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OPTIMIZING TAPER IN CONTINUOUS SLAB CASTING MOLDS USING MATHEMATICAL MODELS

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Synopsis: Mold taper is one of the few easily-changed and controllable casting variables. It has an important influence on the early stages of solidification in the mold, and the ultimate quality of the continuously cast steel. Two-dimensional, transient finite-element models have been developed to simulate heat flow, shrinkage, and stress generation in the solidifying steel shell in the mold region of a continuous slab casting machine. The models are applied to explore the influence of mold taper, particularly along the narrow face, on development of temperature and shape of the shell. These calculations indicate that the shell shrinks much more in the top portion of the mold than near the bottom. This non-linearity is greater at low casting speed. Mold distortion may partially compensate for this shrinkage. Inadequate taper may contribute to off-corner surface depressions and/or longitudinal cracks by allowing the combination of bulging (where the taper is too little) and/or compression (where the taper is too great). Mathematical models can help to prevent this by matching taper with shell shrinkage.

Key Words: taper, continuous casting, mold, mathematical model, finite element method, heat flow, stress, shrinkage, steel, slab

1. Introduction

The behavior of the thin, growing shell during the early stages of solidification in the continuous casting mold is very important to the ultimate quality of the final slab. During this time, the shell dissipates the superheat contained in the liquid, solidifies, cools, and attempts to shrink away from the mold due to thermal contraction. This may create a gap between the shell and the mold, where heat flow is greatly reduced. The extent of this gap depends on the strength of the thin shell to withstand the ferrostatic pressure pushing it outward, the casting speed, the casting powder heat transfer characteristics, and the position of the mold walls. The latter is determined by the mold distortion and mold taper.

Mold taper is one of the few important casting variables that is readily controllable and adjustable. The long, weak, unsupported shell solidifying against the wide face is generally held against the mold copper by ferrostatic pressure, so is not very affected by taper. To compensate for shrinkage of the wide face, the mold walls on the narrow face are usually given a linear taper. Figure 1 shows the major source of shrinkage is thermal strain due to contraction of the wide face from the initial solidification temperature of about 1500 °C to a mold exit surface temperature of about 1000 °C. For a typical low carbon steel, this requires an average linear taper down the mold of:

$$\%\ \text{taper} = \frac{2\,\Delta W}{W} = \alpha\,\Delta T = (0.002\ \%/^{\circ}\text{C}) * (1000 - 500\ ^{\circ}\text{C}) = \underline{1\%} \qquad (1)$$

It should be cautioned that taper is also commonly reported on the basis of "per unit length down the mold":

$$\%\ \text{taper} / \text{m} = \frac{2\,\Delta W}{L\ W} \qquad (2)$$

This produces a taper of 1.4%/m for a typical mold length of 0.7m, so it is important to distinguish between these two different methods for measuring mold taper. Tapers here are reported on "per mold" basis using Eq. (1).

The previous calculation assumed a continuous, linear shrinkage of the shell. However, previous work has determined that more shrinkage occurs near the top of the mold. (1-4) Thus, billet casting machines often employ a multiple taper. (2) Most slab molds usually use a simple linear taper. Some recent work in slab molds suggests that more taper near the top would be beneficial for slab mold narrow faces also. (5,6)

Inadequate taper can give rise to many different quality problems. These arise from two causes: excessive gap formation, where the shell shrinks away from the mold due to insufficient taper, and mechanical forces compressing the shell, where the taper exceeds the shrinkage. Both of these conditions lead to quality problems. They are not mutually exclusive, since taper can be too high in some places and not enough in others.

