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SIMULATION OF LONGITUDINAL OFF - CORNER DEPRESSIONS IN CONTINUOUSLY - CAST STEEL SLABS

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ABSTRACT

The formation of longitudinal off-corner depressions or "gutters" in continuous-cast steel slabs has been investigated using coupled finite-element models. Thermal-mechanical behavior of the solidifying shell has been simulated as it moves down through the mold and upper support rolls in the spray chamber. The calculation includes solidification, intermittent gap formation, plastic creep, bulging due to ferrostatic pressure, interaction with the mold and rolls, and phase transformations. The effects of turbulent flow in the liquid pool, flow and melting of the powder layers, superheat dissipation, taper, and thermal distortion of the mold walls are accounted for using separate models. Together, these models illustrate a multi-stage mechanism for gutter formation. The problem starts with a hot, thin region down the off-corner wide face. This may be caused by locally-inadequate liquid powder feeding, or by insufficient taper of the upper portion of the narrow face mold walls, allowing corner rotation within the mold. Depressions may then be created by excessive taper, buckling the thin shell near mold exit. Alternatively, they may evolve during bulging between support rolls below the mold, due to bending of the thin off-corner region. The results suggest that the problem can be avoided by optimizing the mold flow pattern and powder properties to obtain adequate liquid flux coverage and uniform shell growth; and by optimizing mold taper, water sprays, roll alignment and decreased roll spacing.

INTRODUCTION

Continuous-cast steel is subject to several different types of quality problems, including those illustrated in Fig. 1. One of the problems affecting stainless-steel slabs is the formation of longitudinal surface depressions, 2 to 8 mm deep, just off the corner along the wide faces of conventionally-cast slabs, as pictured in Fig. 2. Similar off-corner depressions, or "gutters" have been observed in plain carbon steel.[1, 2] These gutters are usually accompanied by bulging along the narrow face. Gutters are a costly problem for 304 stainless steel slabs, because the surface must be ground flat in order to avoid slivers and other defects after subsequent reheating and rolling operations.[3]

The off-corner depressions (gutters) are often associated with a variety of other defects. Most serious are longitudinal subsurface cracks, particularly in plain-carbon steel slabs.[2] For example, the sulfur print in Fig. 3 reveals a series of short cracks extending from 13 to 19 mm beneath the gutter. These cracks may become exposed to the surface during subsequent reheating and rolling operations, leading to internal oxidation and again producing slivers in the final product. This is very costly because detection and rejection occurs after so much investment in later processing.[3]

The gutter region may also exhibit deep oscillation marks and surface imperfections.[3, 4] Other defects observed in the gutter, such as double skin and open tears, suggest that this off-corner wide-face region of the solidifying shell may "breakout" in the mold and reseal before mold exit.

The cause(s) of the gutter, subsurface cracks, and related surface quality problems remain unclear. Fig. 4 illustrates some of the different phenomena which may play a role. Steel flowing from the submerged entry nozzle controls flow in the liquid steel pool, which in turn affects behavior of the top-surface flux layers. This affects the initial solidification of the steel shell and the infiltration of liquid powder into the interfacial gap between the shell and the water-cooled copper mold walls. As the shell is withdrawn down the mold, its growth and shape continues to be affected by this gap, which is influenced by the taper and distortion of the mold walls relative to the shell shrinkage. After exiting below the mold, spray cooling and bulging between the support rolls further affects the mechanical behavior of the shell. How these phenomena combine to form gutter-related problems is the subject of this paper.

PREVIOUS WORK

Although the gutter problem has been experienced by many different steel producers, relatively little information has been published. Gutters are usually observed on all four off-corner regions of slab wide faces.[5] However, the severity can vary greatly between locations.[6] It is generally thought that the inside radius (top surface) of curved-mold casters experiences the most severe gutters.[2, 7] Indeed, the name “gutter” refers to the channeling of the flow of accumulated spray water down the off-corner depressions along the inside radius of the strand, which looks like rain water in a roof gutter.

Industry experience suggests that worse gutters accompany higher superheat, lower casting speed, and wider slabs.[3, 6] Low basicity, high viscosity, non-crystalline fluxes and lower powder consumption are also symptoms of aggravated depressions.[8] Nozzle submergence, nozzle geometry, mold taper, and below-mold spray practice are all believed to affect gutter.

