

**OPTIMIZACION OF NARROW - FACE WATER SLOT DESIGN FOR THE  
SIDERAR SLAB CASTING MOLD**

B. G. Thomas\*, M. Langeneckert\*, L. Castellá°, M. Dziuba°, G. Di Gresia+,  
W. Balante+.

\* University of Illinois.

° Instituto Argentino de Siderurgia, [dziuba.ias@cablenet.com.ar](mailto:dziuba.ias@cablenet.com.ar),

[www.cablenet.com.ar/ias](http://www.cablenet.com.ar/ias)

+ SIDERAR S.A.I.C.

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### **ABSTRACT**

A study of a mold narrow plate was performed at IAS, in order to assess the plate condition after its life, in this case 2227 heats. A finite element model of steady heat conduction in the mold narrow face has been developed using ANSYS with 8-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 mold was calculated, and alternatives to optimize the water slot design by altering the geometry in order to minimize both: corner temperature, and temperature variation across the hot face, were analyzed.

According to results the existing narrow face design does not produce excessive temperatures anywhere in the mold. However, a gradient exists across the hotface. 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 redesign.

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.

**Key words:** continuous casting, mold, copper plate temperature, slot design, model

## 1. INTRODUCTION

Problems of breakouts due to infiltration<sup>1</sup> of steel in the corners between the mold plates arose after casting speed was increased at the continuous caster of SIDERAR (see Table 1). To investigate the causes of these problems the following investigations, among others, were carried out: a study of a used plate and an analysis of the continuous casting mold narrow plate with a finite element model (see Figure 1). The purpose of this work was to study whether too high a temperature in the narrow plate could be generating a distortion of the mold 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.

## 2. STUDY OF A USED PLATE

The plate (see Figure 2) was 200 x 900 x 45 mm, and had a nickel coating of 3 mm all over the surface, and 1 mm in the edges, plate material was SeCuAg (0,08 - 0,13 % Ag). The mold is curved.

The plate was cut in several pieces and hardness measurements and other studies were carried out. Figure 3 shows the longitudinal hardness profile, and Figure 4 shows the hardness of a section of the plate in the meniscus area.

In Figure 4 is possible to see that the hardness of the copper is lower near the hot face than in the rest of the plate, where it remains almost constant.

### **3. FINITE ELEMENT MODEL**

Eight different cases were modeled with ANSYS<sup>2</sup>, including the original mold design (both opposite from a bolthole and in between boltholes) and six redesigns, based on variations from the original by changing the water slot.

As the meniscus level remains below the end of the water slot curvature, 100 mm below mold top, the curvature at the top of the slot need not be modeled, so only 2-D analyses needed to be performed to investigate the relative effects of different slot geometries.

In developing the models, symmetry was assumed and 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 modeling conditions are given in Table 2.

#### **3.1 - Results**

The calculated temperatures for the original mold geometry (2 cases) and six different redesigns are given in Figures 5 to 13, and are summarized and compared in Table 3.

### 3.2 - Original Design

Analysis of the original narrow-face mold design reveals that the maximum temperature is found at the corner where the narrow face hotface contacts the wideface (Table 2 and Figure 5). This location is of critical importance because it must transmit all of the clamping force load from the widefaces<sup>3</sup>. Breakouts due to steel infiltration into a corner gap are possible (especially during mold filling) if this corner becomes crushed due to high temperature creep. This is exacerbated by scraping against any powder buildup on the widefaces, which is compounded by many width changes.

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 molds. 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 hotface corner is 49 °C hotter than the center of the narrowface hotface and a consistent gradient exists across the hotface.

Temperature in a horizontal section through the mold 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<sup>4</sup>. The critical meniscus region is found between bolt holes (located 42 mm and 150 mm from mold top), so is close to original case 2 (Figure 6). 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 the hotface temperature is calculated to be only 2 °C on the hotface temperature. The greatest effect of the bolt is to change the temperature at the thermocouple location from 137 °C to 152 °C.

These effects are of no consequence, unless it is desired to use the thermocouples to calculate hotface heat flux, or other quantitative heat transfer data.