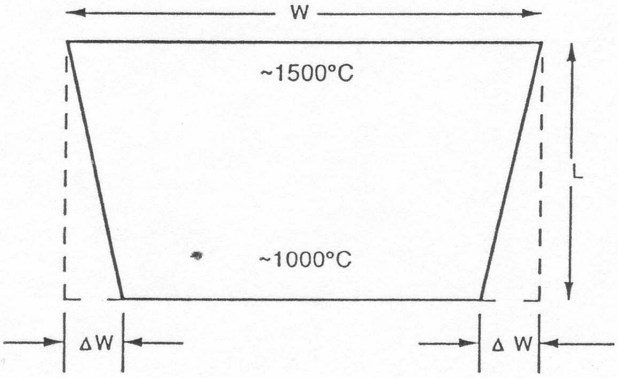


Fig. 1 - Approximate shrinkage of shell on mold wide face

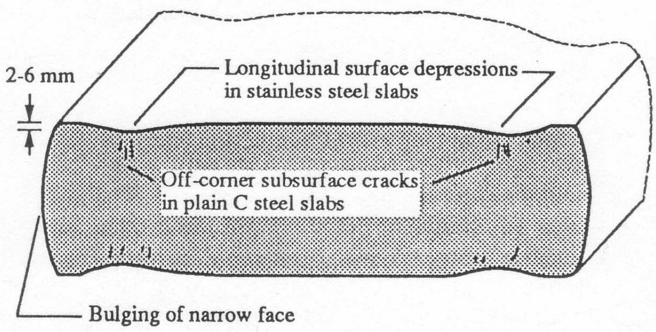


Fig. 2 - Schematic of some problems attributed in part to mold taper

The problem of too little taper leads to decreased heat flow, high surface temperatures, and consequently a thin shell. This in turn can lead to bulging both in and below the mold, with the generation of longitudinal cracks in fragile steel grades and surface shape problems such as longitudinal depressions, or "gutters" down the off-corner region of the wide face surface. These are illustrated schematically in Figure 2. Too much taper also produces many problems such as: 1) Excessive mold wear, which may also cause star cracks by rubbing copper from the mold into the surface of the steel shell, 2) Deformation and distortion of the shell, and 3) High friction and binding of the shell in the mold, which can produce transverse cracks or even breakouts.

The present research applies mathematical models to explore the influence of mold taper on temperature and stress development in the solidifying shell. The goal is to find taper designs for the narrow face that more closely match the natural shrinkage of the shell, in order to improve heat transfer, reduce mold wear, and avoid defects caused by deformation and stress of the shell. This study is part of a larger project to understand and solve defects that arise during continuous casting through the development and application of a comprehensive system of mathematical models of the process. Separate models are being developed of fluid flow and heat transfer in the liquid pool, heat transfer, shrinkage, and stress generation within the steel shell and thermal distortion of the mold. They will be coupled together to predict and understand the effects of such diverse variables as nozzle design and mold distortion on behavior of the solidifying shell.

2. Model Description

To predict shrinkage of the solidifying steel shell as it moves down through a tapered mold, a two-dimensional, transient, heat transfer and stress model has been developed. This program tracks the behavior of a transverse slice through the strand in attempting to simulate longitudinal phenomena. Previous thermal stress models have successfully employed this same approach.(7-9) The present model consists of separate finite-element programs for heat flow and stress generation that are coupled together through the size of the interfacial gap.

2-1. Heat Flow Model

The heat flow model solves the transient, two-dimensional heat-conduction equation over the domain shown in Figure 3, using a finite-element formulation. (10) Because heat flow in the axial direction is negligible, and the defects of interest are primarily longitudinal and usually exhibit two-fold symmetry, only one quarter of a transverse section through the slab is considered.

Convection in the liquid pool is accounted for in the present work by simply increasing the effective thermal conductivity of the molten steel. The results given here ignore the significant influence of fluid flow from the submerged bifurcated entry nozzle which delivers a maximum heat input from superheat at the point of impingement low on the narrow face walls. Work is underway to incorporate results from a fluid flow / heat flow model in the liquid pool to provide boundary conditions for the solid / liquid interface that better account for dissipation of superheat.

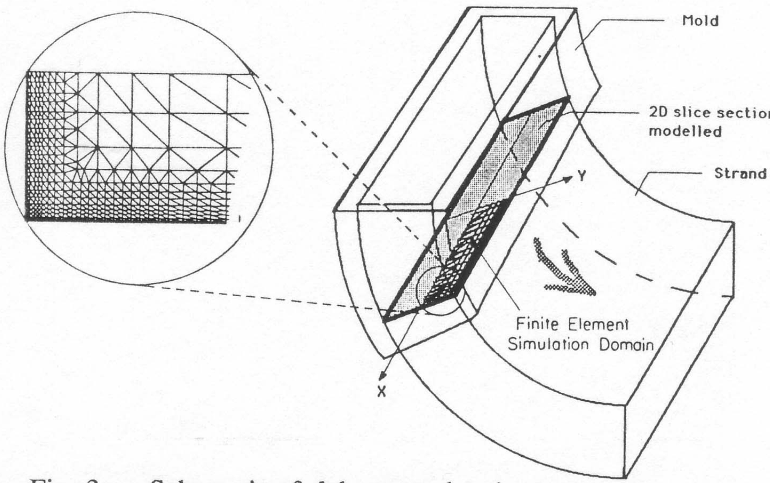


Fig. 3 - Schematic of slab caster showing transverse section simulation domain and mesh

