Optimisation of narrow face water slot design for Siderar slab casting mould

B. G. Thomas, M. Langeneckert, L. Castellá, M. Dziuba, G. Di Gresia and W. Balante

A study of a mould narrow plate was carried out at Instituto Argentino de Siderurgia (IAS), to assess the plate condition after its life, in this case 2227 heats. A finite element model of steady heat conduction in the mould narrow face was developed, using ANSYS software, with eight node rectangular elements. Attention was focused on the hot face temperature distribution, including the corner temperature and the difference between the maximum and minimum temperatures across the hot face. Temperature distribution in the narrow face of the Siderar slab casting mould was calculated, and alternatives to optimise the water slot design by altering the geometry to minimise both corner temperature and temperature variation across the hot face were analysed. According to the results, the existing narrow face design does not produce excessive temperatures anywhere in the mould. However, a gradient exists across the hot face. In addition, an accurate equation was developed to predict corner temperature as a function of hot face heat flux and water slot geometry. Several other water slot geometry redesigns were investigated, which further improved potential hot face temperature uniformity at the expense of increasing complexity of the water slot design. The predictions of the model are in agreement with observations made in a previous post-mortem study carried out at IAS on a narrow plate. I&S/1664

Dr Thomas and Dr Langeneckert are at the University of Illinois, USA, Dr Castellá and Dr Dziuba (dziuba@siderurgia.org.ar) are at the Instituto Argentino de Siderurgia, Carlos Maria Della Paolera 226, C1001 ADB, Buenos Aires, Argentina and Dr Di Gresia and Dr Balante are with Siderar S.A.I.C., Argentina. Manuscript received 5 December 2001; accepted 19 September 2002.

INTRODUCTION

Problems of breakouts owing to the infiltration[1] of steel into the corners between the mould plates arose after the casting speed was increased of the Siderar continuous caster (Table 1). To determine the causes of these problems, the investigations carried out included the study of a used plate and an analysis of the continuous casting mould narrow plate by means of a finite element model (Fig. 1). The purpose of the work was to study whether too high a temperature in the narrow plate could be generating a distortion of the mould corner below the meniscus, and, if so, to evaluate an alternative design for the narrow plate. The result is a tool capable of predicting the temperatures of the hot face of the plate.

Table 1 Main characteristics of Siderar caster

Machine type	Concast, two strands
Builder	Schloemann-Siemag AG (1984)
Type	Bow
Radius	10 400/20 000 mm
Width range	750–1650 mm
Thickness	180/200 mm (165/250 mm)
Mould	Curved, 900 mm Length
Strand guide	Grid Y rolls
Dummy bar system	Bottom insertion
Annual capacity	2 200 000 t

STUDY OF USED PLATE

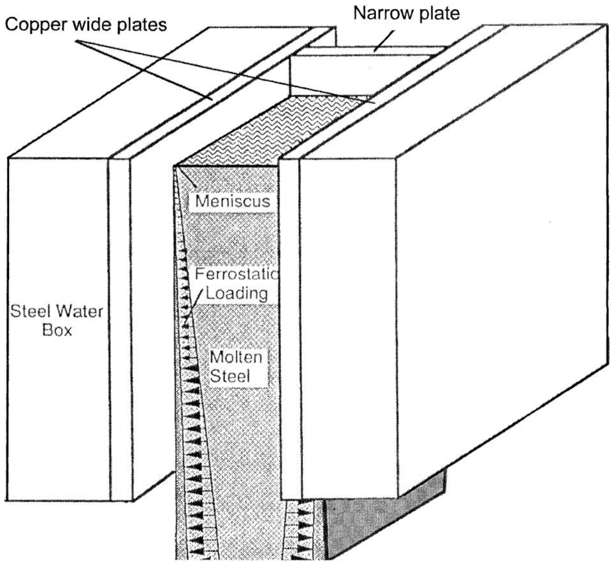
The plate (Fig. 2) was of dimensions 200 × 900 × 45 mm, with a nickel coating of depth 3 mm all over the surface and 1 mm at the edges, and the (copper) plate material was Se–Cu–Ag (0·08–0·13%Ag). The mould of the caster is curved.