Many diverse mechanisms have been proposed to explain the gutter problem. Some industry experience suggests that non-uniform or inadequate powder feeding is crucial to the formation of short, longitudinal depressions on the narrow- and off-corner wide face.[8] Wolf[9] has attributed the formation of transverse depressions to local overcooling of the strand during initial solidification, followed by contraction due to a “plastic hinge effect” and rebending. According to Wolf, depression incidence can be reduced by lowering heat flux near the meniscus, and suggested that this can be achieved with higher casting speeds, higher superheat, and an optimized mold flux. To avoid transverse depressions, the flux should have a low viscosity and high-melting point, in order to achieve a thick interfacial flux layer with uniform feeding.[9]

Others suggest that mold taper is important to gutter. Insufficient mold taper produces gaps between the shell and the narrow face mold walls. Combined with ferrostatic pressure, this has been proposed to allow bulging of the thin narrow face shell within the mold. This could rotate the cold, rigid corner and lift the off-corner wide face region, producing a slight gap or depression.[10] This problem was expected in the upper central region of the mold, for linear narrow-face tapers.

Storkman and Thomas[5] proposed that excessive taper of the narrow face mold walls near mold exit could compress the wide face shell, causing it to buckle at the thin off-corner region. Further, this buckling generates tensile strain close to the solidification front beneath the depression, accounting for the subsurface cracks in susceptible steels. This mechanism is illustrated in Fig. 5. Mahapatra et al[2] extended this mechanism by suggesting that excessive slag rims could reduce heat transfer, particularly on the inside radius. This would result in less thermal contraction of the wide-face, making excessive narrow-face taper and shell buckling more likely. As evidence for this mechanism, increased heat flux and excessive wear were observed on the inner-radius side of the narrow face copper near mold exit.[2, 6] At the same time, the inner-radius wide face exhibited decreased heat flux and worse gutters.[2, 6]

Others have suggested that events below the mold may be responsible for depressions. Sorimachi proposed that insufficient narrow-face cooling could cause the narrow face to bulge outward below the mold, rotating the cold, solid corner, and producing longitudinal cracks.[11] This might create subsurface cracks beneath the wide-face gutter as well. The problem was corrected with increased narrow face spray cooling and support.[11] Finally, mechanical calculations on rigid boxes have suggested that longitudinal problems such as gutter might form during unbending.

OBJECTIVES

The present work was undertaken to apply mathematical models to simulate the phenomena and thereby increase understanding of the mechanism(s) responsible for gutter and related problems and to suggest ways to prevent them. To investigate the many diverse inter-related phenomena of potential importance, a system of mathematical models, developed over several years at the University of Illinois, was employed.

MATHEMATICAL MODELS

Simulations were performed to investigate: flow and superheat dissipation in the turbulent steel pool;[12] melting and flow within the top-surface powder layers;[13] and thermal-mechanical behavior of the solidifying steel shell, both in and below the mold.[14]

Flow And Superheat Dissipation In Molten Steel Pool

A three-dimensional (3-D) finite-volume model of turbulent flow and heat transfer in the molten steel pool has been developed.[12] It uses the K-ε turbulence model and includes the effects of argon gas injection and dissipation of superheat to the solidifying interface.[15] This model of the liquid pool takes its input conditions from a separate 3-D finite-element model of the submerged entry nozzle.[16] Both models have been validated using measurements on physical water models.[16] They are being applied to predict the effect of nozzle geometry and casting conditions on liquid steel velocities and the dissipation superheat.[15, 17]

An example of the velocity predictions is illustrated in Fig. 6, for one-quarter of a 229 x 1400 mm strand cast at 16.7 mm / s through a 76 mm-diameter, bifurcated nozzle with 15° downward, 60 x 90 mm square ports, submerged 265 mm. The point of jet impingement occurs near mold exit. As shown in Fig. 7, this jet delivers a maximum superheat dissipation rate of almost 0.6 MW / m^2 to the narrow face and edges of the wide face. This superheat is important to shell growth, because it is similar in magnitude to the heat flux extracted from the shell to the mold. The central portion of the wide face receives relatively little superheat.

Fig. 8 shows a close-up of the upper recirculation zone. Without argon injection, the steel jet impinges on the narrow face and turns upward and back along the top surface toward the SEN at a velocity exceeding 0.2 m/s. Careful rates of argon injection can reduce this velocity.[15] This velocity is important because it affects flow and melting of the powder flux layers above it.

Flow and Melting of Top-Surface Powder Flux Layers

A 3-D finite-element model of steady laminar flow and temperature development has been developed of the top surface powder layers.[13] The model is based on the shape and velocity profile of the top surface of the liquid steel pool. Sample results are presented in Figs. 9 and 10 for the same conditions as the flow model, with a maximum combined powder and liquid flux depth of 35 mm and a uniform liquid flux consumption rate around the mold perimeter of 0.6 kg / m^2. Fig. 9 compares the calculated liquid layer thicknesses along the wideface meniscus and mold centerline with measurements using a nail board experiment.[13] The measurements fall roughly between the predictions, as expected.

