OPTIMIZATION OF WATER CHANNEL DESIGN IN BEAM-BLANK MOLDS

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ABSTRACT

The magnitude and uniformity of the hotface temperature greatly affects the life of continuous casting molds, in addition to affecting surface defects in the product, such as longitudinal cracks. In this work, several different designs for the cooling channels of a beam-blank mold are evaluated using two-dimensional finite-element heat conduction models in order to minimize hotface temperature and to improve its uniformity around the mold perimeter. The maximum hotface temperature is found near the meniscus at the concave internal "corner" of the web where heat flow converges. It is controlled by the maximum distance from the hotface to the cooling water. The best design involves a large-radius annulus formed by putting half-moon shaped copper inserts into a drilled cylinder. Existing molds can be improved by drilling a small extra hole near the critical location. The improved mold designs have been found to improve performance in service at operating beam-blank casters.

1. INTRODUCTION

The magnitude of the hotface temperature has a great effect on the life of continuous casting molds, as it affects wear, thermal distortion and surface cracks in the hot face. In addition, the hotface temperature and its uniformity around the mold perimeter can greatly affect surface defects in the product, such as longitudinal cracks. Mold hotface temperature is controlled by the heat flux (which in turn increases with casting speed and is a maximum near the meniscus), and the copper alloy (thermal conductivity). It is also affected by the mold shape, water channel design, and water velocity through the cooling channels. In beam-blank molds, these behaviours are complicated by the contoured shape of the hotface surface. The present work was undertaken to optimize the cooling design of beam-blank molds using computational models, and testing the designs in service. Specifically, five different designs for the cooling channels of a 730mm (web) x 370mm (flange) x 90mm (thick) beam-blank mold are evaluated using two-dimensional finite-element heat conduction models in order to minimize hotface temperature and to improve its uniformity around the mold perimeter.

Surface defects on the mold copper increase with increasing hotface temperature. Examples with increasing severity are shown in Figure 1. Figure 1a shows a typical beam-blank mold where a patch of chrome plate has peeled off at the meniscus region. There is also some unrelated wear at the mold bottom, due to mechanical abrasion. Figure Ib shows the effect of higher temperature and the presence of Zinc in the steel. Brass is observed to form, and the bare mold copper beneath the delaminated chrome plate now shows thermal fatigue cracks. The cracks align with machining lines on the mold surface, if they are present.

(a)

(b)

Figure 1: Hotface Delaminations and Cracks in chrome-plated copper beam-blank molds

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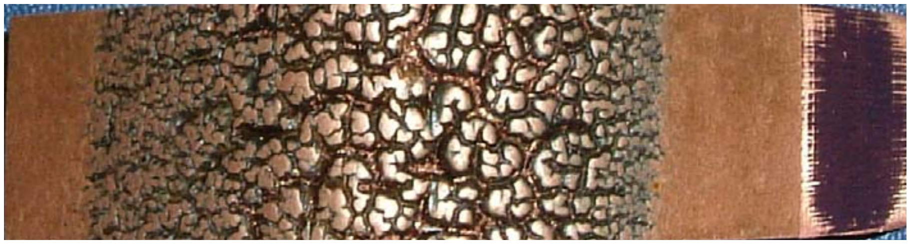

Figure 2: Severe Cracks in Copper Hotface

Figure 2 shows the effect of very high temperature, where severe surface cracks have linked to form a network. The critical temperature for severe cracking is reported to be 300-400 °C, depending on the copper alloy [1]. Previous work has studied thermal fatigue of copper alloys [2, 3]. The detrimental effect of high temperature and zinc on these cracks was confirmed in previous studies of continuous casting molds [4]. Higher temperature is detrimental because it simultaneously increases embrittlement due to grain boundary segregation [5], especially in high-strength copper such as Cu-Cr-Zr [6], and increases inelastic strain during each thermal fatigue cycle[4]. Low strength copper alloys also have severe problems at high-temperature due to thermal distortion from high creep[7].