The plate was cut into several pieces, and hardness measurements and other studies were carried out. Figure 3 shows the longitudinal hardness profile, and Fig. 4 shows the hardness of a section of the plate in the meniscus area. In Fig. 4 is possible to see that the hardness of the copper was lower near the hot face than in the rest of the plate, where it remained almost constant.

FINITE ELEMENT MODEL

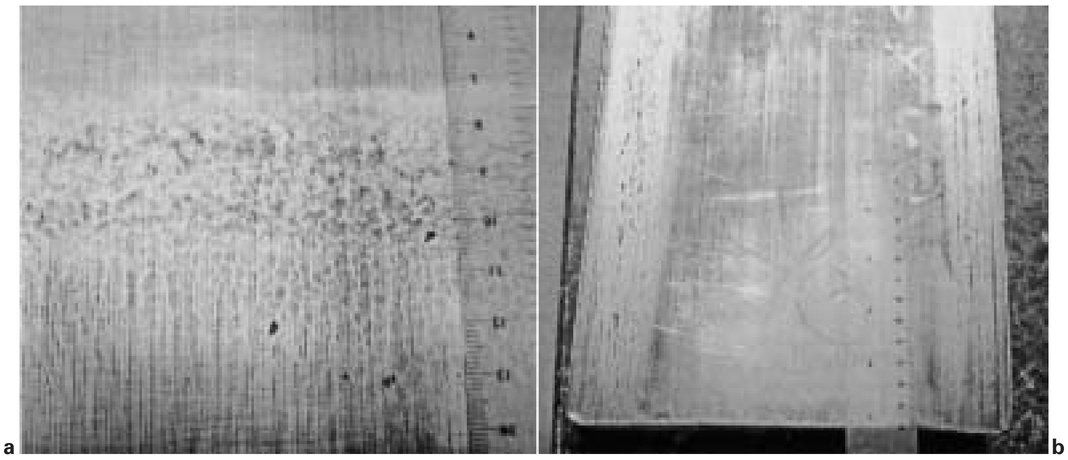
Eight different cases were modelled using ANSYS software,[2] including the original mould design (both opposite from a bolthole and between boltholes) and six redesigns, based on variations from the original by changing the water slots.

As the meniscus level remains below the end of the water slot curvature, 100 mm below the mould top, the curvature at the top of the slot need not be modelled, so only two-dimensional analyses were necessary to investigate the relative effects of different slot geometries.



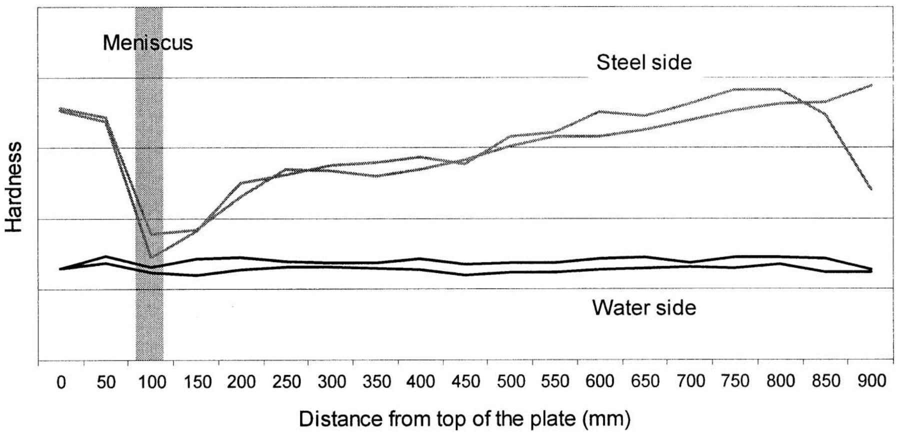
1 Location of copper narrow plate in mould

