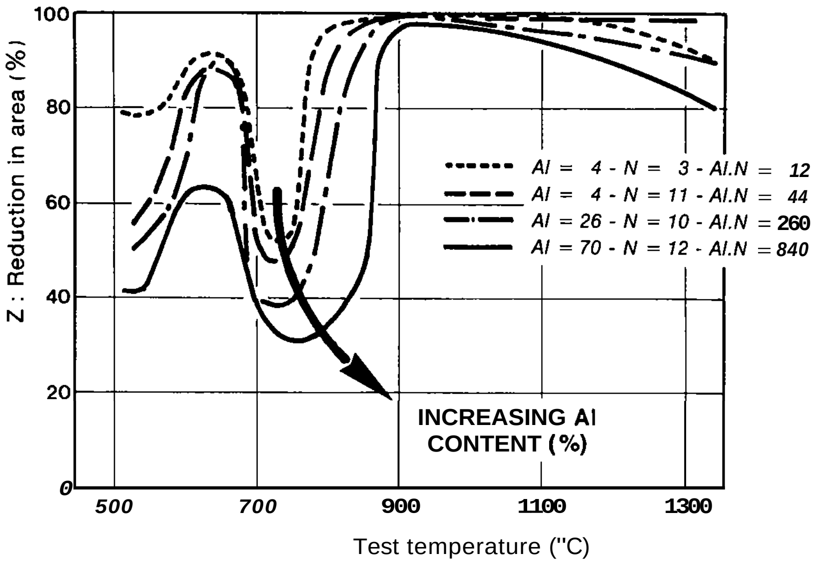

Figure 4. Influence of aluminum and nitrogen on hot ductility (AFNOR 18 M 5 grade - AISI 1518).

Based on these results, three different kinds of cooling strategies have been proposed in the literature:

Sugitani (10) states that transverse cracks are formed in the secondary cooling region and are caused by the temperature fluctuations experienced by the slab surface. He, therefore, proposes the use of low flow rates and very homogeneous cooling. Such a strategy generally leads to a high surface temperature at the unbending point.

Schmidt and Josefson (11) propose to heat treat the slab in such a way that a finer (and hence less brittle) austenite grain is produced in a sub surface layer. This is done by strongly cooling the slab so that the austenite is transformed in this layer and reheating is then allowed to take place. Such a procedure necessitates very high cooling water flowrates, and rather low casting speeds.

Bernard (12) and Kadomani (13) propose the adjustment of the cooling in such a way that unbending takes place at a surface temperature which lies outside the crack sensitive region of the low ductility trough. Depending on whether unbending takes place above or below this zone, so-called "high-temperature" or "low-temperature" strategies are used.

In the cooling strategy used at Usinor-Dunkirk, the latter philosophy was put into operation.

Limitation of slab bulging. Over most of the continuous casting line, the metal consists of a liquid core and a solidified skin. The skin is subjected to:

- ferrostatic pressure directed outwards;
- the guide-roll pressure.

The distance between two consecutive rolls may be sufficient for the slab to become deformed under the effect of internal pressure, this deformation being known as "bulging" (Figure 5).

Throughout the length of the machine, the solidified section undergoes a series of bulges followed by rerolling.

The alternate tensile and compressive stresses thereby set up may cause small cracks to appear on the solidification front (Figure 6). These cracks become filled with segregated metal and are likely to cause internal defects in the form of cracks perpendicular to the surfaces of the slab.

Sensitivity to cracking depends on both the mechanical properties of the solidified skin, the rate of secondary cooling, the gap between guide rolls and the ferrostatic pressure, or in other words, on all the parameters affecting slab bulging. Bulging also leads to centerline segregation. Depending on the roll spacing at the bottom of the solidification pool, the interdendritic liquid may be drawn into or driven from the core region, which then forms a positively or negatively segregated area.

To quantify the influence of casting parameters (casting conditions, machine configuration) on bulging, we have designed a mathematical model of slab skin deformation.

This model was compared with:

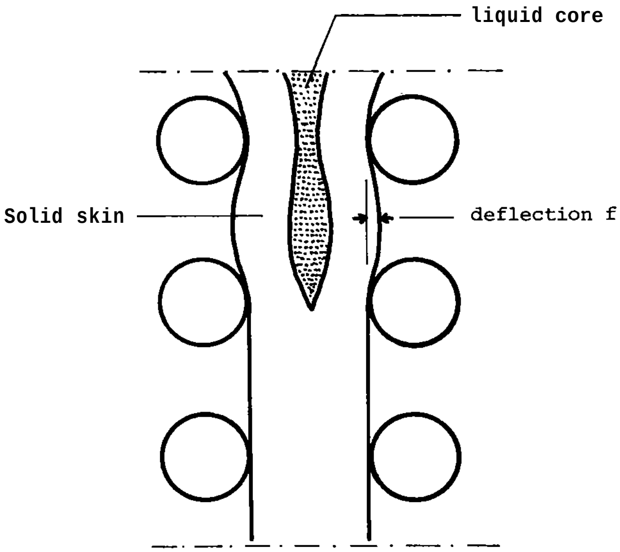

Figure 5. Schematic diagram of bulging.

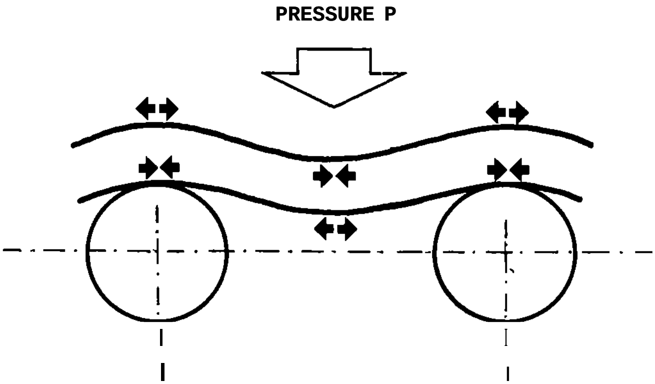

Figure 6. Distribution of stresses due to bulging.