2. MODELING METHODOLOGY

Computational heat conduction models have been successfully applied to continuous casting mold design in previous work on billet molds [8] and slab molds [7, 9, 10], but beam-blank molds have received very little attention. In this work, the finite-element code, FEMLAB-1 [11], was applied to simulate temperature in a section through the wideface of a typical 4-piece 813mm long beam-blank mold near the meniscus, assuming 4-fold symmetry, as shown in Figure 3. The beam-blank cross-section dimensions at mold exit are: 379.5 mm (web) x 748.7 mm (flange height) x 92.3 mm (thickness). The inside edge of the flange is angled at 69° from the web.

The two-dimensional heat conduction equation, $\frac{\partial}{\partial x} k \frac{\partial T}{\partial x} + \frac{\partial}{\partial y} k \frac{\partial T}{\partial y} = 0$ is solved using FEMLAB [11], where T is temperature (°C), k is thermal conductivity of the copper, and the directions (x and y) are given in Figure 3. A finite element mesh was constructed of 8-node quadrilateral elements and 6- node triangles containing 19440 nodes and 36716 elements. The mesh features 15-20 elements across the critical distance from the water slots to the hotface at the concave internal "corner" of the beam-blank with 70-mm radius of curvature (labelled "corner" in Figure 3).

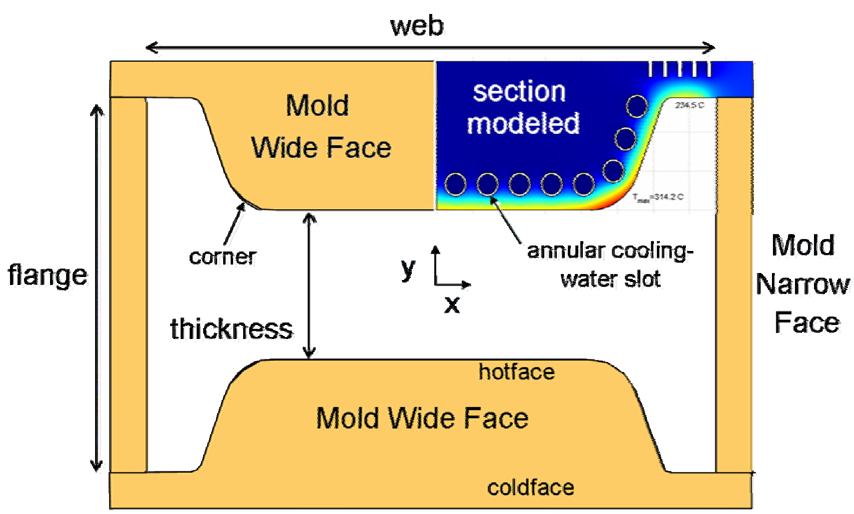

Figure 3: Beam-Blank Mold Schematic (meniscus section)

For a typical commercial beam-blank caster with 0.8 m/min casting speed, low carbon steel alloy, and plain copper-silver-phosphorus mold plate alloy, the conditions given in Table 1 were assumed. Heat flux was assumed to be uniform all along the hotface from the center symmetry plane to the narrow face, located 63.8 mm from the end of the wideface plate. This assumption neglects potential interfacial gap variations that might arise between the mold and shell from taper design problems, which requires further analysis. Convection boundary conditions were applied to the surfaces of the water channels. Heat transfer coefficients at these cold surfaces were computed for two different water velocities in the cooling water channels using the relations of Sleicher and Reusse [12, 13].

Five different water channel configurations were investigated:

1) Conventional Cooling Design: featuring annular channels constructed by filling 30.5 mm diameter holes drilled in the copper mold plate with 25.4 mm diameter solid copper inserts. The holes were spaced 14 mm apart, and 17.8 mm from the hotface (except near the corner). Cooling of the flange end is accomplished with a series of five rectangular water slots machined into the coldface side of the copper wide face.

2) Large Cooling Hole Design: modify conventional design 1 by replacing the two 30.5 mm annular channels closest to the corner with a single large annulus, 62.2 mm in outer diameter, keeping the annular channel thickness constant at 2.54 mm.