These results show that the flow conditions which cause molten steel to move across the meniscus away from the narrow face will drag liquid mold flux back towards the nozzle in the mold center.[13] Combined with the high standing wave created near the narrow face, (See Fig. 4) this creates a thinner coverage of liquid flux layer over the narrow face and off-corner wide-face regions. Fig. 9 shows that the thinnest liquid region is found at the off-corner region along the wide face perimeter. The bottom view of Fig. 10 shows that this effect is caused by the flow separation between liquid flux consumption into the narrow-face gap and that being dragged to the center. Generally thin liquid layers exist around the entire mold perimeter, excepting the central half of the wide face. Consumption of flux to the mold perimeter is seen in the top of Fig. 10 to generally reduce the liquid flux layer thickness close to the mold walls, relative to the central portions.

The consequence of a thinner liquid flux layer is more chance of a problem with flux feeding into the interfacial gap, for a given variation in level. This particularly applies to the narrow face and off-corner wide face, where a local drop in powder consumption would increase the likelihood of an air-filled gap. It would also provoke unstable meniscus solidification, producing deep oscillation marks. This, in turn, would reduce heat flow from this region, producing a thinner shell.

Further model simulations have shown that lower viscosity liquid flux responds more to the steel flow and enhances convective mixing in the liquid layer. This would tend to increase the thickness of the beneficial liquid layer on average, if not for the accompanying increase in the consumption rate of lower viscosity flux at a given casting speed.

Thermal - Mechanical Behavior of Solidifying Steel Shell

A transient, step-wise-coupled thermo-elasto-viscoplastic finite-element model, CON2D,[18] has been developed to study the thermal and mechanical behavior of the solidifying shell as it moves down through the mold and upper spray zones. As shown in Fig. 11, this model tracks the behavior of a two-dimensional (2-D) transverse slice through a continuously cast strand as it moves downward at the casting speed. The 2-D nature of this modeling procedure makes this model ideally suited to simulate defects and phenomena of a longitudinal nature, such as the gutters and longitudinal cracks considered in this work.

The model has been used previously to predict ideal mold taper,[10] and to understand and prevent breakouts associated with localized longitudinal shell thinning.[19, 20] It consists of separate finite-element models of heat flow and stress generation that are coupled through the size of the interfacial gap. A brief description of this model is included here, as further details can be found elsewhere.[19, 21]

The model first solves for the temperature distribution in the solidifying steel shell. Typical boundary conditions acting in the mold region were presented in Fig. 7. The model incorporates the effect of impingement of the superheated turbulent jet of molten steel on the shell growth, using a data base of heat flux results calculated from the turbulent fluid flow model the liquid pool.

Heat transfer by conduction and radiation across the interface between the steel shell and the mold hot face is found by first using mold thermocouple measurements to calibrate a separate one-dimensional model of solidification down the wide face, where ferrostatic pressure prevents air gap formation.[22] This model includes heat, mass, and momentum balances on the interfacial flux layers.

Fig. 12 schematically shows the temperature and velocity distribution that arises across the interface.[23] The steep temperature gradients are linear across each layer. Liquid flux attached to the strand moves downward at the casting speed, including flux trapped in the oscillation marks. The solid flux is attached to the mold wall at the top and creeps along intermittently lower down.

For simplicity, the model assumes a constant average downward velocity of the solid flux, calibrated to be 10 - 20% of the casting speed.

These 1-D results are extrapolated around the mold perimeter by adding an air gap, which depends on the amount of shrinkage of the steel shell. The gap thickness is recalculated at each location and time knowing the position of the strand surface (calculated by the stress model at the previous time step), and the position of the mold wall at that location and time.

Stresses arise primarily due to thermal strains, which are calculated from the heat transfer model results. The out-of-plane stress state is characterized by the "generalized-plane-strain" condition. This allows the 2-D model to reasonably estimate the complete 3-D stress state, for the long thin shells of interest in this work.

The stress calculation incorporates a temperature-dependent elastic modulus and temperature-, strain-rate-, composition-, and stress-state- dependent plastic flow due to high-temperature plastic creep. The elastic-viscoplastic constitutive equations (model III) developed by Kozlowski et al.[24] are used to describe the unified inelastic behavior of the shell at the high temperatures, low strains and low strain rates, important for continuous casting. The equations reproduce both the tensile test data and creep curves for austenite.