- a plasticine simulation model;
- an industrial continuous slab casting machine.

a. Mathematical modelling of bulging

Mathematical modelling is based on the hypothesis of visco-plastic behavior of the hot steel, which is confirmed by high-temperature tensile tests (at 800–1200 C) carried out at IRSID.

The calculations are made in two stages:

1. Static

   a. The solidified skin of the slab is likened to a beam restrained at both ends.

   b. The ferrostatic pressure acts as a load uniformly distributed over the surface of the slab.

   c. The steel's properties are isotropic.

   d. Temperature variations in the steel thickness are linear.

The law of state of steel can be written:

$$\sigma = K \varepsilon^{n} \dot{\varepsilon}^{m}$$

where n is the strain hardening exponent
m is the viscosity exponent

The mean-fibre elastic line is calculated, together with maximum deflection.

2. Dynamic

   a. The beam moves on its supports at speed V. Into the static calculation is introduced the relation between the derivatives of the bending relative to time and space:

$$\frac{dc}{dt} = V \frac{dc}{dx}$$

The calculations were performed for a continuous slab casting machine at Usinor Dunkirk, with the following characteristics:

- radius of curvature: 12 m
- roll spacing : 220 to 540 mm
- casting speed : 0.8 m/min.
- slab size
  .thickness : 250 mm
  .width : 1200 mm

The solidified thickness and skin temperature were determined from models existing at IRSID.

The influence of the following parameters on slab deformation were studied:

1. The material's behavior law

Figures 7 and 8 show the results of static and dynamic calculations of deflection for three laws of visco-plastic behavior of hot steel.

Calculations by the static model give a deflection 2 to 4 times greater than the dynamic calculations.

From these figures, it can be seen that niobium reduces bulging. This is due to the fact that it increases the flow stress of steel at elevated temperatures.

2. The cooling profile

As we have seen, two strategies for secondary cooling are possible: a high temperature one and a low temperature one. In order to know if these two strategies lead to different bulging behavior, a comparison was made between bulging tendancies throughout the length of the machine for two different cooling profiles:

- hot profile : surface temperature = 1050 C
- cold profile : surface temperature = 680 C

The results are shown in Figure 9.

b. Measurements of slab bulging

The results obtained by mathematical modelling of bulging were compared with our experience:

- on a model in which the simulation material is plasticine.
- on an actual continuous castinp machine, by means of a measuring device specially designed for the purpose.

In the two cases, the agreement between the predictions of the model and the bulging measurements is excellent *(14).*

The fifth metallurgical criterion requires that bulging should be limited to a maximum value. Using the model mentioned above, this criterion can be expressed as a limitation on the surface temperature, indexed to steel grade, the casting speed and the roll gap.

As we have seen, niobium is beneficial in decreasing bulging.

Heat Transfer Efficiency of the Secondary Cooling

Mechanisms of heat transfer between the slab and its environment comprise:

1. convection between slab and spray water or atmosphere,
2. conduction between slab and support roll, and
3. radiation from the slab onto the secondary cooling chamber.

The operator can directly control only the spray cooling.

Previous work by IRSID and USINOR (15) has introduced and justified the concept of an overall heat transfer coefficient per zone of secondary cooling.

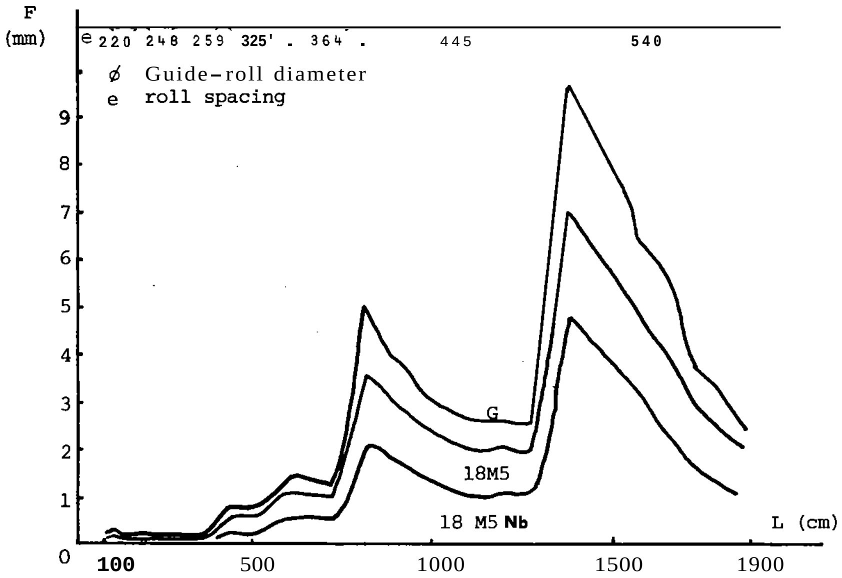

Figure 7. Changes in slab bulging throughout the length of the machine machine (static model) - Influence of the stress-strain law.

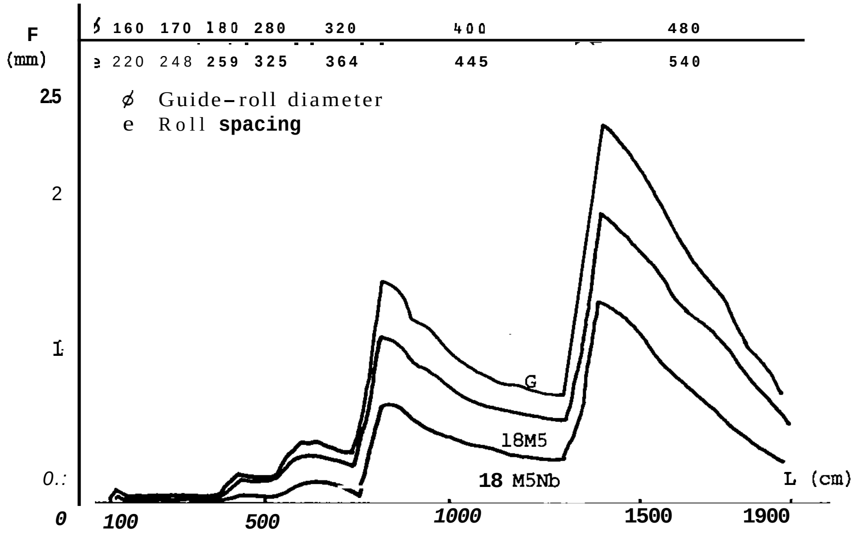

Figure 8. Changes in slab bulging throughout the length of the machine (dynamic model) - Influence of the stress-strain law.