3) Small Cooling Hole Design: modify conventional design 1 by adding a small, 12.7 mm diameter hole between the two 30.5 mm holes closest to the corner. Its minimum distance to the hotface is ~17 mm.

4) Half Moon Cooling Design: modify small-cooling-hole design 3 by reshaping the solid copper inserts to fill in the half of each annulus that is furthest from the hotface. Gaps at the cold face side of these inserts are estimated to be ~0.13 mm, but the corresponding extra contact resistance is estimated to cause a temperature rise of only ~0.8 °C, so was ignored. Of much greater importance: the smaller total water channel area is logically assumed to encourage increased water velocity in the annular channels.

5) Improved Large Cooling Hole Design: move all holes to allow the large cooling hole to be repositioned to follow at a fixed distance from the curved corner of the hot face. Also increase the annulus outer diameter to 101.6 mm. Also adopt the “half moon” design for the copper inserts for the large hole.

Finally, the effect of mold shape was investigated by slightly altering the shape of the hottest part of the mold copper (near the corner). Results are interpreted with the aim to lower maximum hotface temperature to improve copper mold life, assuming that the effect on steel quality will not be detrimental.

Table 1 : Casting Conditions

Heat flux on hot face	$q = 2400\ kW/m^2$	
Water temperature	T_∞ = 30 °C	
Thermal conductivity	k = 350 W/mK	
Velocity of water (in water channels)	V = 6 m/s	V = 12 m/s
Heat transfer coefficient (water channels)	32 kW/m^2	48 kW/m^2

3. RESULTS (EFFECT OF WATER CHANNEL DESIGN AND VELOCITY)

Heat transfer simulations were performed on all five mold geometries for two water velocities (6 and 12 m/s). The results are shown in Table 2 and Figures 4-6, roughly in order of decreasing hotface temperature. Two further runs were done to study the effect of mold shape. The same temperature scale is used in each figure.

Table 2. Water Channel and Velocity Results

velocity / case	Maximum Hotface Temperature (°C)		Typical Hotface Temperature (°C)	
	6 m/s	12 m/s	6 m/s	12 m/s
1. Conventional cooling	314.2	288.0	234.5	224.1
2. Large cooling hole	313.8	286.4	234.5	224.2
3. Small cooling hole	274.4	249.0	234.5	224.0
4. Half moon cooling	274.5	249.1	234.7	224.2
5. Improved large cooling hole	271.3	243.9	233.1	222.6

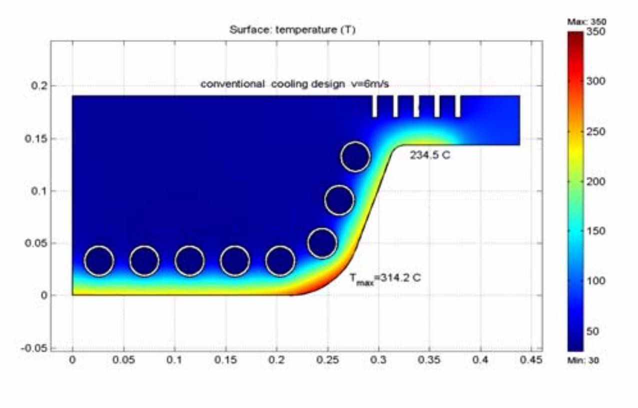

Figure 4.1 : Conventional cooling design (6m/s)

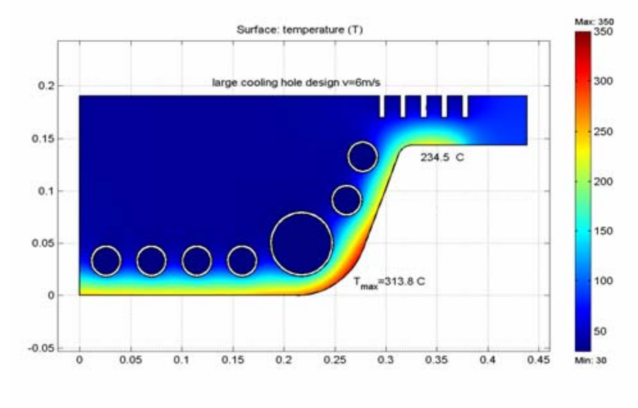

Figure 4.2 : Large Hole Design (6m/s)