DOI 10.1179/030192303225009579



a in meniscus area; *b* lower part

2 Given aspects of plate



3 Longitudinal hardness profile of narrow plate on steel side (nickel coated) and water side (uncoated copper)

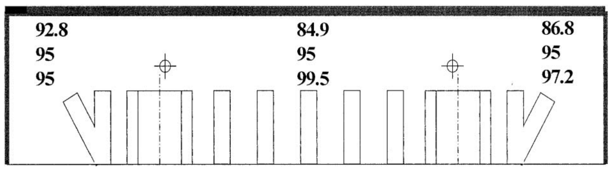
In developing the models, symmetry was assumed, and the hot face heat flux was taken to be a constant, chosen to represent the maximum encountered at the meniscus for the highest casting speed expected. All surfaces were insulated except for the hot face (where a fixed heat flux was imposed) and the water slot surfaces (where a convective boundary condition was specified). The effect of the nickel coating layer is small and was neglected. Other modelling conditions are given in Table 2.

Results

The calculated temperatures for the original mould geometry (two cases) and six different redesigns are shown in Figs. 5 and 6, and are summarised and compared in Table 3.

Original design

Analysis of the original narrow face mould design reveals that the maximum temperature is found at the corner, where the narrow face hot face contacts the wide face (Table 3 and Fig. 5*a*). This location is of critical importance, because it must transmit all of the clamping force load from the wide faces.[3] Breakouts owing to steel infiltration into a corner gap are possible (especially during mould filling) if this corner becomes crushed as a result of high temperature creep. This is exacerbated by scraping against any powder buildup on the wide faces, which is compounded by many width changes.