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 mold hot face temperature is uniform. Thus, there is incentive to explore ways to lower the corner temperature and lower the extent of temperature differences across the hot face.

### 3.3 - Redesigns

The first redesign was to deepen the angled slot from 20 to 30.4 mm (see Figure 7).

This choice was made based on an empirical equation derived from an extensive analysis of mold temperature calculations<sup>5</sup> designed to make the hotface corner temperature equal to the mid-narrow-face temperature:

$$T_c = q \left( 0.655 \frac{L_c}{d_m} + 0.420 \right) \left( \frac{1}{h_{fin}} + \frac{d_m}{k_m} \right) + T_w \quad (\text{Eq. 1}).$$

In equation. 1,  $T_c$  is the corner temperature (°C),  $q$  is the hot face heat flux (W/mm<sup>2</sup> 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 mold conductivity (W/(mm-K)), and  $T_w$  is the water temperature (°C). The effective heat transfer coefficient at the cold face,  $h_{fin}$ , W/(mm<sup>2</sup>-K), is defined based on extended surface theory<sup>5,6</sup> by:

$$h_{fin} = \frac{h_w w_{ch}}{L_{ch}} + \frac{\sqrt{2h_w k_m (L_{ch} - w_{ch})}}{L_{ch}} \tanh \sqrt{\frac{2h_w d_{ch}^2}{k_m (L_{ch} - w_{ch})}} \quad (\text{Eq. 2})$$

where:

$h_{fin}$  = mold cold face h (W mm<sup>-2</sup> K<sup>-1</sup>)

$h_w$  = mold surface / water heat transfer coefficient (W mm<sup>-2</sup> K<sup>-1</sup>)

$w_{ch}$  = cooling water channel width (mm)

$d_{ch}$  = cooling water channel depth (mm)

$L_{ch}$  = cooling water channel spacing (mm)

$k_m$  = mold thermal conductivity (Wmm<sup>-1</sup>K<sup>-1</sup>)

This relation was found by a linear fit of the results of about 30 finite element simulations, shown in Fig. 8. This relationship to predict the corner temperature was used to adjust the depth of the angled slot until it matched the mid-narrow face temperature. Specifically, decreasing  $L_c$  from its value of 36mm in the original design to 25mm is predicted by Eqs. 1 and 2 to lower the corner temperature from 279 to 227 °C, based on other values in Table 2. A very close match was 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.

1A). A less drastic redesign is to deepen the angled slot only to 25 mm (see Figure 8). This produces the same degree of hot face uniformity, (maximum variation of 26 vs 23 °C). This redesign should have no impact in overall mold life, as the slot depth is less than the thermocouple hole, so does not interfere with remachining tolerances. This redesign should have minimal effect on hot face temperatures, so should not impact steel quality in any way.

2). The next redesign deepens the slots adjacent to the bolthole, in order to compensate for the lower heat extraction at this location where slots have a wider spacing. The result is better hotface temperature uniformity, (only 16 °C difference) at the expense of lower temperatures overall, see Figure 9. Although this should be beneficial for mold life, it will also change the behavior of the gap and the mold flux. This could affect steel quality in an unknown way (either positive or negative) and would require plant trials to investigate.

3). The next redesign changes Redesign #1A by reducing the depth of the central three water slots from 20 mm to 12 mm, like shown in Figure 10. This improves hot face temperature uniformity to about the same as Redesign #2, (17 °C) but at an overall higher hotface temperature.

4). 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 likely has the advantage over Redesign #3 of lower stress concentration around the slot roots, see Figure 11.

5). Redesign #5 is a modification of Redesign #4, which increases the angle of the angled slot from 30° to 45°. Its results are similar, see Figure 12.



#### 4. ANALYSIS

In Figure 13, a comparison is made between the temperatures predicted by the FEM and the values of hardness measured in the plate.

Recrystallization temperature of the 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 % of cold reduction are observed at 195 °C – 215 °C<sup>7</sup>. The arrow in Figure 13, 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 center slots (95 or 97 vs 99) is consistent with the better cooling found there, as predicted by the model. On the other hand, the higher hardness measured near the corners, suggests that the heat flux in the narrow face corners might drop somewhat (relative to the narrow face centerline), thereby leading to lower hotface temperatures than predicted by the model in those locations.