2-2. Interfacial Gap Heat Conduction Model

The model results have been found to be quite sensitive to the heat transfer function employed across the interfacial gap between the shell and mold. The model calculates this heat flow at every location and time step based on the temperature of the mold surface (found from a separate model) and the calculated shell surface temperature. It assumes a transparent mold powder, so uses a resistance due to radiation in parallel with a series of four resistances to heat conduction across the gap, representing:

(1) Contact resistance between the mold and solid flux film
(2) Conduction through the solid and liquid flux film layers, (which is based on average thermal conductivity measurements for mold powder and a thickness that is assumed to increase from a minimum at the meniscus to a maximum depending on the flux viscosity, melting rate and casting speed (10))
(3) Conduction through the air (or gas vapor) gap, if shrinkage calculations indicate one exists.
(4) Contact resistance between the solid flux layer and the steel shell, (if there is no air gap)

This heat transfer function is particularly sensitive to the thickness of the air gap that forms as the shell solidifies and shrinks away from the mold wall. Since ferrostatic pressure prevents a gap from forming over most of the wide face, this is most important in determining heat transfer to the narrow face and off-corner region of the wide face. The thickness of the gap is calculated at each location and time, knowing the position of the strand surface (from the stress model), and the position of the mold wall (from the mold taper) at that location and time. Thermal distortion of the mold also affects the mold wall position, and will be discussed later.

The accuracy of this model for heat flow across the gap, and the gap calculations from the stress model, verified approximately by comparing the calculated total heat flux removed from the slab with experimental measurements. (11) In fact, the contact resistances were chosen to ensure this agreement, so the model is presently dependent on accurate experimental data.

2-3. Stress Model

The stress model is *stepwise coupled* with the heat flow model, as the solution alternates between the thermal and stress calculations as the slice moves down through the mold in successive time steps. At each time step, the load increments from the thermal strain are calculated from the temperatures generated by the heat flow model, using an input function for the thermal linear expansion. This is facilitated by use of the same domain and finite element mesh, shown in Figure 3, for both the temperature and stress calculations.

As many as three levels of iteration are then required to calculate displacements and stresses. The first difficult task is to properly account for the restraining effect of the mold on the thin shell, deforming in the presence of internal ferrostatic pressure. To do this, gap elements are created between nodes on the surface of the solidifying shell and the mold wall. Iterative checks are required at each time step to ensure that only nodes that attempt to move through the mold wall are restrained, and that nodes that "wish" to shrink away from the mold wall are unrestrained.

Next, iteration is usually required to ensure that plastic strain rates are consistent at the beginning and end of each time step. Plastic strain increments can be calculated from a plastic strain rate function that incorporates temperature-, stress-, strain- and time-dependent plastic behavior over the entire wide range of strain rate, temperature, strains, and stresses encountered by the steel shell. (10,12) However, plastic flow due to creep at elevated temperature tends to compensate for inadequate mold taper by distorting the shell or allowing it to bulge to fit the contour of the mold. In order to clearly see when mold taper is inadequate, the present results neglect the effects of plastic flow due to creep. The greatly reduced strength of the steel at high temperature is accounted for by radically reducing the elastic modulus with increasing temperature. (1,10) This also has the advantage of reducing computational effort by eliminating iteration to converge on the plastic strain rates at the beginning and end of each time step.

The present work assumed plane stress conditions and also neglects mold oscillation and friction between the shell and mold. However, an iteration procedure can also be performed to converge on strain in the out-of-plane z direction for generalized plane strain simulations, which is a better assumption for solidification problems.