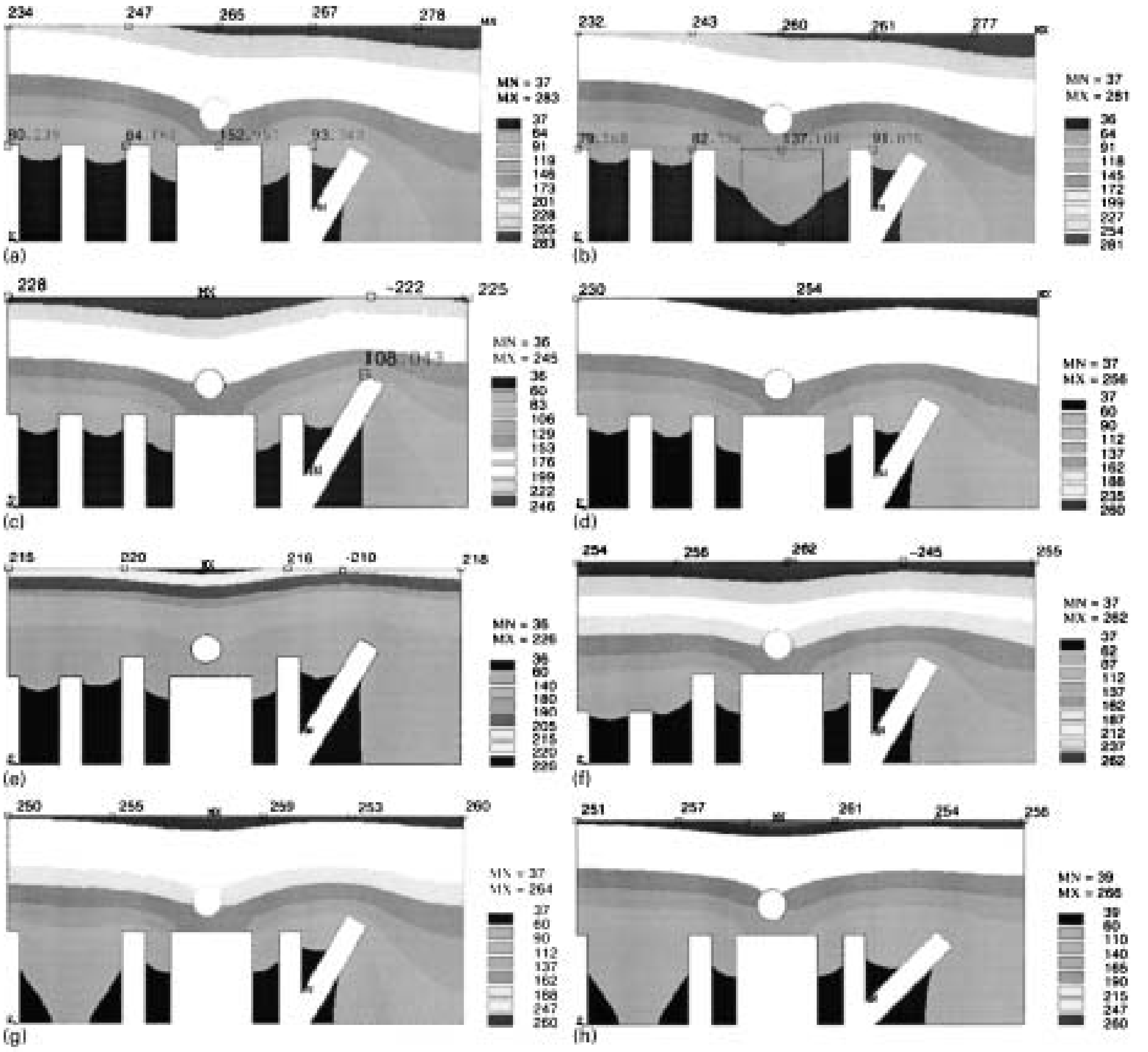


4 Hardness values, HB (2·5/62·5) at given locations on transverse section of used narrow plate: 115 mm below top

For the assumed typical conditions, this corner temperature is 283°C. This does not appear to be excessive, relative to the higher operating temperatures experienced in thin slab moulds. However, calculations show that the angled water slot is not sufficient to compensate for the great distance of the corner from the cooling water. Thus, for the assumed conditions, the hot face corner is 49 K hotter than the centre of the narrow face hot face, and a consistent gradient exists across the hot face.

Table 2 Standard conditions: narrow face mould copper plate analysis

Mould width × thickness	206 mm × 45 mm
Distance from hot face to water slot root d_m	25 mm
Water slot depth d_{ch}	20 mm
Water slot thickness w_{ch}	5 mm
Slot spacing (typical central slots) L_{ch}	13·5 mm (centre to centre)
Hot face heat flux q	2·0 W mm^{-2}
Water slot heat transfer coefficient h_w	0·045 W mm^{-2} K^{-1}
Copper thermal conductivity k_m	0·350 W mm^{-1} K^{-1}
Steel thermal conductivity	0·05 W mm^{-1} K^{-1} (original geometry case 2 only)
Water temperature T_w	35°C



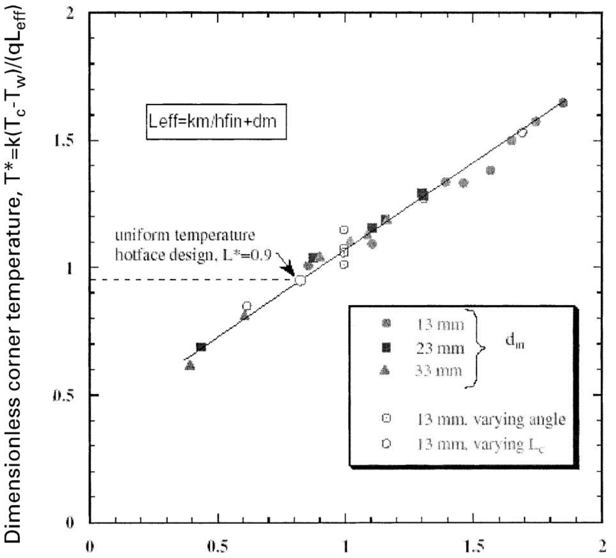
a original geometry 1, insulated bolthole, edge and back, standard fine mesh, element size ~1 mm; *b* original geometry 2, effect of perfectly fitting steel bolt, element size ~1 mm; *c* redesign 1, deepened angled slot from 20 to 30·4 mm to cool down corner, angled slot length calculated from corner temperature equation; *d* redesign 1A, conservative, minimal change from original design, increased length of angled slot from 20 to 25 mm; *e* redesign 2, based on redesign 1 with deepened slots adjacent to bolt from 20 to 24·6 mm, standard coarse mesh, element size ~1–3 mm; *f* redesign 3, based on redesign 1A, three centre slots shallower, reduced from 20 to 12 mm; *g* redesign 4, based on redesign 1A, removed two slots adjacent to centre slot; *h* redesign 5, based on redesign 4 with 45° angled slot