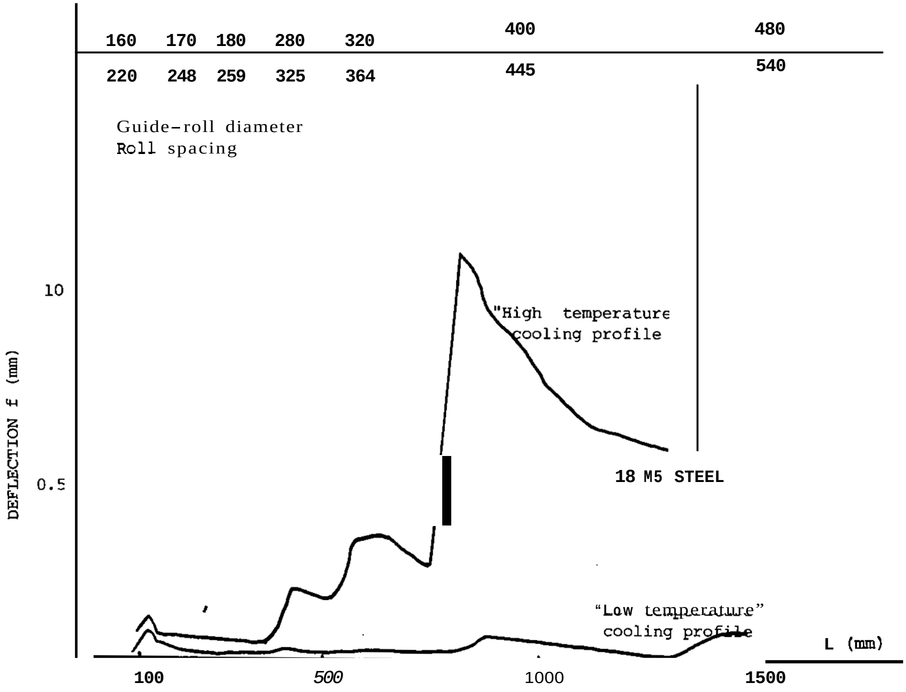

Figure 9. Influence of the cooling profile on slab bulging (dynamic model).

Additional determinations of this overall heat transfer coefficient had to be carried out in order to assess the specific behavior of No. 12 slab caster in Dunkirk. Measurements of slab surface temperatures were carried out at the exit of each secondary cooling zone, using either two color pyrometers (above 900 C). These experimental values were plugged into a heat transfer simulation model (15) from which the overall heat transfer coefficients per zone were calculated. The results are presented in Figure 10.

The main conclusion is that the overall heat transfer coefficient per zone, h, is not only a function of the specific water flowrate, but also of the slab surface temperature, if the latter is lower than 800 C. The parameter, h, then increases with decreasing slab temperature.

Additional conditions of a technological nature limit the range in which the secondary cooling can be regulated:

The range of low rates that can be used in a given secondary cooling zone is bounded, the ratio of upper to lower bounds being generally less than 3 for commercially available spray systems.

The total water flowrate available for all the secondary cooling zones is also limited by the hydraulic characteristics of the circuits (usually the pumps themselves).

Optimization of the Cooling Strategy on No. 12 Slab Caster in Dunkirk

The steps taken to optimize the cooling strategy on No. 12 slab caster in Dunkirk will be presented here. They involve a detailed study of past cooling strategies on that caster and the implementation of new and better cooling schemes. Both their heat transfer and metallurgical impact will be reviewed.

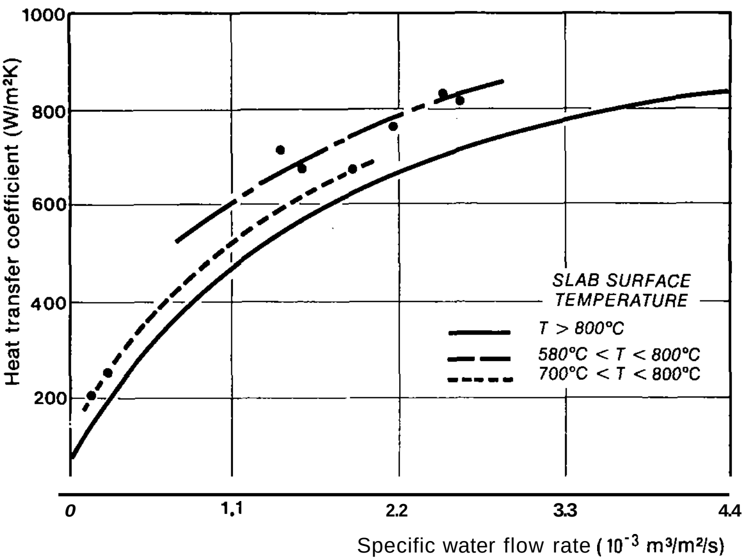

Figure 10. Heat transfer coefficient in the secondary cooling region. Measurements carried out on a slab caster.

The slabs cast on No. 12 caster have widths of 210, 250 and 300 mm. There are nine cooling zones along each strand as shown in Figure 11. Zones 1, 3, 4 and 9 spray both the inside and outside faces of the slab, whereas zone 2 only sprays the edge faces.

Study of the initial cooling strategy

The initial cooling strategy implemented on No. 12 slab caster for plate grades consisted of using a constant cooling intensity of 0.5 l/Kg independent of casting speed.