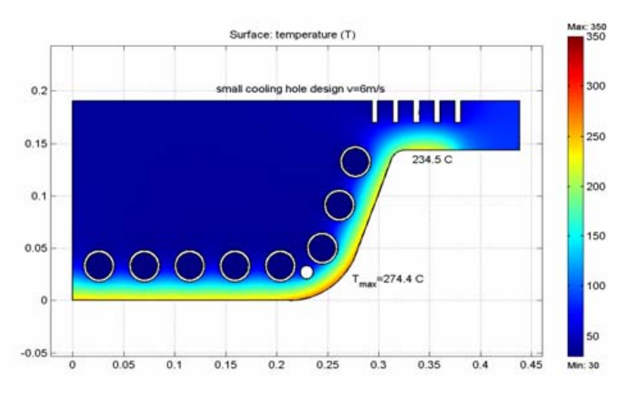

Figure 4.3 : Small Cooling Hole Design (6 m/s)

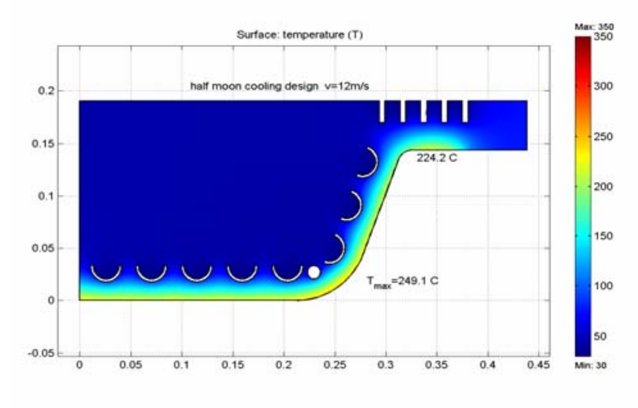

Figure 4.4 : Half-moon Cooling Design (12 m/s)

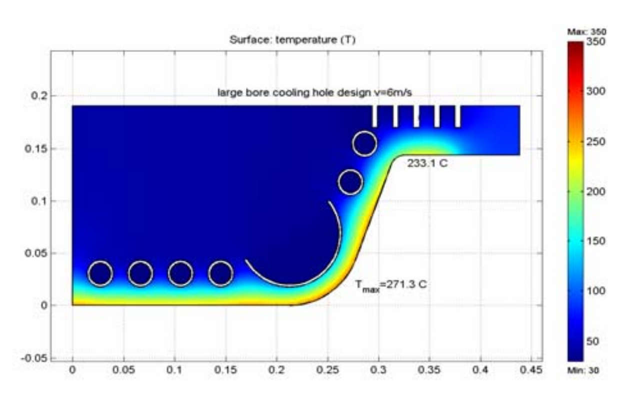

Figure 4.5 (a) : Improved Large Hole Design (6 m/s)

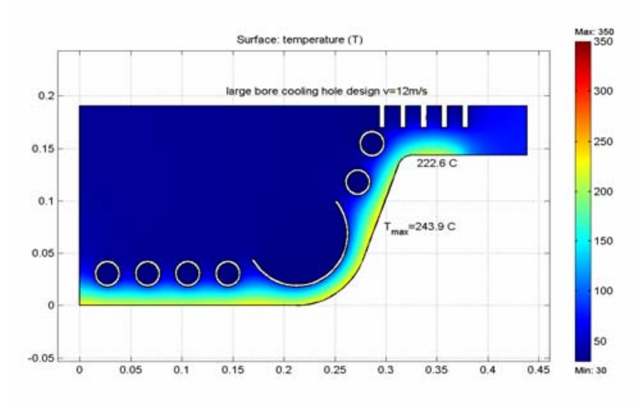

Figure 4.5 (b) : Improved Large Hole Design (12 m/s)

These results clearly show that the maximum hotface temperature is always located near the internal corner of the beam-blank. This location corresponds to the convex-curved corner of the mold hotface surface, where heat flow from the beam flange and web converge to cause excessive heating. The water channels are designed to achieve cooling that almost matches heat extraction from the hotface opposite from the annular channels. The typical hotface temperature (away from the corner) is thus almost identical for all five water channel designs at a given water velocity. Increasing water velocity is assumed to have negligible effect on the heat flux, which is controlled by the interfacial gap. However, it is seen to decrease the coldface heat extraction coefficient, which results in lowering the hotface temperature by about 10 °C.