5 Calculated temperatures for given mould geometries

The temperature in a horizontal section through the mould varies slightly, depending on whether the section is taken through a bolthole or through the solid copper, and whether there is a gap between the bolt and the slot root.[4] The critical meniscus region is found between boltholes (located 42 mm and 150 mm from the mould top), so is close to original case 2 (Fig. 5*b*). The bolthole affects the temperature distribution slightly, as the bolt itself can remove a small amount of extra heat if there is no gap, lowering the local temperature. The maximum effect on

Table 3 Hot face temperatures calculated using finite element model for different slot geometries

	Originals		Redesigns					
	1	2	1	1A	2	3	4	5
Slot depths, mm								
Two angled slot	20	20	30·4	25	30·4	25	24·5	24·5
Two slots adjacent to bolt	20	20	20	20	24·6	20	20	20
Two slots adjacent to centre	20	20	20	20	20	12	0	0
Centre slot	20	20	20	20	20	12	20	20
Angled slot angle, deg	30	30	30	30	30	30	30	45
Hot face tempratures, °C								
Corner	283	281	225	256	218	255	260	256
Min. between corner and bolt	...	...	222	...	210	245	...	...
Across from bolthole	265	260	245	254	226	262	264	266
Centre	234	232	228	230	215	254	250	251
Max. −min, K	49	49	23	26	16	17	14	15



6 Normalised two-dimensional finite element corner temperatures plotted for various thickness moulds and end slot designs as function of dimensionless length: L_{eff} effective length, k_m mould conductivity, h_{fin} heat transfer coefficient at cold face, d_m distance from water slot to hot face, L_c distance from root of angled water slot to corner, T_c corner temperature, T_w water temperature, q hot face heat flux

the hot face temperature is calculated to be only 2 K. The greatest effect of the bolt is to change the temperature at the thermocouple location, from 137 to 152°C. These effects are of no consequence, unless it is desired to use the thermocouples to calculate the hot face heat flux, or other quantitative heat transfer data.

The copper strength will increase if the corner temperature is lowered. Furthermore, hot face heat transfer will become more uniform (possibly leading to improved steel quality) if the mould hot face temperature is uniform. Thus, there is an incentive to explore ways of lowering the corner temperature, thus lowering the extent of temperature differences across the hot face.

Redesigns

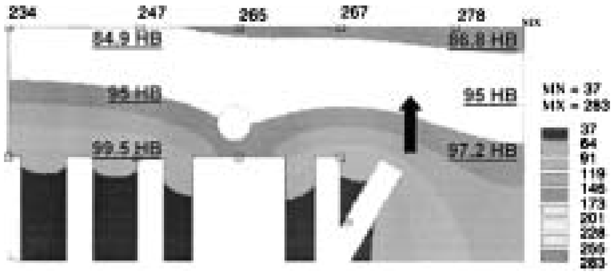
The first redesign is to deepen the angled slot from 20 to 30·4 mm (redesign 1) (Fig. 5*c*).