Results from the simulation of this cooling strategy are shown in Figure *12* for the case of 250 mm thick slab. It is clear that at all casting speeds, a number of cooling criteria are properly followed : the surface temperature of the slab remains below 1100 C, and its profile does not exhibit any prohibitive reheating or cooling. However, as soon as the casting speed becomes greater than 0.8 m/min, the liquid pool extends beyond the unbending point. On the other hand, below 0.5 m/min., the surface temperature of the slab at this point falls below 900 C.

In order to increase the surface temperature at the tangent point, one slightly different cooling strategy has been simulated and implemented for trials on the caster. In this case, cooling was cut off in zone 8 and 9.

Results are plotted in Figure 13, where the variations of pool length and surface temperature at the tangent point are shown as a function of casting speed for 250 mm thick slabs and the two cooling strategies mentioned above. The modified cooling strategy made it possible to increase the unbending temperature by about 20 C.

Metallurgical results are shown in Figure 14 where a crack index, proportional to the number of surface transverse cracks per unit area of the slab surface, is plotted against unbending temperature, and against aluminum and nitrogen contents (16). These results confirm the remarks made in part 2 of this chapter.

Both types of results show the limitations of a "high temperature" cooling strategy for the continuous casting of plate grades. In order to meet the metallurgical requirements expressed by the cooling criteria, the casting speed must be chosen within a narrow range, the scope of which decreases when the grade has a wider ductility trough. In some special cases, it is not even possible to find an acceptable speed or, in other words, it is not possible to avoid, in this way, the formation of transverse cracks.

Study of a "low temperature" cooling strategy

A "low temperature" cooling strategy offers definite advantages over a "high temperature" strategy. Indeed, since the lower limit of the crack sensitive region of the low ductility trough is almost independent of the grade of steel, the admissible casting speed can be chosen regardles of steel quality. In the same manner, when the casting speed decreases, it is easier to modify the secondary cooling in order to maintain a constant surface temperature at the unbending point. Moreover, a "low temperature" strategy makes it possible to attain a higher productivity on the caster than a "high temperature" strategy.

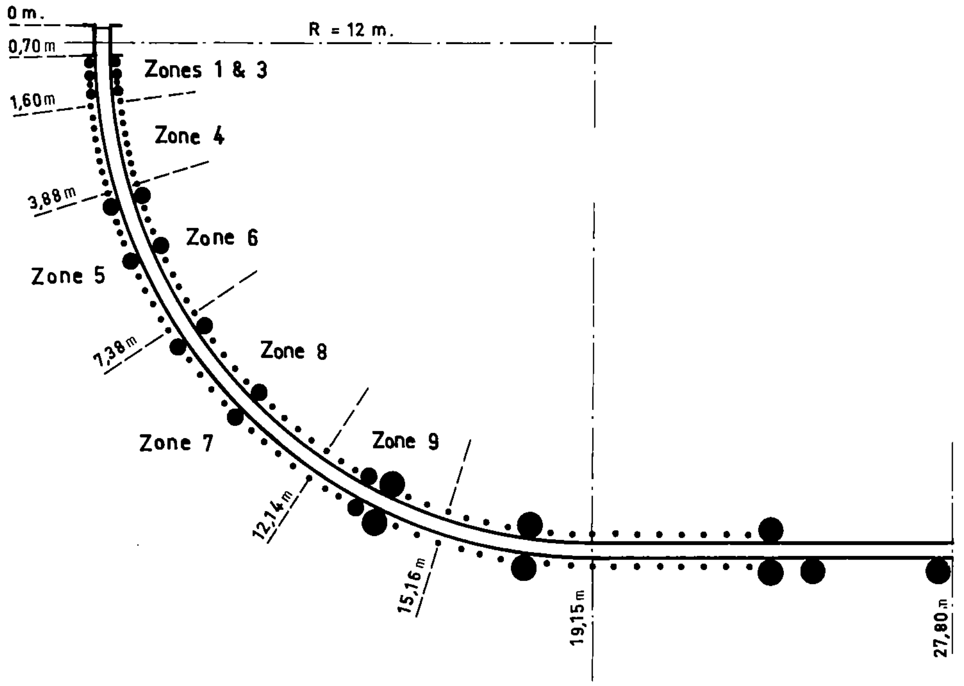

Figure 1 No. 12 slab caster in USINOR Dunkirk Position of secondary cooling zones.