These constitutive equations are integrated using a new two-level algorithm,[21] which alternates between solutions at the local node point and the global system equations. The effects of volume changes due to temperature changes and phase transformations are incorporated using a temperature- and grade-dependent thermal-linear-expansion function.

The mechanical boundary conditions and mesh are illustrated in Fig. 13. Intermittent contact between the shell and the mold is incorporated by imposing spring elements to restrain penetration of the shell into the mold. The exact shape of the rigid boundary of the water-cooled copper mold is imposed from a data base of results obtained from a separate 3-D calculation of thermal distortion of the mold.[25] To extend model simulations below the mold, the shell was allowed to bulge outward only up to a maximum displacement, whose axial (z) profile was specified. In order to observe the effect of the bulging over only two roll spacings, the magnitude of the bulging displacements (3 mm maximum) were specified to be much larger than those normally encountered (less than 0.5 mm).

Thermal-Stress Model Verification

The thermal-mechanical model has been validated using analytical solutions, which is reported elsewhere.[21] The model was next compared with measurements of a breakout shell from an operating slab caster. The interface heat flow parameters (including thickness profile of the solid and liquid mold flux layers) were calibrated using thermocouple measurements down the centerline of the wideface for typical conditions at LTV Steel.[19] Thus, good agreement was expected and found in the region of good contact along the wideface, where calibration was done (see Fig. 14). Around the perimeter, significant variation in shell thickness was predicted, due to air gap formation and non-uniform superheat dissipation.

An example of the predicted temperature contours and distorted shape of a region near the corner are compared in Fig. 15 with the breakout shell measurements. Near the corner along the narrow face, steel shrinkage is seen to exceed the mold taper, which was insufficient. Thus, an air gap is predicted.

This air gap lowers heat extraction from the shell in the off-corner region of the narrow face, where heat flow is one-dimensional. When combined with high superheat delivery from the bifurcated nozzle directed at this location, the shell growth is greatly reduced locally. Just below the mold, this thin region along the off-corner narrow-face shell caused the breakout.

Near the center of the narrow face, creep of the shell under ferrostatic pressure from the liquid is seen to maintain contact with the mold, so much less thinning is observed. The surprisingly close match with measurements all around the mold perimeter tends to validate the features and assumptions of the model. It also illustrates the tremendous effect that superheat has on slowing shell growth, if (and only if!) there is a gap present, which lowers heat flow.

SIMULATION OF DEPRESSIONS

The thermo-mechanical model was applied to understand the cause of off-corner surface depressions and longitudinal cracks in continuous-cast steel slabs. To investigate these defects, thermal-mechanical behavior of the shell was simulated both in and below the mold. Simulations were performed for a 203 x 914 mm strand cast through a 810 mm long mold, at 16.9 mm/s with 25˚C superheat, no wide-face taper, and several narrow-face tapers, grades, mold heat flow conditions, and spray conditions.

Shell Behavior Inside Mold

The results of many simulations in the mold show that along most of the wide face, ferrostatic pressure maintains good contact between the shell and the mold walls. Several possible conditions may occur, however, to produce a hot, thin region on the off-corner region of the wide face shell at mold exit, such as predicted in Fig. 16.

Firstly, the typical lack of taper on the wide face creates an inherent tendency to form a gap between the shell and mold wide face in the off-corner region. In addition, thermal distortion tends to bend the mold walls towards the shell at the center of the wideface[25] and away from the shrinking corner region. The result is a thin (0.1 - 0.3 mm) gap, extending 60 mm along the wide face from the corner, as shown in Fig. 17.

Secondly, insufficient taper of the narrow face mold walls may cause the solidified corner to rotate inside the mold, lifting the shell slightly away from the off-corner mold wall.[5]

Thirdly, excessive taper of the narrow face mold walls may compress the wide face shell, causing it to buckle at its weakest point: the thin shell at the off-corner region.[5] With large enough taper, this mechanism alone could create gutters, entirely within the mold.[2, 5] The effect is most extreme at mold exit, where a linear taper naturally tends to exceed shrinkage of the shell. However, this compression could propagate a gap higher up within mold as well.

Any of these three ways could produce an off-corner gap. However, if the gap is thin (< 0.2 mm) and filled with mold flux, its effect on heat transfer and shell thickness will not be critical. On the other hand, even a very thin gap can significantly decrease heat flow, and produce a thin shell locally, if it is filled with air.