#### 5. CONCLUSIONS

The existing narrow face design does not produce excessive temperatures anywhere in the mold. The maximum temperature, found at the hotface corner, is 283 °C for the conditions studied. However, this corner is about 50 °C hotter than the center, so a gradient exists across the hotface.

An accurate equation was 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 hotface uniformity to a variation of only 26 °C. If taper is optimal (such that no gaps are formed near the corner and hotface heat flux is relatively uniform), then this redesign should result in slightly improved mold life, less crushing of the corner, and possibly fewer quality problems, such as longitudinal off-corner cracks, due to the hotface temperature nonuniformities.

Several other water slot geometry redesigns (1 - 5) were investigated which further improved potential hot face temperature uniformity, at the expense of increasing complexity of the water slot redesign.

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.

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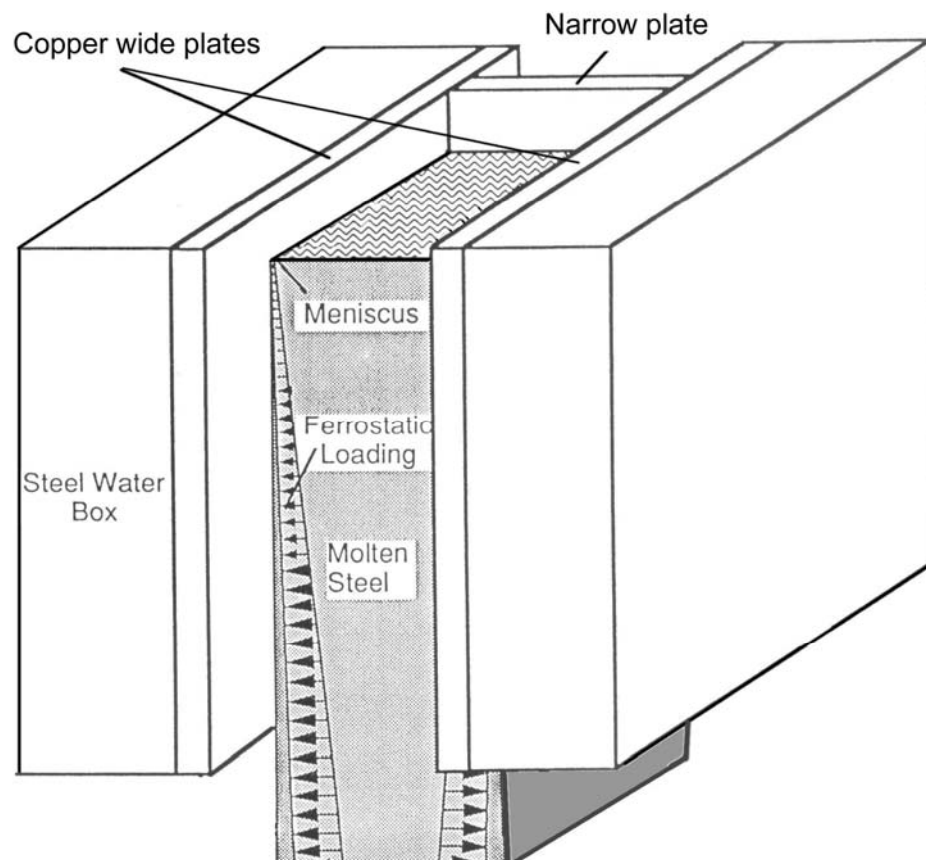


Figure 1. Location of the copper narrow plate in the mould.