Once convergence is achieved within the stress model, a further level of iteration is required within each time step to ensure that the size of the gaps calculated by the stress model are consistent with with those assumed by the heat flow model. These displacements must agree within 10% before the stress, strain, and displacement increments are added to the accumulated totals, and the solution can proceed to the next step. If not, gaps are recalculated from the previous and current values using a relaxation factor of 0.4, and the entire process of calculating temperatures in the heat flow model, and iterating in the stress model until the incremental displacements satisfy all convergence criteria, is repeated. A typical run of the elastic model takes about 10 minutes on the Cray X/MP supercomputer or 80 minutes on an Iris 4D/25 workstation. Further details regarding the models are given elsewhere. (10)

3. Results and Discussion

Several model simulations were performed on a 203 x 914 mm slab mold with a working mold length of 650 mm. Standard operating conditions assumed a casting speed of 0.9 m/min (0.015 m/s or 35.4 inches/min) and a superheat of 30 °C. Material properties for a typical 304 stainless steel were assumed. (1,10)

3-1 Insufficient taper

Figures 4 and 5 present example results from the model, run using a narrow face taper of only 0.3%/mold and a wide face taper of 0.1%. These conditions model a loss of taper condition that could produce a break-out in extreme circumstances and were chosen to illustrate behavior of the shell when insufficient taper is employed. The calculated temperature distribution in the shell at various times during cooling in the mold is presented in Figure 4, along with the corresponding deformed shape and mold wall position, which are shown magnified 30 times. The shrinkage of various points on the narrow face away from the mold wall is shown in Figure 5 a).

Just below the meniscus, steel solidifies against the mold to form a continuous shell and starts to shrink away from the mold walls. This occurs first near the corner, where an air gap forms. Two dimensional heat flow keeps the corner cold, thick, and rigid. However, the gaps reduce heat flow in the off-corner regions of both narrow and wide faces, resulting in hotter, thinner shells there.

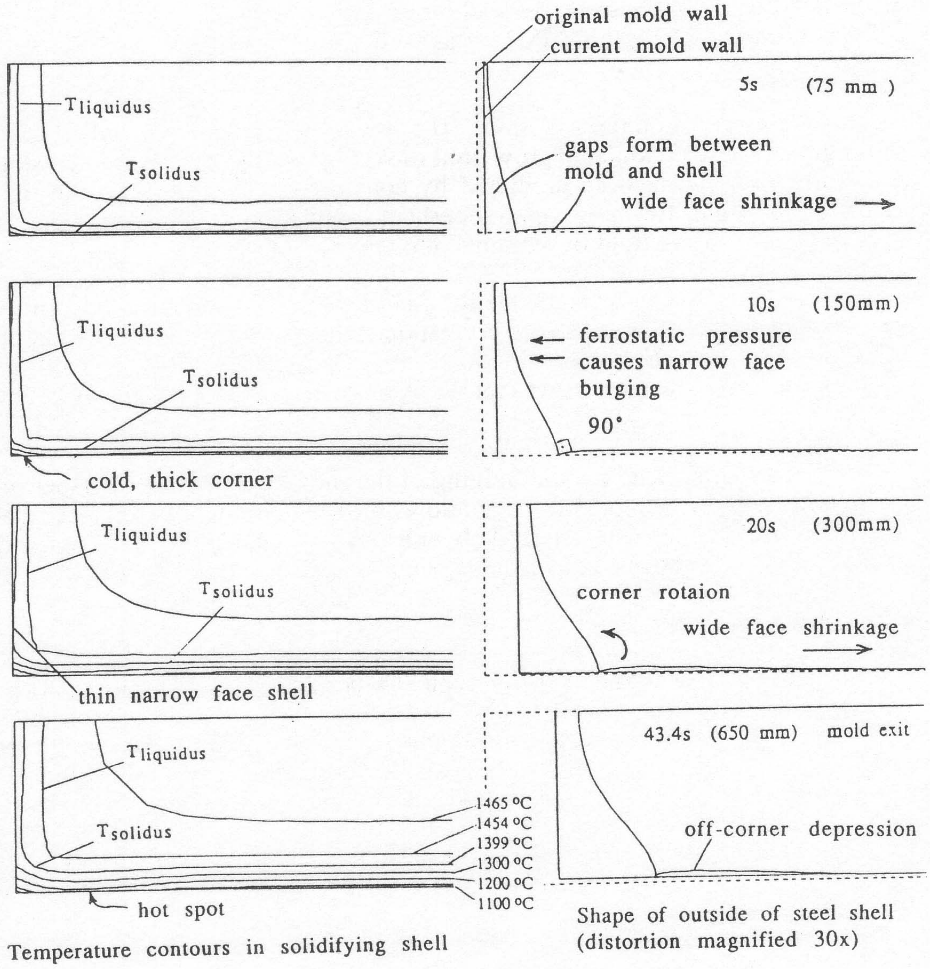
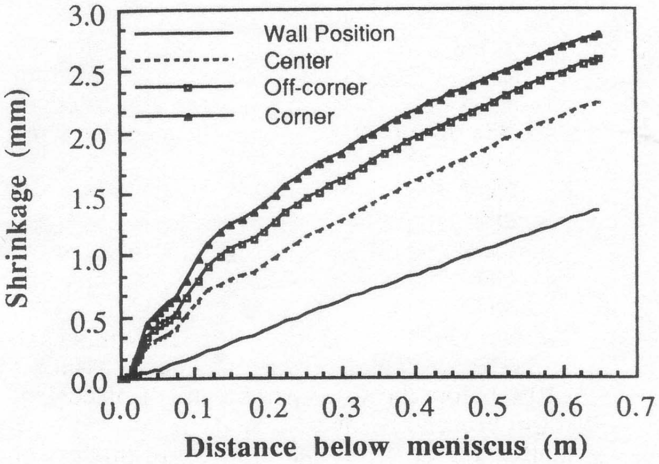
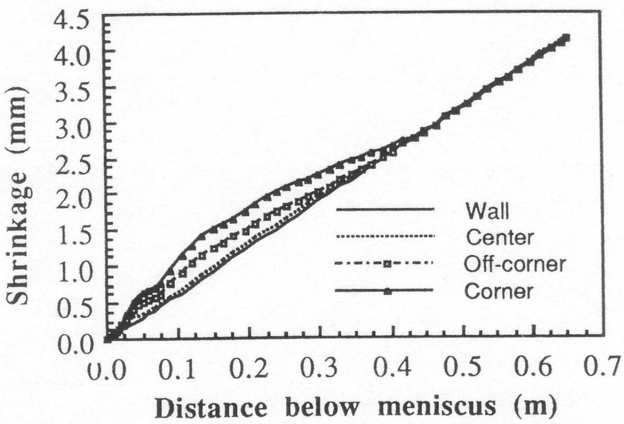