The previous section on flow in the melting powder layer has revealed a tendency for non-uniform feeding of liquid flux into the gap. In particular, potential feeding problems exist along the narrow face and off-corner region of the wide face for typical steel flow conditions. In addition, powders with high solidification temperatures combined with low casting speeds increase the likelihood of complete solidification of the flux in the gap prior to mold exit. Either of these mechanisms creating a lack of liquid in the interfacial gap could greatly reduce heat flow across any extra gap that forms.

Finally, when this thin air gap is combined with enhanced superheat delivery by the fluid jet impingement in this vicinity, a significant reduction in shell growth can occur. As previously discussed, Figs. 14 - 15 show that superheat has little influence if there is no significant air gap to reduce heat extraction to the mold.

This mechanism is predicted to generate a hot, thin shell on the off-corner region of the wide face. This "hot spot" is predicted in Fig. 16 to reach several hundred degrees in extreme cases, and has been reported previously.[26, 27]

Fig. 16 also predicts the hot spot to be accompanied by tensile stresses on the shell surface. This tension might encourage longitudinal surface cracks, particularly in grades where the slower cooling rate in the depression embrittles the microstructure, such as by encouraging microsegregation, precipitate formation, and grain size enlargement in this region. Of added importance is the consequence of the hotter, thinner shell on bending below the mold.

Shell Behavior Below Mold

Model simulations were extended below the mold, based on several different conditions at mold exit. These included three cases:

1) reduced heat transfer at the off-corner wide face;
2) uniform shell growth along the wide face;
3) enhanced heat transfer at the off-corner wide face.

Longitudinal depressions were predicted to form along the off-corner wide face, if and where that region of the shell was very hot and thin at mold exit. Figs. 18 a) and 19 a) show the sequence of steps calculated for the first case, assuming uniform narrow face growth, achieved from a high 1.35%/m taper. No depression is predicted at mold exit (0.8m below meniscus).

Bulging between mold exit and the first support roll (reaching a first maximum peak at 0.90m below the meniscus) causes the weak off-corner region to bend and curve away from the cold, rigid corner. Then, passing beneath the first support roll (0.96m) bends the wide face back into alignment with the corner. Due to permanent creep strain, the curvature remains, in the form of a longitudinal depression. At the same time, the rotation of the rigid corner causes the narrow face to bend outward, (as in Figs. 2 and 3). High subsurface tension is generated beneath the depression, leading to subsurface cracks in crack-sensitive steel grades.

The maximum depth of the calculated gutter after the first roll is 2 mm, growing to 3 mm at the second roll. The calculated shape corresponds to the location of the thin spot. It roughly matches the observed surface profile, as seen in Fig. 20. Passing beneath each subsequent support roll causes the depression to deepen, but by lessening amounts. This continues for several more rolls, until solidification evens out the shell thickness, and the shell becomes strong enough to avoid further permanent curvature.

The final stage of altering the surface profile of some slabs, is flattening of the corner and central wide face by squeezing the strand between the rolls lower in the caster. Evidence for this can be seen in Fig. 2. This effect makes problems such as deep oscillation marks in the gutter easier to spot.

Fig. 18 b) (case 2) shows the effect of inadequate narrow face taper on shell deformation below the mold. A thin region off the corner of the narrow face is seen to encourage significant bulging of the narrow face below the mold, particularly if spray cooling and support are inadequate. If combined with a thin off-corner wide face, then rotation of the rigid corner below the mold can produce a gutter on the off-corner wide face.

It is important to note, however, that a uniform wide face shell at mold exit does not produce any gutter, as shown in Fig. 18 b). In fact, every simulation starting with a uniform shell thickness at mold exit avoided gutter formation.

Subsurface Cracks

The typical stress profile through the shell thickness at mold exit is shown in Fig. 21, for the center of the wide face of a low-carbon steel slab at mold exit. The surface is in compression and the subsurface is in tension. The subsurface tensile peak has a spike due to the delta ferrite to austenite phase transformation. The magnitude of the spike is small, however, if the enhanced creep rate during the transformation to delta ferrite is taken into account in the constitutive law.

This subsurface tension peak occurs at high temperatures near the solidification front. It creates a generic potential for subsurface cracks in sensitive grades, particularly if mechanical bending occurs as well.

Fig. 19 b) reveals the typical sequence of alternating tension and compression of the shell surface and interior, as the shell moves downward between spray nozzles and alternately bulges and is compressed between support rolls. A jump in subsurface tensile stress is produced as the shell passes beneath each roll. Stress beneath the gutter (off-corner wide face location) depends on the uniformity of shell growth. If the shell there is thin, then the local bending seen in Fig. 18 a) between mold exit and the first peak bulge produces stresses that greatly exceed those beneath the mid-wideface (shown in Fig. 19 b). These stresses beneath the gutter are likely to generate subsurface cracks in susceptible steel grades, (Fig. 3) as the corresponding strains are also relatively large. On the other hand, shells with a uniform thickness show similar stress profiles across the wideface.