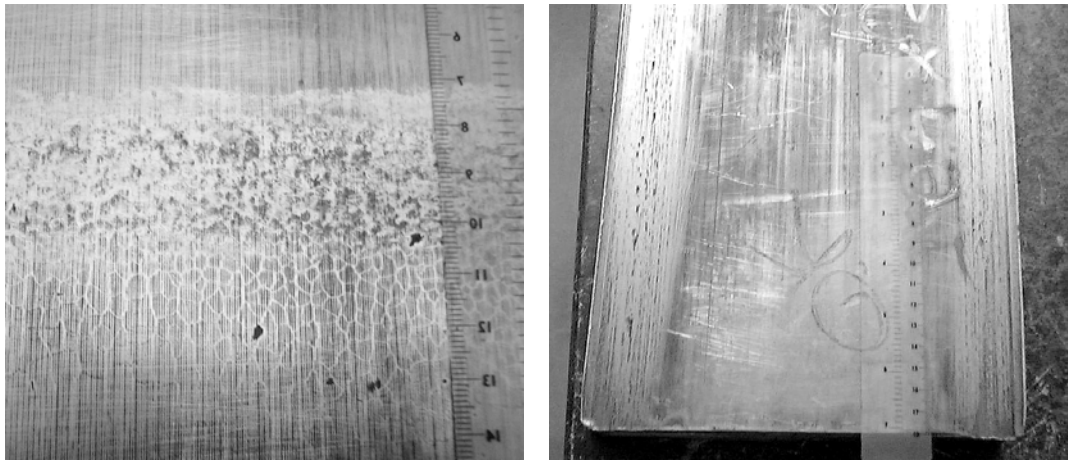


Figure 2. Left: aspect of the plate in the meniscus area, right: lower part of the plate.

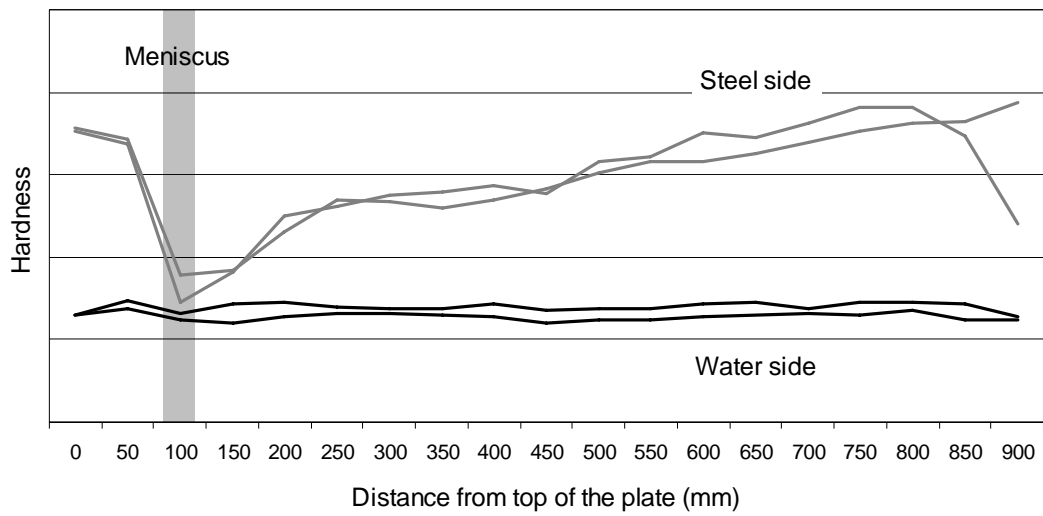


Figure 3. Longitudinal hardness profile of the narrow plate in the steel side (nickel coated) and water side (copper).

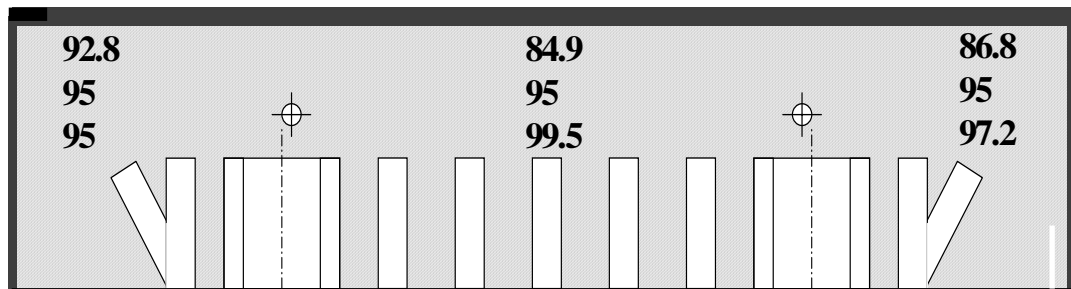


Figure 4. Hardness values HB (2,5/62,5) in different locations on a transverse section of a used narrow plate, 115 mm below the top.