This choice was made based on an empirical equation derived from an extensive analysis of mould temperature calculations,[5] designed to make the hot face corner temperature equal to the mid-narrow face temperature

$$T_c = q\left(0{\cdot}655\frac{L_c}{d_m} + 0{\cdot}420\right)\left(\frac{1}{h_{fin}} + \frac{d_m}{k_m}\right) + T_w \quad . \; . \; . \; (1)$$

where T_c is the corner temperature (°C), q is the hot face heat flux (W mm^{-2}, assumed uniform), L_c is the distance from the root of the angled water slot to the corner (mm), d_m is the distance from the typical water slot to the hot face (mm), k_m is the mould conductivity (W mm^{-1} K^{-1}), and T_w is the water temperature (°C). The effective heat transfer coefficient at the cold face h_{fin} (W mm^{-2} K^{-1}) is defined based on extended surface theory[5,6] by

$$h_{fin} = \frac{h_w w_{ch}}{L_{ch}} + \frac{[2h_w k_m (L_{ch} - w_{ch})]^{1/2}}{L_{ch}} \times \tanh\left[\frac{2h_w d_{ch}^2}{k_m (L_{ch} - w_{ch})}\right]^{1/2} \quad . \; . \; . \; . \; . \; . \; . \; . \; (2)$$



7 Original geometry 1 (same as in Fig. 1) and hardness values of copper determined in recent study

where h_w is the mould surface–water heat transfer coefficient (W mm^{-2} K^{-1}), w_{ch} is the cooling water channel width (mm), d_{ch} is the cooling water channel depth (mm), L_{ch} is the cooling water channel spacing (mm), and k_m is the mould thermal conductivity (W mm^{-1} K^{-1}).

This relationship was found by a linear fit of the results of ~30 finite element simulations, shown in Fig. 6, and was used to adjust the depth of the angled slot until the corner temperature matched the mid-narrow face temperature. Specifically, decreasing L_c from its value of 36 mm $\boxed{2}$ in the original design to 25 mm is predicted by equations (1) and (2) to lower the corner temperature from 279 to 227°C, based on other values in Table 2. A very close match is produced, as confirmed by the finite element simulation results for these conditions. However, it does not account for the increase in temperature opposite from the bolt or for the orientation of the slot.

A less drastic redesign is to deepen the angled slot to only 25 mm (redesign 1A) (Fig. 5*d*). This produces the same degree of hot face uniformity (maximum variation of 26 *v.* 23 K). This redesign should have no impact on overall mould life, as the slot depth is less than the depth of the thermocouple hole, so does not interfere with machining $\boxed{3}$ tolerances. Redesign 1A should have minimal effect on hot face temperatures, so should not influence steel quality in any way.

The next redesign deepens the slots adjacent to the bolthole, to compensate for the lower heat extraction at this location where slots have a wider spacing (redesign 2). The result is better hot face temperature uniformity (only 16 K difference) at the expense of lower temperatures overall (Fig. 5*e*). Although this should be beneficial for mould life, it will also change the behaviour of the gap and the mould flux. This could affect steel quality in an unknown way (either positive or negative), and would require plant trials to investigate.

The next redesign changes redesign 1A by reducing the depth of the central three water slots from 20 to 12 mm, as shown in Fig. 5*f* (redesign 3). This improves hot face temperature uniformity to about the same as that for redesign 2 (17 K), but at an overall higher hot face temperature.

Redesign 4 is an alternative change to redesign 1A, which achieves improved hot face temperature uniformity, similar to redesign 3, by removing one of the central water slots. This probably has the advantage over redesign 3 of lower stress concentration around the slot roots (Fig. 5*g*).

Redesign 5 is a modification of redesign 4, which increases the angle of the angled slot from 30 to 45°. Its results are similar (Fig. 5*h*).

ANALYSIS

In Fig. 7, a comparison is made between the temperatures predicted by the finite element model and the values of hardness measured in the plate.