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Considering mold life, the conventional cooling design is the worst, having the highest hotface temperature, exceeding 310 °C. (Figure 4.1). The large cooling hole design offers almost no advantage (Figure 4.2). This is because it is not centered properly at the corner, owing to the non-optimal spacing of the other annular channels. Instead using the small cooling hole design drops the maximum hot face by 39 °C (Figure 4.3). The small hole design is more effective than the large hole design because it has a smaller maximum distance from the water channel to the hotface. Specifically, the maximum distance from the hotface to the water channel decreases from ~30mm to ~22mm (26% decrease), for a hotface temperature drop from 314.2 to 274.5 °C (14% decrease relative to water temp.). At the same water velocity, the half-moon cooling design is virtually identical (within the model accuracy of 1 °C), which shows that the inner half of the annular channel is unimportant, as expected. More importantly, the water velocity is expected to increase for the smaller total channel area (same pressure-driven flow), of the half-moon cooling design. Specifically, increasing the cooling water velocity to 12 m/s is predicted to lower hotface temperature to 249 °C, (Figure 4.4) which is almost 65 °C lower than the conventional design (23%).

Finally, the best design is to reposition every annular cooling channel in the entire mold, to allow the large hole to exactly follow the convex shape of the corner, staying a fixed distance from the hotface. As shown in Figure 4.5, this lowers the maximum temperature a few degrees further than the best of the other designs. The exact location of the maximum temperature moves a little, according to the water velocity. At lower velocities, the maximum temperature is midway around the convex curve, which receives the most heat. At higher velocities, this region is cooled sufficiently that the adjacent region where the large annular channel curves away from the hotface becomes the maximum. This finding shows that enlarging the diameter of the large hole to approach the radius of curvature of the corner also helped to achieve the improvement in cooling efficiency.

4. RESULTS (EFFECT OF MOLD GEOMETRY)

Knowing that the maximum distance from the hotface to the cooling water controls the maximum hotface temperature, the exact geometry of the internal corner (flange – web junction) of the beam-blank mold is critical. To investigate the effect of minor changes in this geometry, such as caused by wear or taper design changes, two further runs were conducted. These were based on varying the conventional cooling design at 12 m/s by adding or removing a thin layer of copper at the corner. This extra layer reaches a maximum thickness of +/- 3.7 mm, as shown in Figure 5. The results are presented in Table 3 and Figure 6.