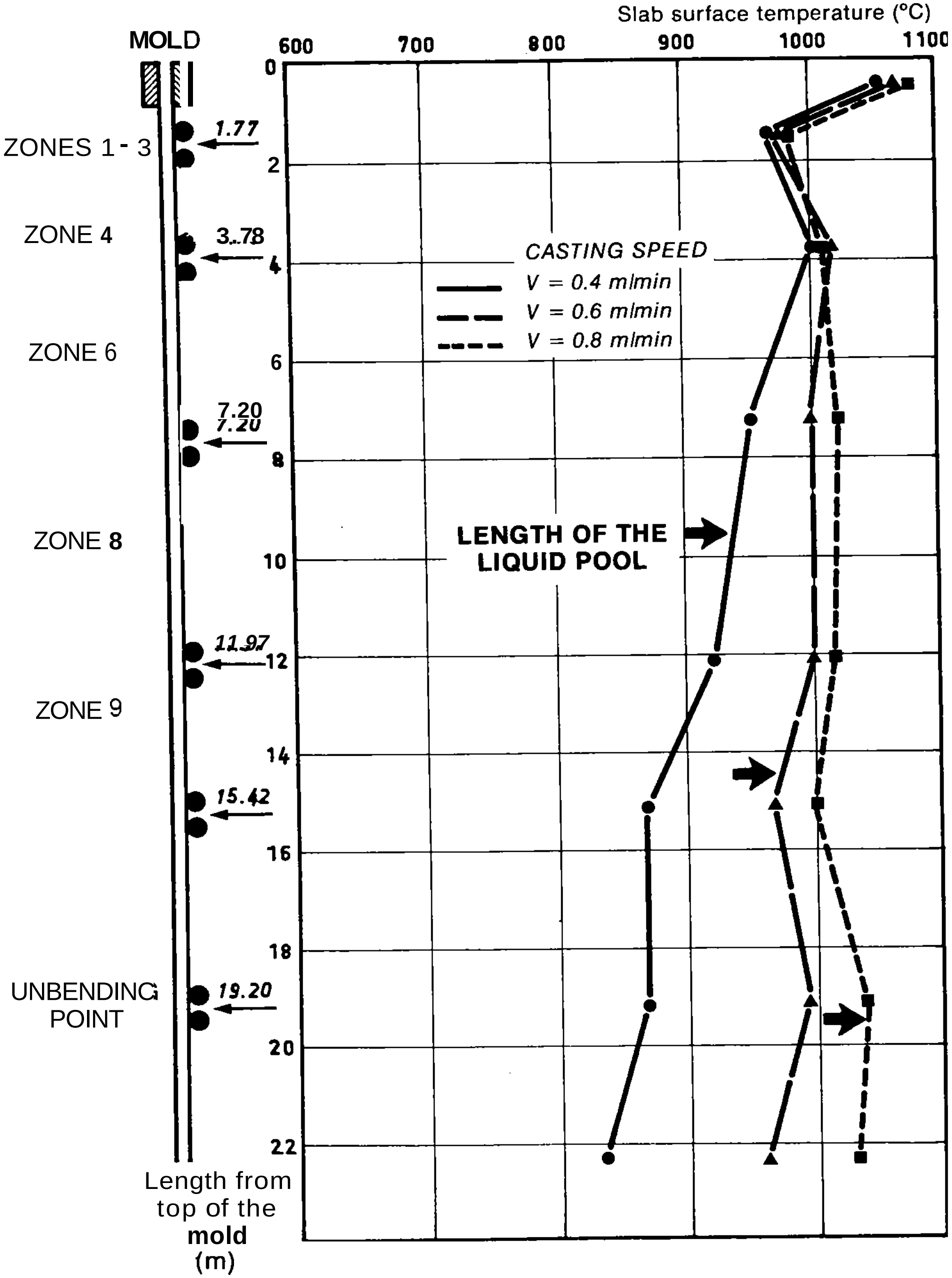

Figure 12. Temperature profiles on USINOR'S slab caster. High temperature solution No. 1 (Slab thickness : 25 mm)

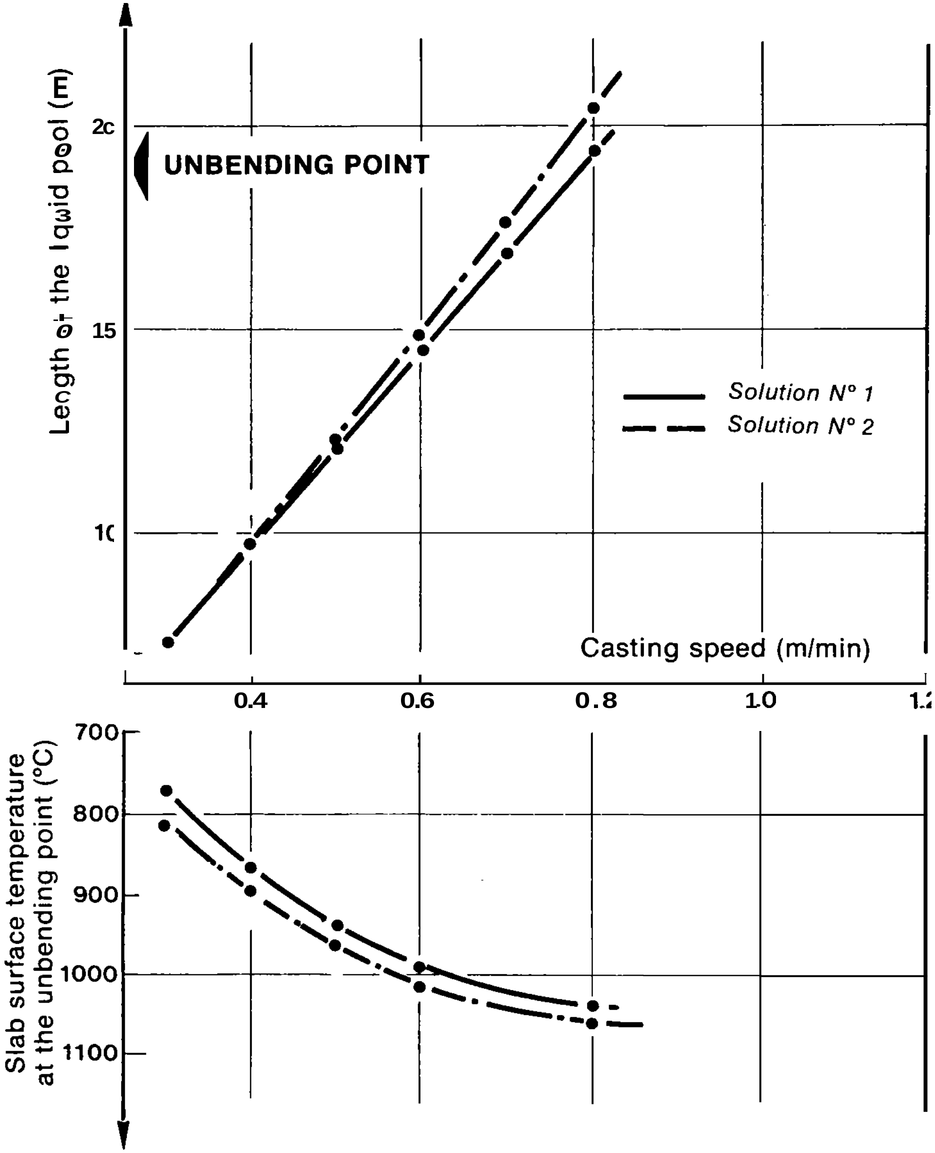

Figure 13. Correlation between pool depth and surface temperature at the unbending point (High temperature solutions).