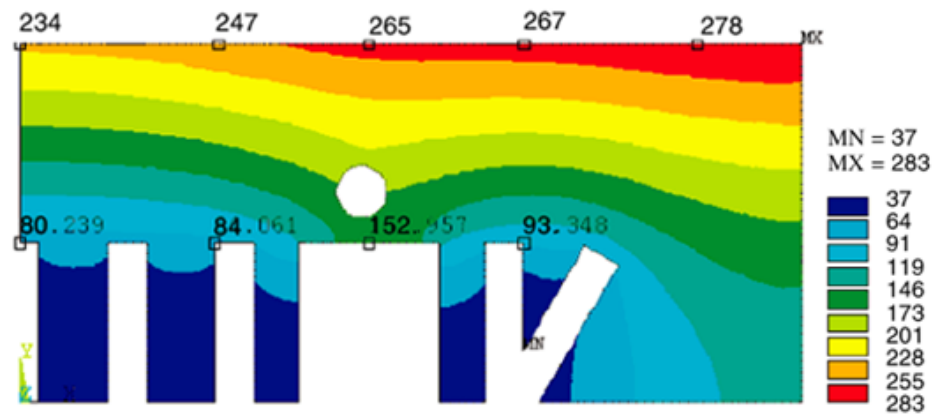


Figure 5. Original geometry #1: insulated bolt hole, edge and back, standard fine mesh, element size ~ 1 mm.



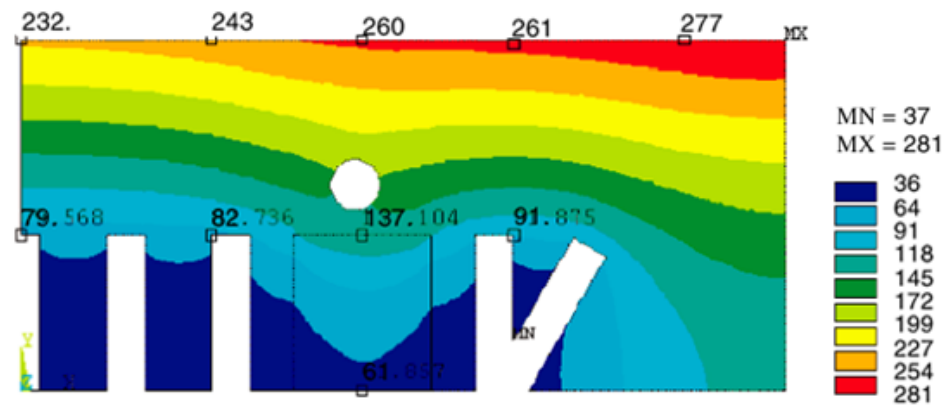


Figure 6. Original geometry #2, effect of perfect fitting steel bolt, element size ~ 1 mm.

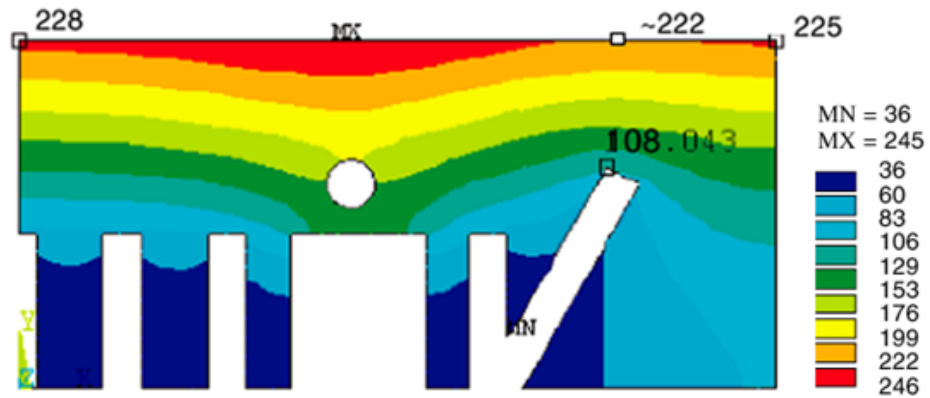


Figure 7. Redesign #1: deepen angled slot from 20 mm to 30.4 mm to cool down corner, angled slot length calculated from corner temperature equation.