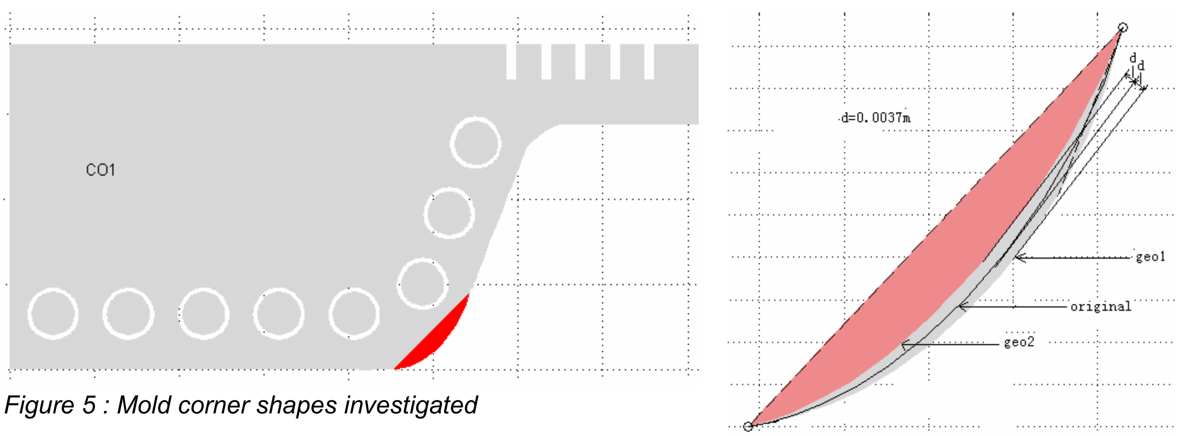

Figure 5 : Mold corner shapes investigated

Table 3. Mold Geometry study: (conventional cooling design 1 at 12m/s)

	Max. Hotface Temp (°C)	Typical hotface temp (°C)
(a) Thicker corner: (case 1)	296.0	224.0
(b) Conventional geometry	288.0	224.1
(c) Thinner corner: (case 2)	281.2	224.0

As expected, adding copper to the corner increases the hotface temperature. Specifically, the 3.7mm increase causes a 8 °C increase in hotface temperature. Correspondingly, decreasing the thickness by the same amount causes a 6.8 °C decrease. Naturally, the hotface temperature elsewhere is unaffected. These results quantify the importance of corner shape, and are consistent with the previous finding that distance from the cooling water channel to the hotface controls the mold temperature and quality problems. These results also suggest that

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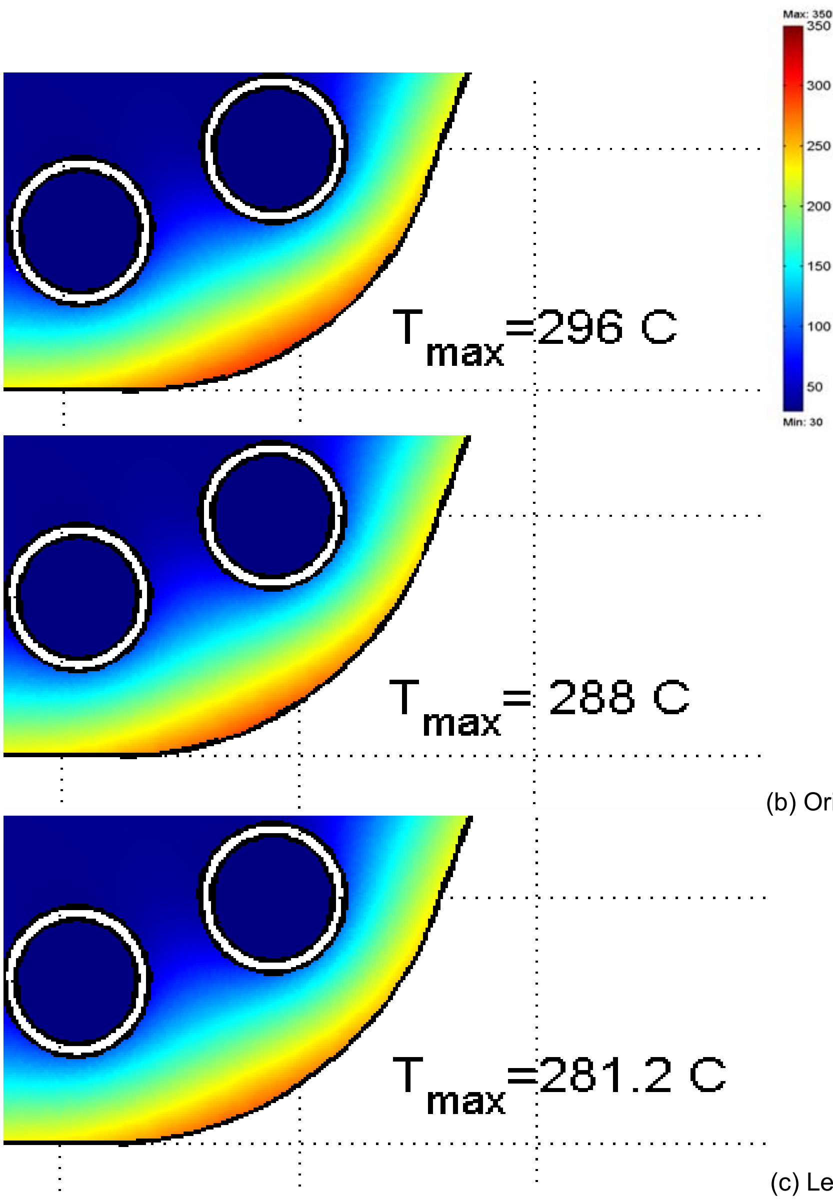
contact between the steel shell and the mold at this critical corner location should have an even greater effect, which indicates the great importance of mold taper.