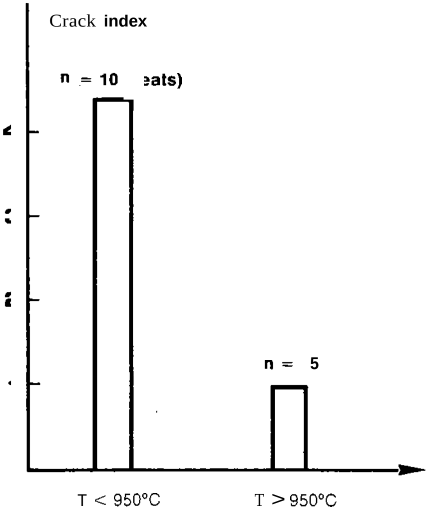

Figure 14(a). Influence of unbending temperature.

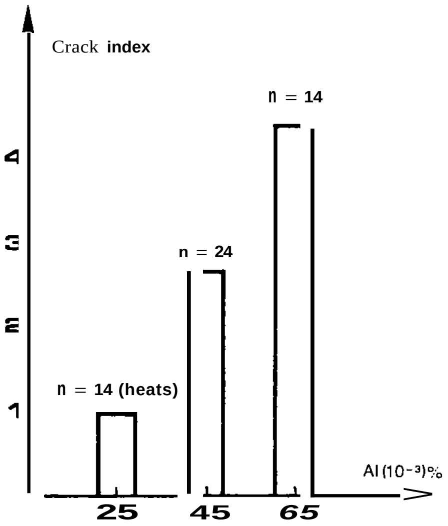

Figure 14(b). Influence of Al content.

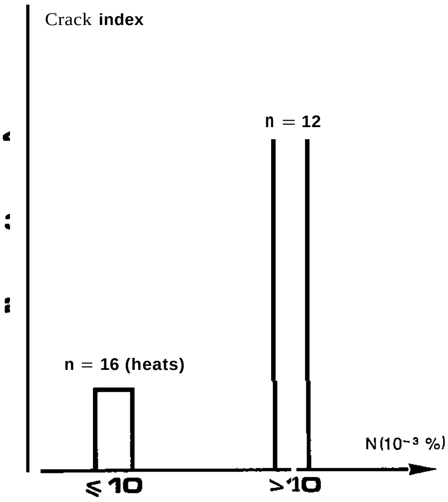

Figure 14(c). Influence on N content.

Figure 14. Results of transverse crack observations on slabs.

A "low temperature" strategy was tentatively developed for No. 12 slab caster, using the heat transfer simulation model. However, due to the low water flowrates available on the machine, low casting speeds had to be proposed : 0.5 m/min for 210 m thick slabs and 0.4 m/min for 250 m slabs. Corresponding temperature profiles are shown in Figure 15. Clearly, such a strategy meets all the metallurgical criteria, and particularly, at the bottom of the liquid pool, the risks of bulging are minimized.

Such a strategy was implemented on a trial basis on No. 12 slab caster. The steel grade had the following composition (in weight percents):

C = 0.135	S = 0.003	P = 0.017	Si = 0.287
Mn = 0.931	Al = 0.050	Nb = 0.040	

Conclusions

Niobium microalloying is now accomplished without any difficulties. Problems may arise when the steelmaking procedure used increases the nitrogen content. Thus, steelmaking and continuous casting must be carefully controlled.

A general method has been described for choosing a casting and coling strategy for use on a continuous caster dedicated to the production of slabs for plates, most of them having niobium additions. The method is based on a metallurgical analysis of defects and their causes, and on an experimental heat transfer study of the efficiency of secondary cooling.

When applied to the No. 12 slab caster in Dunkirk's plant of USINOR, this method has allowed an assessment of the advantages and disadvantages of two methods of cooling.

1. The "high temperature" strategy is limited by the impossibility of preventing the formation of transverse cracks on certain high nitrogen grades, the low ductility trough of which extends up to about 1050 C in the presence of aluminum and niobium.

2. The "low temperature" strategy is a worthwhile method for avoiding transverse cracks. However, this strategy needs a long secondary cooling zone in the caster, if loss of productivity is to be avoided.

The method presented here is very general and can be applied to any quality grade or shape. This steel exhibits a crack sensitive temperature range of 740 to 1030 C. "Low temperature" slabs were compared to "high temperature" slabs cast at the same time on the other strand. Whereas the reference slabs had numerous transverse cracks, the low temperature slabs were almost completely devoid of cracks. It was also confirmed metallographically that no cracks were present below the surface of the slab.

During one of the trial casts, the surface temperature at the tangent point was allowed to increase, by letting the casting speed increase. The temperature change as a function of temperature is shown in Figure 16 along with change in quality, of the corresponding slabs. It can be seen that a temperature change from 710 to 760 C is sufficient to cause numerous transverse cracks to appear; indeed all the slabs cast above 0.6 m/min had to be scrapped because of severe cracks.