Simulations with enhanced transfer at the off-corner region (case 3) also produced a significant gutter within the mold. However, after initial formation of the gutter, it is difficult to explain how an increase in heat flux across the gap could be sustained in this region. In addition, this rapid cooling condition produced tension at the off-corner surface, with compression beneath the surface, so cannot explain the subsurface cracks. Finally, locally-enhanced cooling would logically be intermittent, producing shrinkage in both transverse and longitudinal directions. It would be surprising if this could maintain the strong longitudinal uniformity characteristic of gutters. It is more likely that this mechanism acts only near the meniscus and is responsible for the transverse depressions[9] and short, intermittent longitudinal depressions[8] observed in other work.

MECHANISMS

This work suggests that a multi-step mechanism acts to produce off-corner "gutter" depressions, and the accompanying subsurface cracks, on the wide face of continuous-cast slabs. It consists of two separate stages:

1) Formation of a hot, thin region in the off-corner of the wide face shell in the mold.

2) Bending of the shell due to buckling at mold exit, if the narrow face taper is excessive, and / or cyclic bulging of the shell between rolls below the mold.

The first stage, thinning of the off-corner shell, requires three separate conditions to arise simultaneously:

1.1) formation of a thin gap between the shell and the off-corner region of the mold;
1.2) low conductivity material filling this gap; and
1.3) high superheat delivery from the impinging liquid jet to the solidification front opposite the gap.

The off-corner gap could arise in several ways:

1.1.1) generic lack of wide-face taper
1.1.2) thermal distortion of the wide face
1.1.3) rotation of the corner inside the mold due to insufficient narrow face taper
1.1.4) buckling of the wide face shell due to excessive narrow face taper.

The low-conductivity of the material in this gap, likely air, could arise in several ways. These include:

1.2.1) inadequate feeding of liquid flux at the meniscus. A high standing wave on the top surface near the narrow face, combined with a high steel surface velocity back towards the SEN creates an inherent tendency for poor liquid flux coverage and feeding to the off-corner region of the wide face.

1.2.2) lack of liquid flux in the gap further down the mold. Complete solidification of the flux in the interfacial gap, prior to mold exit, may leave no liquid flux to fill any enlargement of the gap, that could occur lower down. This complete solidification is most likely at low casting speed with high solidification-temperature mold fluxes.

The second stage of gutter formation is bending of the thin region of the shell, which forms the associated subsurface cracks at the same time. This stage may be produced in any of several different ways, which could act together:

2.1) buckling of the shell by compression near mold exit, if the narrow face taper exceeds the shell shrinkage. This is most likely if there is also a reduction in heat flow, leading to less wide-face shrinkage.

2.2) cyclic bulging of the wideface shell below the mold, which bends the thin off-corner region during bulging between each support roll. This curvature remains after the wide face is forced back into alignment by the support rolls. This mechanism also rotates the corner, bending the narrow face outward.

2.3) bulging of the narrowface shell below the mold, due to corner rotation, if narrow face support and sprays are insufficient.

DISCUSSION OF SOLUTIONS

In light of the model results and the mechanism proposed in the previous section, the effects of important casting variables on avoiding or reducing gutter may be evaluated.

Mold Flow Pattern

To avoid shell thinning, particularly in the susceptible off-corner region, it is important to maintain complete coverage and uniform feeding of liquid flux around the top surface perimeter. To do this, velocities across the top surface, the standing wave, and variations in liquid level should all be minimized. This can be done by avoiding nozzle angles and shallow submergence depths which produce jets that impinge upon the top surface. In addition, carefully-controlled and optimized amounts of argon injection can slow down steel velocities there.[15]

Powder properties

An adequate mold powder is an essential requirement to achieving a uniform supply of liquid flux to the shell / mold interface. By moving to fill in the interfacial gap, the presence of liquid flux should minimize local drops in heat flow and steel shell thinning, even if a thin gap develops. The results presented here suggest that lower viscosity liquid flux should increase liquid supply to the liquid flux pool[13], in addition to its well-known effect of increasing consumption rate. This is consistent with industrial observations that longitudinal depressions may be reduced using lower viscosity powder.[3, 8] It is also consistent with industry findings that increasing powder consumption (to above 0.4 kg/T-s) can avoid problems.[8]

Steel Grade

Stainless steel experiences higher creep rates (and faster stress relaxation) than plain carbon steel at high temperature.[28] This might lead to more bulging below the mold and explain the propensity for gutter on stainless steel slabs. Alternatively, depression sensitive grades, including 0.12 %C steels and 304 stainless steel are subject to less microsegregation so have higher strength shells.[9] This would enhance gap formation inside the mold, thereby making thinner shells at mold exit more likely. More work is needed to better understand the effect of steel grade.