Fig. 4 - Model calculated results showing possible mechanism for longitudinal defect formation with insufficient taper (straight 0.3% narrow face taper; 0.1% wide face taper)



a) .3% narrow face and .1% wide face taper.



b) .9% narrow face and .5% wide face taper.

Fig. 5 - Calculated shrinkage of narrow face surface compared with wall position

With very little narrow-face taper, shrinkage of the wide face produces large gaps on the narrow face, as shown in Figure 5 a), so the entire narrow face remains quite hot and thin, particularly in the off-corner region. (Figure 4).

Ferrostatic pressure makes the narrow face shell bulge outward toward the mold wall. As the wide face cools and shrinks, this further increases the gap near the corner along the narrow face, maintaining high temperatures there. It also causes the shell to rotate slightly about its rigid solidified corner, which maintains its original 90° angle. This produces a slight gap near the corner along the wide face and results in a "hot spot" in the off-corner region along the wide face as well. This hot spot is only observed when wide face taper is relatively small.

The hot spot on the wide face off-corner coincides with the broad gap, or depression, and thinner shell in this region. These continue to grow until mold exit and beyond. It is interesting to note that shell thinning and hot spot formation can also be predicted by consideration of fluid flow in the mold alone.(13,14) The relative importance of gap formation and superheat dissipation on growth of the shell on the narrow face should be resolved by including fluid flow results into the present model.

These results show evidence for a potential mechanism of defect initiation in the off-corner region. The gap predicted along the wide face corresponds approximately with the longitudinal depression defect observed after the shell exits the mold and cools. Strain on the inside of the shell in the off-corner area caused by the bending might initiate subsurface cracks. A mechanism similar to this is believed to be responsible for off-corner internal cracks in billets. (15)

In the mold, bending and bulging of the shell is limited by the taper of the mold walls. Upon exiting the mold, however, the lack of constraint allows further bulging of both faces. The thin, weak shell at the off-corner positions would bend easiest and likely enhance growth of the depression and subsurface cracks initiated in the mold, as proposed above. The model is being extended below the mold to investigate this.

3-2. Excessive taper

The model was then run for typical taper conditions. Figure 5 b) presents a plot of shrinkage of the narrow face surface for a taper of 0.9% on the narrow face and 0.5% on the wide face. This figure shows that this linear taper is a reasonable overall approximation to how the narrow face desires to shrink. However, the wide face surface cools fastest just after solidification at the top of the mold. Thus, near the top of the mold, a simple linear taper cannot compensate for the rapid shrinkage of the wide face, and an air gap is still able to form along the narrow face. Further down the mold, cooling is slower so wide face shrinkage is less. The linear taper then exceeds the shrinkage and forces the narrow face wall to push against the shell. This produces a compressive stress within the wide face and contributes to increased mold wear near the bottom.