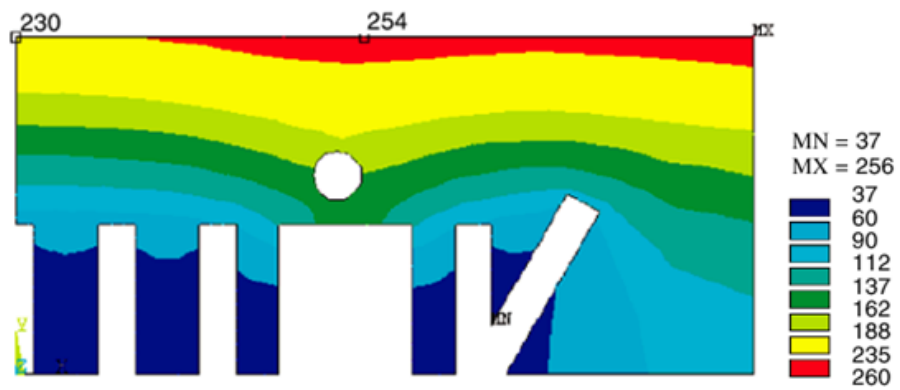


Figure 8. Redesign #1A: conservative, minimal change from original design, increase length of angled slot from 20 mm to 25 mm.

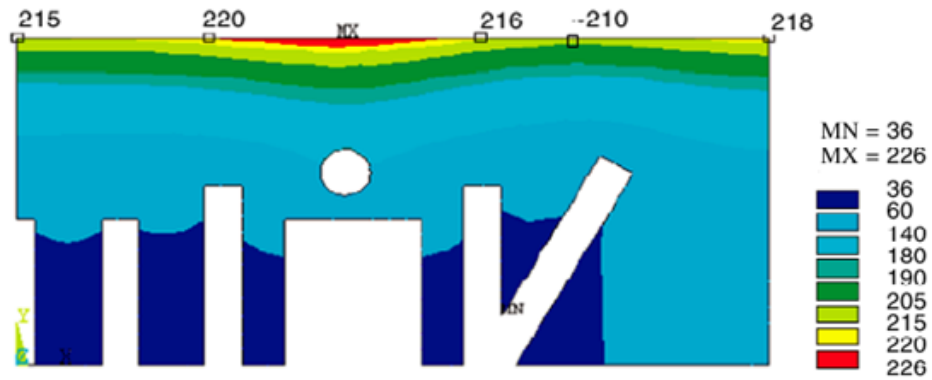


Figure 9. Redesign #2: based on redesign #1 with deepen slots adjacent to bolt from 20 to 24.6 mm, standard coarse mesh, element size ~ 1 to 3 mm.

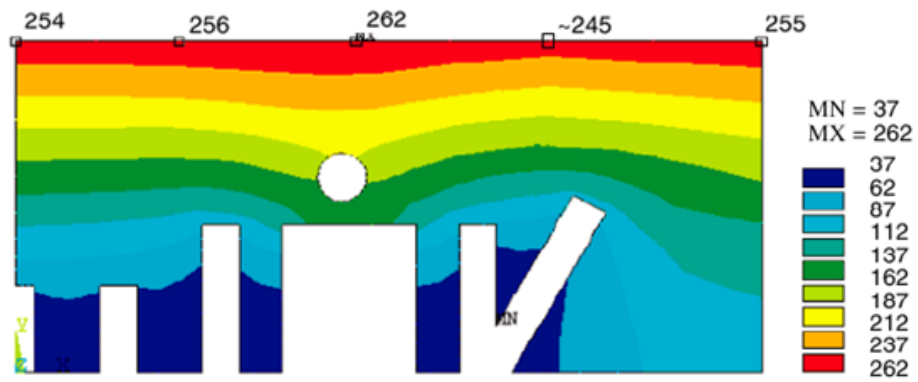


Figure 10. Redesign #3: based on redesign #1<sup>a</sup>, three center slots shallower, reduced from 20 mm to 12 mm.