(a) Extra copper in corner (case 1)

(b) Original Conventional geometry

(c) Less copper in corner (case 2)

Figure 6 : Effect of mold shape on hotface temperature (conventional cooling design; 12 m/s)

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5. PLANT EXPERIENCE

The original cooling channel design in operating beam-blank molds, (conventional design #1), produced the excessive hotface temperatures and mold cracks shown in Figure 1, which caused mold lifetimes to reduce drastically and prompted this study. To address this problem, existing molds were modified by drilling extra holes (small cooling design #3). More than fifteen of these modified molds have been in constant service in the steel plant for over one year. During this time, the casting conditions, steel alloys, and other aspects of mold design (eg. chrome plating) have not been changed. To date, there has not been a single recurrence of mold failure due to hotface cracking at the meniscus. Recently, several new molds were constructed with the large-hole design (improved large hold degisn #5), and put into service. They have experienced similar success. Thus, the problem of mold failures due to hotface cracking at the meniscus is considered to be solved.

Mold lifetime is now determined by other factors. One such factor is wear in the lower portion of the mold (especially near mold exit), caused by mechanical abrasion, and also seen in Figure 1. This problem was addressed by improving the alignment of footrolls to lessen both the bulging of the strand below mold exit, and the corresponding pressure against the mold walls. Together with implementation of the improved cooling channel designs, these measures have caused the average mold lifetime to double from ~500 to ~1000 hours of operation.

6. RECOMMENDATIONS

This study was undertaken to optimize the design of a copper mold for continuous-casting of steel beam-blanks to improve lifetime and steel quality. A computational heat conduction model was applied to investigate the effect of cooling channel geometry and water velocity on the mold temperature distribution. Attention was focussed on the hotface at the internal corner of the wide face, where temperature reached a maximum, owing to converging heat flux.

Assuming that it produces uniform water flow, and that lowering hotface temperature will have no detrimental effect on steel quality, then the best design is the “Improved large hole design #5”. Specifically, a large hole should be bored with the same center as the radius of curvature of the corner, in order to maintain cooling water flow at a fixed distance from the hot face around this critical region of the mold. The other holes should be positioned around the perimeter relative to this large hole, with close-enough spacing to keep the hotface below the maximum temperature. This design lowers this maximum temperature by 43 °C (15%) relative to the conventional design.

In addition, the internal copper inserts that create the annular flow area should be jogged to achieve a “half-moon” shape, (semi-circular annular water channel). This decreases the total water channel area and thereby encourages increased water velocity, for a given pressure drop. Water in the other far-away half-moon, comprising the rest of the annular space, has negligible effect on mold heat removal. The resulting doubling of the cooling water velocity lowers the maximum hotface temperature a further 27 °C (10%). Overall, this optimal design lowers the maximum hotface temperature by 70 °C (25%) relative to the conventional design.

If the optimal large-hole design is not feasible, such as for the redesign of existing molds, then the next-best strategy is to add a small extra hole (or holes) to the part of the critical corner region with the largest maximum distance between the hotface and cooling water channels (small cooling hole design #3). Furthermore, the jogged inserts achieving the “half-moon” cooling design with the higher water velocity should be used. This design lowers the maximum hotface temperature by 65 °C, (23%) relative to the conventional design.

Heat flux in the corner region is also important and is likely affected greatly by mold taper and other parameters that influence the interfacial gap between the solidifying steel shell and the mold hotface. Further study is needed to improve these aspects of mold design and operation.

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