Figure 6 shows that the temperature histories of various locations on the shell surface correspond closely to the size of the gap there. The off-corner of the narrow face is very hot in the top part of the mold, due to the large gaps. Once the mold wall catches up and contacts it, this position cools rapidly. The center of the wide face cools relatively quickly due to the good contact produced by ferrostatic pressure over most of its length. The corner is coldest due to 2D heat flow. All of the points can be seen to cool, however, after the gap is closed at about 0.4 m down the mold.

Figure 7 shows how the narrow face induces compression throughout the wide face in the lower part of the mold. Maximum stresses occur at the surface and decrease when moving beneath it, since the hotter steel is softer there. If the compressive stress is high enough, the model has calculated that the shell could even buckle slightly at its weakest point, which is the thinned region off the corner of the wide face where the small depression is already present. This provides an alternative method to deepen surface depressions and initiate subsurface cracks. The effect was not pronounced and is only found with narrow face tapers of 1.3% or above. (10)

3-3. Ideal taper

To compensate for the above problems, a three-fold taper was designed for the narrow face, which includes more taper in the upper part of the mold than near the exit. It decreased from 1.50% at the top to 0.40% at the bottom and included an increased wide face taper of 0.8%. As seen in Figure 8a), this taper design matches the shrinkage of the shell much better. The gap between each point on the narrow face never moves very far from the mold wall, so excessive temperatures along the narrow face are avoided. As the shrinkage subsides with increasing distance down the mold, the taper is reduced to prevent much contact with the narrow face.

Figure 7 shows that compressive stress in the wide face shell is avoided at mold exit for this ideal taper. Slight compression is found at the surface of the shell, which arises in the following way. The thin shell high in the mold is free to contract around the liquid core, which offers no resistance. As the shell thickens while moving down through the mold, the surface temperature remains relatively constant , while the interior of the shell cools and

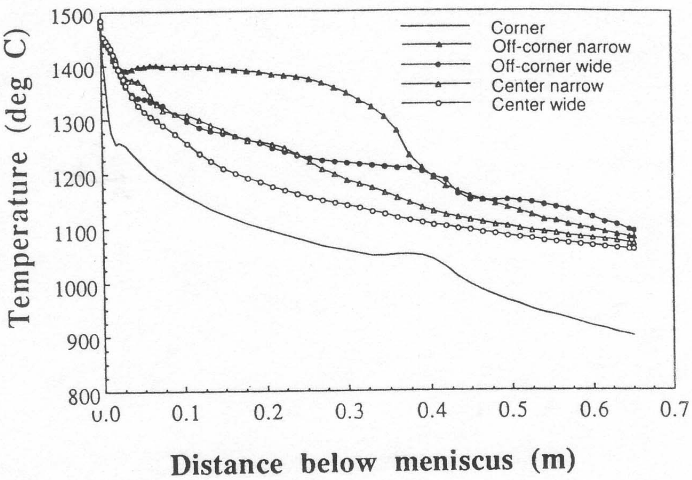


Fig. 6 - Calculated temperature contours at various locations on the steel shell surface (straight 0.9% narrow face taper, 0.5% wide face taper, and 0.9 m/min casting speed)