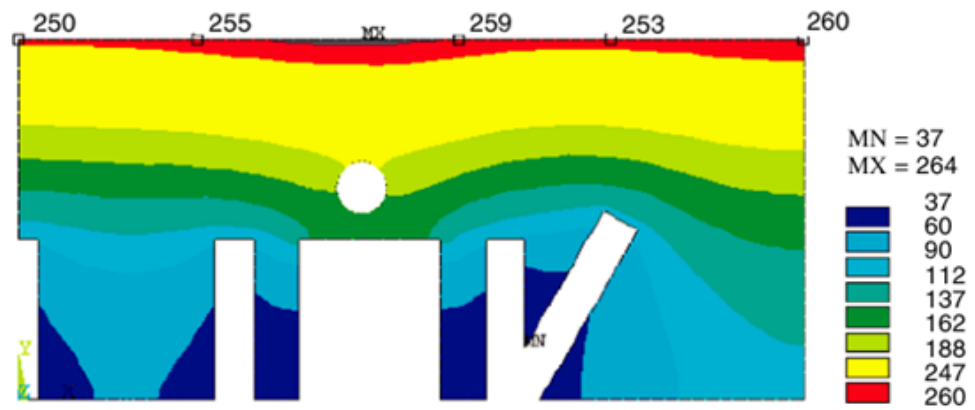


Figure 11. Redesign # 4: based on redesign # 1<sup>a</sup>, removed two slots adjacent to center slot.

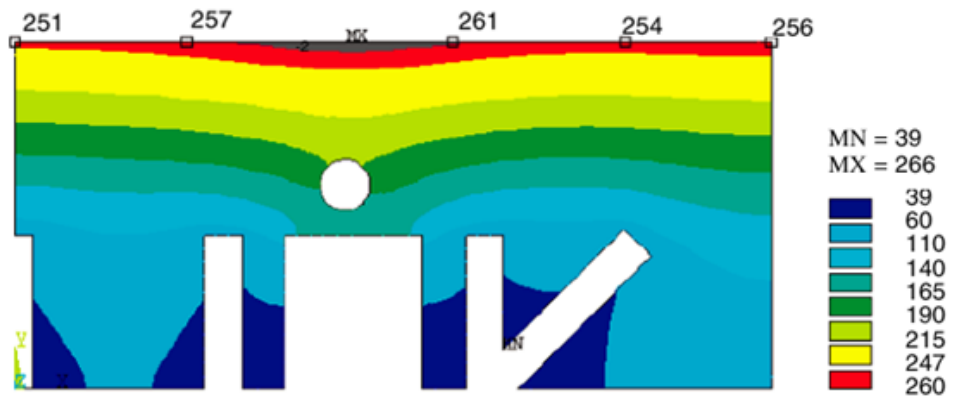


Figure 12. Redesign # 5: based on redesign # 4 with 45°-angled slot.