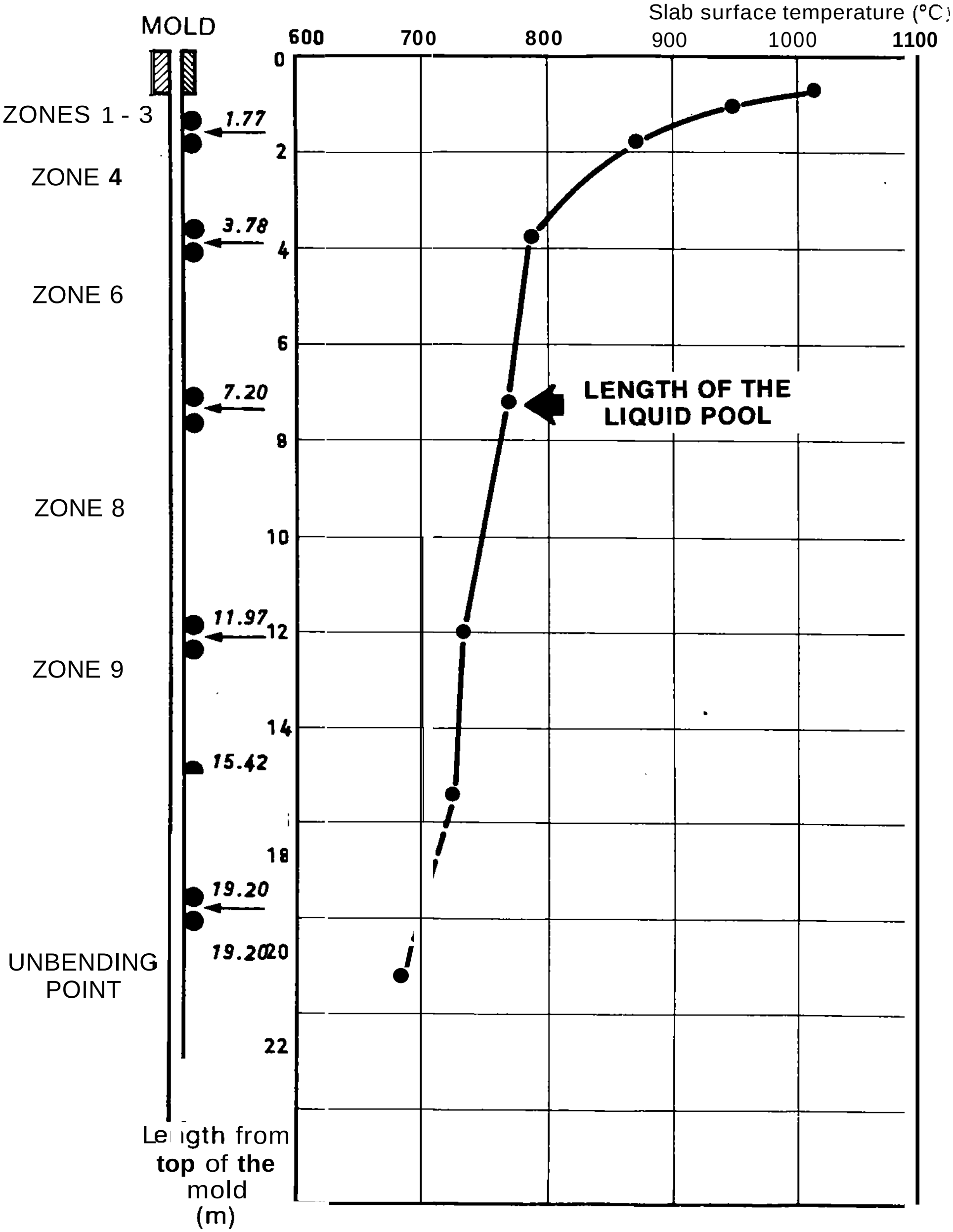

Figure 15. Temperature profiles on USINOR'S slab caster. Low temperature solution No. 1 (Slab thickness : 250 mm, Casting speed : 0;4 m/min).

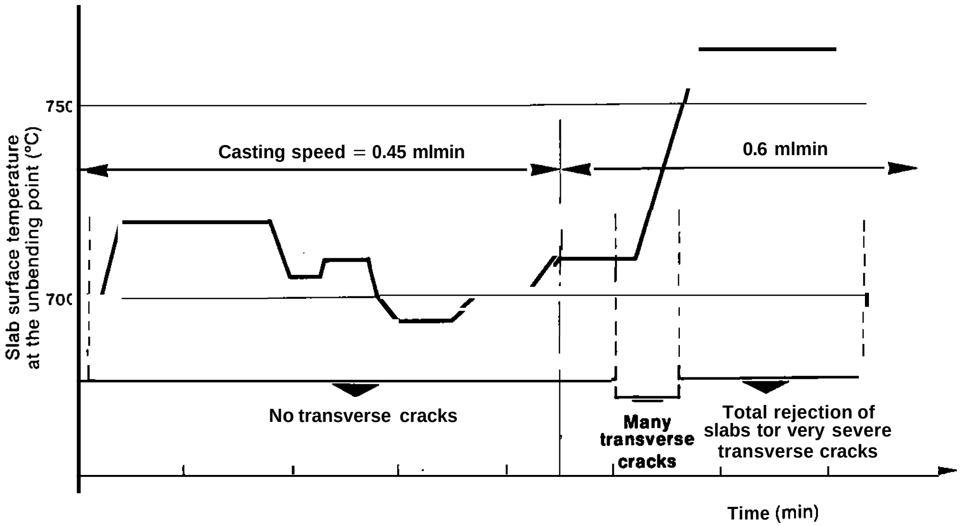

Figure 16. **Results of transverse crack observations on slabs. Influence of unbending temperature. (Low temperature solution no. 1).**