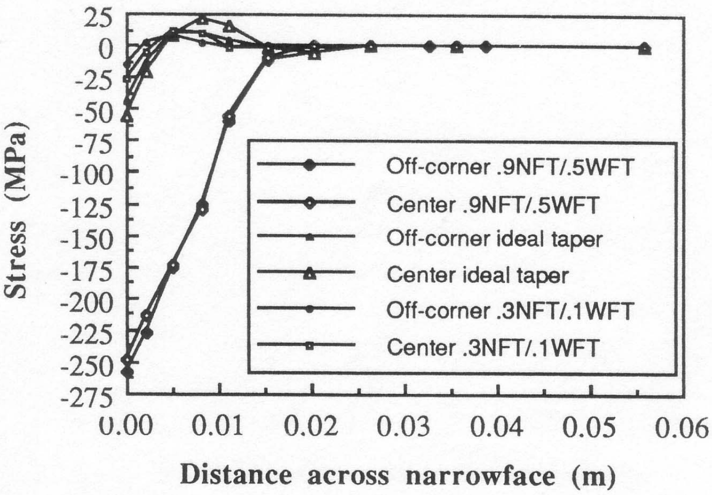
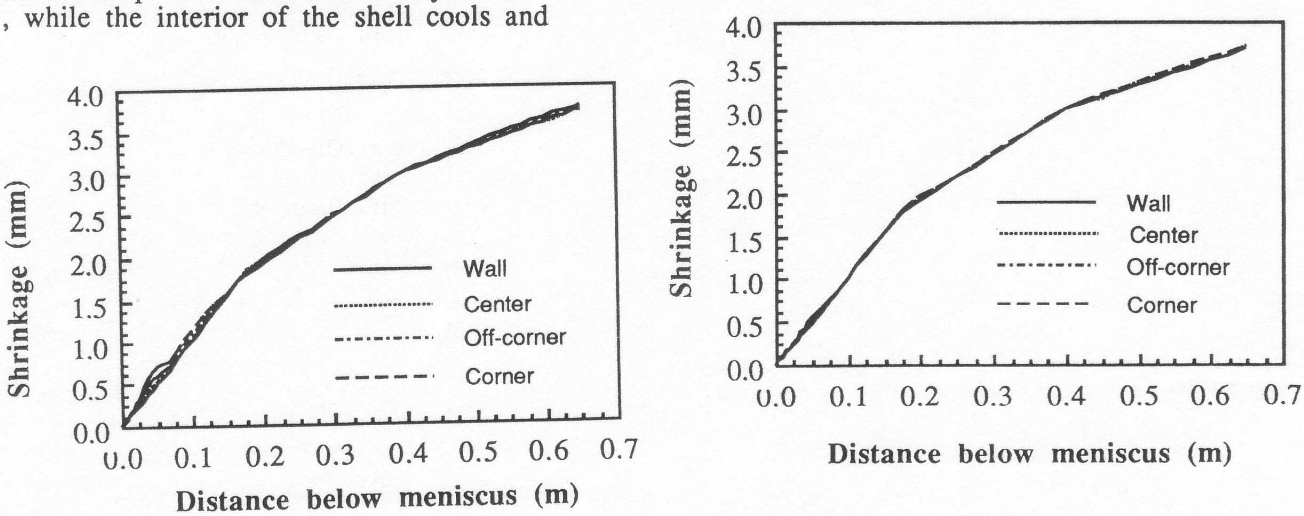


Fig. 7 - Stress distribution within the wideface shell for two different tapers at 0.9 m/min.



a) Ideal 3-fold taper for 0.9 m/min.

b) Same taper as a) for 1.5 m/min.

Fig. 8 - Calculated shrinkage of narrow face surface compared with wall position

and shrinks considerably. By the time of exit from the mold, this forces the surface layer into compression and induces complementary tensile stresses just beneath the surface. This behavior is essentially independent of narrow face taper, if it is not too large and does not vary much across the wide face surface.

3-4. Effect of casting speed

Before implementing an optimized taper design into service, it is important to consider the range of operating conditions the mold taper must accommodate. Thus, the effect of increasing casting speed was investigated, using the ideal taper found above for 0.9m/min. Figure 8 b) shows that increasing the casting speed to 1.5m/min. prevents any gap from forming on the narrow face, so the mold wall coincides exactly with the narrow face shell. This was caused by high compressive forces exerted on the shell, which were revealed by large compressive stresses in the wide face, similar to those found at mold exit for the 0.9% taper in Figure 7.

This result was expected because increasing casting speed increases shell surface temperature on the wide face, since the shell has less time to cool. The higher temperatures result in less shrinkage of the wide face, which results in closer contact of the narrow face wall with the mold for a given taper. The accompanying compressive stresses exerted on the wide face shell are detrimental to both slab quality and mold wear. Closing the air gaps also increases heat flow to the narrow face, producing lower surface temperatures and a thicker narrow face shell. This contrasts with the wide face surface, which experiences both increased heat flux and temperature at the higher casting speed.