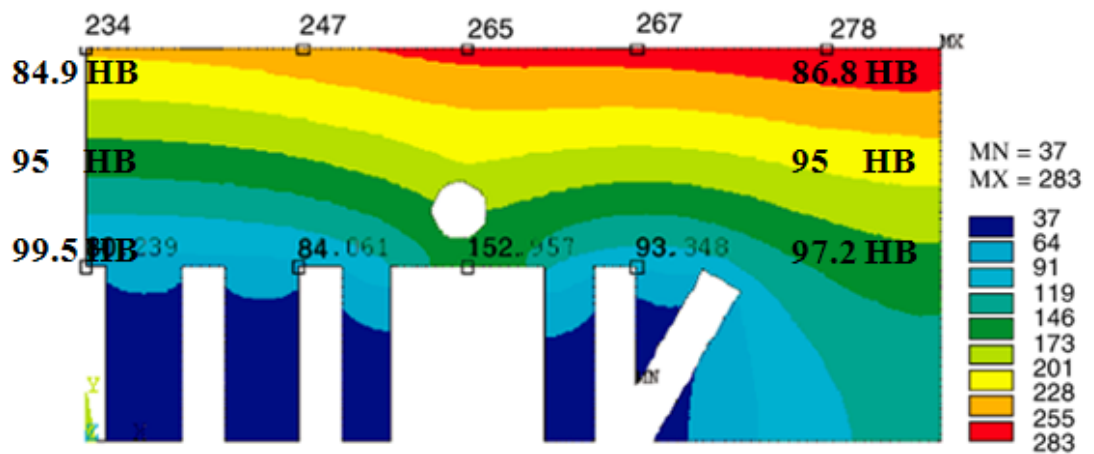


Figure 13. Original geometry #1 (same as in figure 1) and hardness values of the copper determined in a recent study.



|                          |                             |
|--------------------------|-----------------------------|
| <u>Machine type:</u>     | CONCAST - 2 STRANDS         |
| <u>Builder:</u>          | SCHLOEMANN-SIEMAG AG (1984) |
| <u>Type:</u>             | BOW TYPE                    |
| <u>Radius:</u>           | 10400 / 20000 mm            |
| <u>Width range:</u>      | 750 - 1650 mm               |
| <u>Thickness:</u>        | 180 / 200 mm (165 / 250 mm) |
| <u>Mold:</u>             | CURVED - 900 mm LENGTH      |
| <u>Strand guide:</u>     | GRID Y ROLLS                |
| <u>Dummy bar system:</u> | BOTTOM INSERTION            |
| <u>Annual capacity:</u>  | 2200000 ton                 |

Table 1. Main characteristics of the SIDERAR caster.

|  |  |
|--|--|
| Mold width x thickness                           | 206 mm x 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 (center to center)                     |
| Hot face heat flux, $q$                          | 2.0 W/mm <sup>2</sup>                          |
| Water slot heat transfer coefficient, $h_w$      | 0.045 W/(mm <sup>2</sup> -K)                   |
| Copper thermal conductivity, $k_m$               | 0.350 W/(mm-K)                                 |
| Steel thermal conductivity                       | 0.05 W/(mm-K) (original geometry case #2 only) |
| Water temperature, $T_w$                         | 35 °C  |

Table 2. Standard Conditions (narrow face mold copper plate analysis).

|                                   | Originals |     | Redesigns |     |      |     |      |      |
|-----------------------------------|-----------|-----|-----------|-----|------|-----|------|------|
|                                   | #1        | #2  | #1        | #1A | #2   | #3  | #4   | #5   |
| <u>Slot Depths [mm]</u>           |           |     |           |     |      |     |      |      |
| angled slot                       | 20        | 20  | 30,4      | 25  | 30,4 | 25  | 24,5 | 24,5 |
| 2 slots adjacent to bolt          | 20        | 20  | 20        | 20  | 24,6 | 20  | 20   | 20   |
| 2 slots adjacent to center        | 20        | 20  | 20        | 20  | 20   | 12  | 0    | 0    |
| center slot                       | 20        | 20  | 20        | 20  | 20   | 12  | 20   | 20   |
| Angled slot angle [degrees]       | 30        | 30  | 30        | 30  | 30   | 30  | 30   | 45   |
|                                   |           |     |           |     |      |     |      |      |
| <u>Hot-face Temperatures [°C]</u> |           |     |           |     |      |     |      |      |
| corner                            | 283       | 281 | 225       | 256 | 218  | 255 | 260  | 256  |
| min. between corner and bolt      | n/a       | n/a | 222       | n/a | 210  | 245 | n/a  | n/a  |
| across from bolt hole             | 265       | 260 | 245       | 254 | 226  | 262 | 264  | 266  |
| center                            | 234       | 232 | 228       | 230 | 215  | 254 | 250  | 251  |
| (max. - min.)                     | 49        | 49  | 23        | 26  | 16   | 17  | 14   | 15   |

Table 3. Hot face temperatures calculated using FEM model for different slot geometries.