The recrystallisation temperature of copper varies considerably with composition, grain size, amount of cold reduction, and time of holding temperature. For example, the first effects of softening in tough pitch copper (99·9%Cu + Ag) with 69% cold reduction are observed at 195–215°C.[7] The arrow in Fig. 7 indicates the isotherm above which copper should become softer. This in fact is observed, so the temperature distribution predicted by the model seems to be consistent with the hardness profile detected on the used plate.

The slightly lower hardness near the corner slots than near the centre slots (95 or 97 *v.* 99/HB) is consistent with the better cooling found there, as predicted by the model. On the other hand, the higher hardness measured near the corners, relative to the narrow face centreline, suggests that the heat flux in the narrow face corners might drop
4 somewhat, thereby leading to lower hot face temperatures than predicted by the model in those locations.

CONCLUSIONS

The existing narrow face design does not produce excessive temperatures anywhere in the mould. The maximum temperature, found at the hot face corner, is 283°C for the conditions studied. However, this corner is $\sim$50 K hotter than the centre, so a gradient exists across the hot face.

An accurate equation has been developed to predict corner temperature as a function of casting conditions (hot face heat flux) and water slot geometry.

Redesign 1A, which deepens the angled slot from 20 to 25 mm, results in lowering the corner temperature to 256°C and improves theoretical hot face uniformity to a variation of only 26 K. If taper is optimal (such that no gaps are formed near the corner and hot face heat flux is relatively uniform), then this redesign should result in slightly improved mould life, less crushing of the corner, and possibly fewer quality problems, such as longitudinal offcorner cracks, owing to the hot face temperature non-uniformities.

Several other water slot geometry redesigns (1–5) have been investigated, which further improve potential hot face temperature uniformity, at the expense of increasing complexity of the water slot design.

The predictions of the model are in agreement with observations made in a previous post-mortem study carried out at Institute Argentino de Siderurgia on a narrow plate.

REFERENCES

1. M. DZIUBA, L. CASTELLÁ, J. MADÍAS, A. CASTELLÁ, G. DI GRESIA, W. BALANTE and J. USART: 'Mould corner infiltration breakouts in CCM of Siderar', 433–440; 2000, Pittsburgh, PA, ISS. 5
2. G. J. DeSALVO and J. A. SWANSON: 'ANSYS user's manual'; 1991, Houston, TX, Swanson Analysis Systems, Inc.
3. B. G. THOMAS, G. LI, A. MOITRA and D. HABING: *Iron Steelmaker*, 1998, **25**, (10), 125–143.
4. M. LANGENECKERT: 'Influence of mould geometry on heat transfer, thermocouple and mould temperatures in the continuous casting of steel slabs', MS thesis, University of Illinois, USA, 2001.
5. B. G. THOMAS, B. HO and G. LI: Proc. Alex McLean Symp., 177–193; 1998, Warrendale, PA, ISS. 6
6. B. G. THOMAS, B. HO and G. LI: 'CON1D User's manual', University of Illinois, USA, 1994.
7. S. L. HOYT: 'ASME handbook: metal properties', 1954, New York, McGraw-Hill. 7

Authors Queries

Journal: **Ironmaking and Steelmaking**
Paper: **1664**

Dear Author
During the preparation of your manuscript, the queries listed below have arisen. The text to which the queries pertain is indicated on the proof by a numbered box in the margin. Please answer the queries and return this form with your corrected proof. Many thanks for your co-operation.

Query Refs	*Query*	*Remarks*
1	Please check authors' titles – Dr, Mr, Ms, Prof. Etc.	
2	Sense OK as given?	
3	Sense OK as changed?	
4	Sense OK as given?	
5	Is this the title of a book? – or the title of a paper in a book, proceeding or journal. If in a book or proceeding – please give the title of the complete work – or if in a journal the name of the journal – Ref. 1	
6	Give editor(s) of McLeasn symp. if known – Ref. 5	
7	Please confirm book details – Ref. 7	