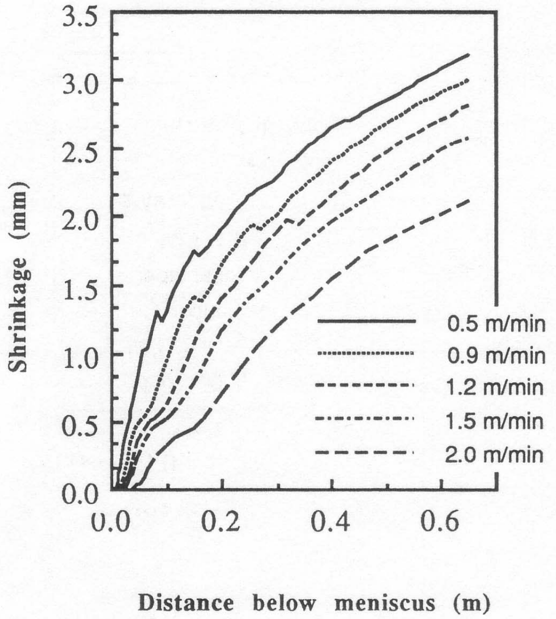


Fig. 9 - Effect of casting speed on ideal calculated shrinkage of narrow face surface

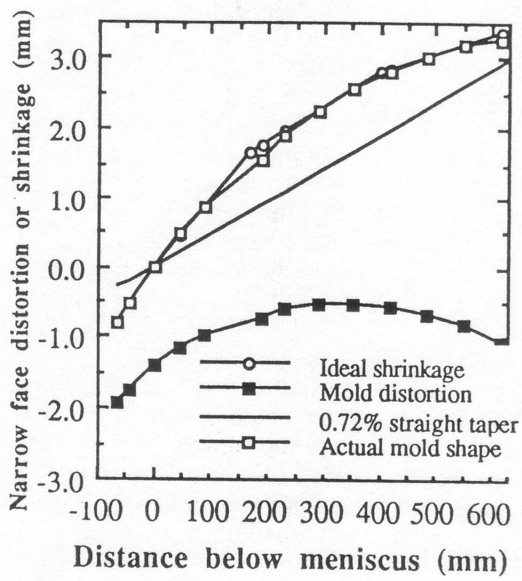


Fig. 10 - Effect of mold distortion on shrinkage and taper design

The model was then used to calculate the ideal tapers that would have avoided these problems at other casting speeds. Figure 9 shows the narrow face mold wall profile needed to exactly match the shrinkage of the wide face for a range of casting speeds. These results were obtained by matching the mold wall position to the center of the narrow face (allowing for the 0.5mm minimum flux layer thickness). This allowed the narrow face to shrink as it pleased (after first solidifying against a resisting wall) with heat transfer behaving as if a fortuitous continuously-varying taper had been employed along the narrow face.

This figure confirms that less shrinkage is found at higher casting speeds. In addition, it shows that the shrinkage is more uniform down the mold, so a straight, linear taper should produce less problems at higher casting speeds. Shrinkage is the most non-linear at low casting speed, such as encountered during a ladle change. Thus, a single taper design cannot match shrinkage under all casting conditions.

3-5. Effect of mold distortion

Another factor that should be considered is thermal distortion of the narrow face. The narrow face bends inward toward the steel a significant distance during operation, due to the expanding copper surface constrained by a cold copper layer and water box beneath it. (16) Figure 10 adds the calculated distorted shape of the narrow face onto a straight linear taper of 0.72%. The surprizing result is that this calculated actual shape of the mold during operation exactly matches the shrinkage of the shell for this particular set of conditions. Thus, thermal distortion of mold may actually be beneficial in many cases and should be taken into account when designing taper.

Other factors such as the build-up of solidified mold flux against the mold walls, can also contribute to altering the effective taper. In light of these uncertainties, and others such as fluid flow effects, it is presently difficult to design a continuous narrow-face taper that follows shrinkage of the shell any better than a simple, experimentally-validated linear taper.

4. Conclusions

A finite element model has been developed to simulate heat flow, shrinkage, and stress generation in the solidifying steel shell of a continuously cast slab. Plans are underway to couple this model with separate models of both fluid flow and heat transfer in the liquid pool, and mold distortion, in order to predict this behavior more realistically. Models such as these are useful tools in predicting ideal taper designs and in understanding how defects form.

The present model has confirmed that the shell shrinks more in the top of the mold than in the bottom. Problems arise if the taper is either too large or too small. A continuous, ideal taper that compensates for this was proposed. However, when variable casting speed, mold distortion, and other uncertainties such as fluid flow and mold flux build-up are considered, at present, a well-chosen linear taper appears reasonable. Further enhancement and validation of these mathematical models is recommended before non-linear multiple tapers or contoured end-wall designs are implemented.

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