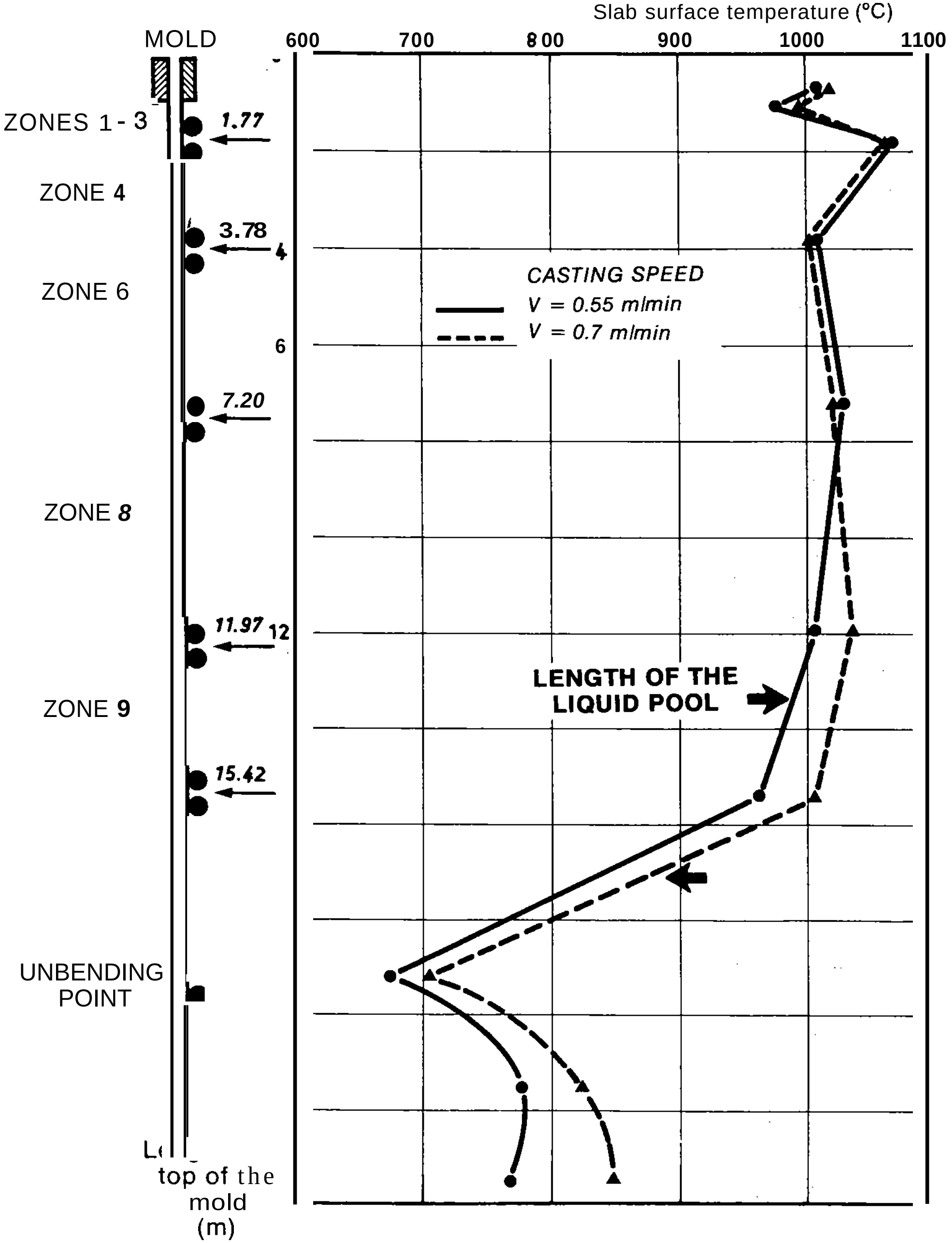

Figure 17. Temperature profiles on USINOR'S slab caster. Low temperature solution No. 2. (Slab thickness : 250 mm).

These trials have thus demonstrated that a "low temperature" strategy makes it possible to cast crack-free slabs, and that this can be obtained by aiming at an unbending temperature lying a few tens of degrees below the temperature of the minimum ductility point for that particular steel grade.

Obviously it was not possible to use the "low temperature" strategy on an industrial basis, since caster productivity would have been too low. Modifications of the secondary cooling geometry were therefore studied to obtain a low temperature at the tangent point and maintain casting speed.

The proposed solution is shown in Figure 17 for 250 mm thick slabs. It is thus possible to cast at 0.7 m/min (0.95 m/min for 210 mm thick slabs). It can be seen that an extra cooling zone has been added at the bottom of the machine, the purpose of which is to bring the surface temperature of the slab down to about 700 C. All the metallurgical criteria are thus successfully met.

References

1. J. LeClerc, W. Pollak, International Congress on Continuous Casting, Biarritz (France), 1976.

2. M. David, M. Jeanneau, M. Poupon, D. Senaneuch, The ladle treatment of steel by the injection of Si-Ca. Industrial practice - Congress SCANNINJECT II, 12-13 June 1980, Lulea, Sweden.

3. T. Inouye, H. Tanaka, NSC Technical Report no. 13, June 1979, 1-23.

4. J. P. Birat, J. Foussal, M. Larrecq, C. Saguez, M. Wanin, Solidification and technology in the foundry and casthouse Warwick (U.K.), 1980.

5. H. Nashiwa, K. Yoshida, A. Mori, H. Tomono, K. Tada, Sumitomo Metals, Vol. 32, no. 1, January 1980, 15-23.

6. G. Van Drunen, J. K. Brimacombe, F. Weinberp, Ironmaking & Steelmaking (Quarterly), 1975, no. 2, 125-133.

7. Tinozaki, J. Matsuno, K. Murata, H. 001, M. Kodama Trans. ISIJ, Vol. 18, 1978, 330-338.

8. W. R. Irving, A. Perkins, International Congress on Continuous Casting, Biarritz (France), 1976.

9. G. Bernard, J. P. Birat, B. Conseil, J. C. Humbert, Revue de Metallurgie Juillet 1978, 75, no. 7, 467-480.

10. Y. Sugitani, Tetsu to Hagane, March 1974, Vol. 60, no. 4, 540.

11. L. Schmidt, A. Josefsson, Scandinavian Jour. of Metal., 3, 1974, 193-199.

12. G. Bernard, CIT, Revue de Metallurgie, April 1980, no. 4, 307-318.

13. E. Kadomani, J. Yamagami, Y. Settai, Tetsu to Hagane, 1975, Vol. 61, no. 2, A13-A16.

14. M. Larrecq, Z. Smarzynski, G. Tourscher, Bulging of continuous cast slabs. Modelling and measurement - IRSID. Report MIE. 81. N. 288, April, 1981.

15. R. Alberny, A. Perroy, D. Amory, M. Lahousse, Revue de Metallurgie, June 1978, 6, 53-362.

16. D. Amory, M. Jeanneau, M. Poupon, D. Senaneuch, Mannesmann Conference, October 1980.