Mold taper

This work suggests that taper must be optimized to match the shrinkage of the shell all the way down the mold on both narrow and wide faces, in order to prevent gutter. Avoiding insufficient narrow face taper is important to prevent corner rotation within the mold, in addition to avoiding breakouts. Preventing corner rotation helps to avoid forming the thin gap in the off-corner region, responsible for gutter.

It also important to avoid excessive narrow-face taper, to prevent compression and buckling of the shell in the lower regions of the mold. Reducing taper has been found to lessen gutters in practice.[3, 6] However, gutter cannot be prevented solely by optimizing taper. This is consistent with the two-stage mechanism presented here.

Superheat

Superheat has a tremendous influence on thinning the shell locally, wherever there is reduced heat extraction to the mold. This is illustrated in Fig. 15. High superheat delivery to the narrow face and edges of the wide face is natural for flow patterns in slab casters with bifurcated nozzles. Thus, higher superheat is predicted to increase gutter, which is consistent with some industrial observations.[3, 6] The sensitivity to superheat depends greatly on the extent of gap formation between the shell and the mold, however.

Superheat increases with increased pouring temperature and casting speed. The latter can be mimicked by non-uniform clogging of a nozzle port to increase the steel flow rate through the opposite port. In addition, a slight nozzle misalignment could direct superheat directly towards one of the off-corner regions. These two effects might explain the observed variations in gutter between opposite sides or corners of a given slab.

The association between shell thinning and gutter is consistent with the increased likelihood for breakouts beneath the mold corner region. It also explains their association with breakouts inside the mold, which reheal before mold exit, but leave tell-tale surface defects in the eventual gutter.

Below the mold, superheat has been dissipated.[12] When combined with a uniform spray practice, shell thickness tends to become more uniform with time below the mold. When further combined with an overall growth in thickness and strength of the shell, the growth of the gutter (and accompanying subsurface tensile stress) is expected to slow down.

Spray water rate

Further model runs reveal that the depression depth increases with decreased spray cooling on either the narrow face or wide face. Thus, to minimize gutter, it is important to provide adequate narrow face sprays just below the mold. This is also needed to prevent longitudinal corner cracks.[11] It is equally important to ensure adequate, uniform spray cooling across the entire width of the strand, including the off-corner wide face. Insufficient spray cooling far from the centerline could explain increased gutter in wide slabs.

Roll alignment and spacing

Further model simulations found that depression depth increases with increased maximum bulge displacement. This implies that decreased roll spacing and careful maintenance of roll alignment are important to minimizing gutter, once it has started. Adequate, aligned support rolls are necessary along both the narrow and wide faces.

Casting Speed

The effect of casting speed is complex, because it influences several phenomena. Firstly, higher speeds increase superheat delivery to the inside of the shell, which should worsen shell thinning and gutter. Secondly, higher speeds likely increase bulging below the mold, which should also worsen gutter.

Thirdly, higher speeds increase the average temperature of the strand, which decreases shell shrinkage. This would improve contact with the mold. If the taper is generally excessive, this aggravates compression and buckling of the shell and worsens gutter. However, if the mold generally has insufficient taper, better narrow-face contact allows less corner rotation in the mold, and less off-corner gap formation. Finally, higher strand temperature makes complete solidification of the liquid flux layer less likely. The latter two effects of higher casting speed both help to ensure good heat transfer and less shell thinning. Consequently, there should be less gutter, which is consistent with some plant findings.[3, 6]

Slab Width

Based on the proposed mechanism, decreasing slab width might be expected to lessen gutter. Firstly, narrow slabs experience less wide-face mold distortion, leading to less gap formation. Secondly, the smaller absolute shrinkage of the wide face of narrow slabs lessens the consequences of non-optimal taper. Finally, narrow slabs might experience less severe standing waves in the mold, due to lower flow rates for a given casting speed. Naturally, this depends on the flow pattern in the molten steel. These mechanisms are consistent with industry observations of less gutter for decreasing strand width from 1300 to 900 mm.[3, 6]

Time

More frequent inspection and maintenance should decrease the likelihood of deviations from optimum mold taper, roll misalignment, inadequate liquid flux feeding due to alumina pickup in the liquid flux, and other problems associated with the suggested mechanism for gutter. This is consistent with findings that gutter becomes worse with time.[3]

Surface Grinding

Although it is an expensive solution, grinding the slab surface can remove gutters. However, the gutter itself is likely not a quality problem. Rather, gutters may simply indicate the presence of associated defects. These include surface defects (caused by non-uniform meniscus solidification and lubrication problems) and the subsurface cracks (caused by bending below the mold). These serious quality problems are likely responsible for the generation of slivers during later processing.

Extensive grinding to remove the gutters and round off the slab corners has been reported to reduce the associated sliver problems as well.[3, 6] This might be due reducing tensile stresses generated beneath the depressions during rolling, thereby preventing crack formation.[6] Alternatively, grinding and scale formation during reheating may simply remove the steel containing the subsurface cracks and other defects, if they are shallow. In either case, this work suggests that it is better to prevent the formation of the gutter and associated problems using other means, as discussed above.

CONCLUSIONS

1) A system of mathematical models of the continuous slab casting process has been developed and validated with plant measurements. It has been applied to simulate phenomena such as melting of the top surface powder layers, and the thermal-mechanical behavior of the solidifying steel shell as it moves through the continuous casting mold and below. The coupled thermal-stress model includes the effects of non-uniform superheat dissipation, thermal distortion of the

mold, dependence of heat conduction on the shrinkage-dependent air gap, phase transformation, bulging due to ferrostatic pressure, and complex constitutive behavior.

2) The model has been applied to illustrate a new multi-step mechanism for the formation of longitudinal off-corner surface depressions during continuous casting of steel slabs:

   a) creation of a hot, thin region on the off-corner of the wide face shell in the mold

   b) cyclic bending of the shell due to bulging between rolls below the mold

3) The results suggest several ways to alleviate the quality problems associated with these depressions without grinding:

   a) control steel flow pattern (nozzle angle and submergence depth) and powder properties to maintain adequate liquid mold flux distribution around the perimeter of the meniscus.

   b) avoid taper of the narrow-face mold walls that is either too large or too small

   c) lower superheat

   d) maintain uniform spray intensity on the shell perimeter below the mold, to cool and strengthen the shell.

   e) maintain roll alignment and minimize roll spacing, to reduce bulging below mold on both wide and narrow faces.

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LIST OF FIGURES

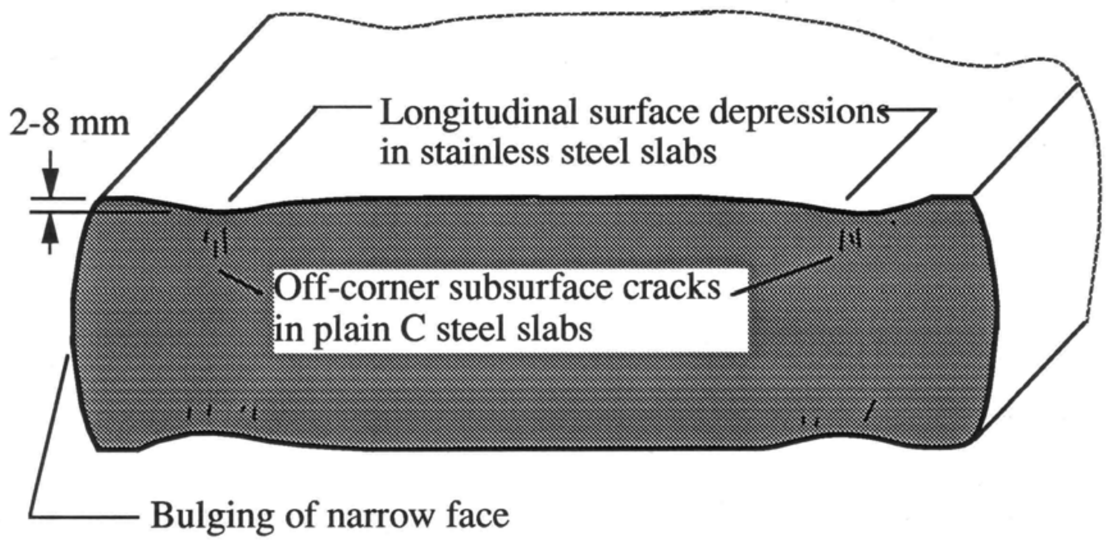


Fig. 1 Schematic of depressions and associated subsurface cracks.

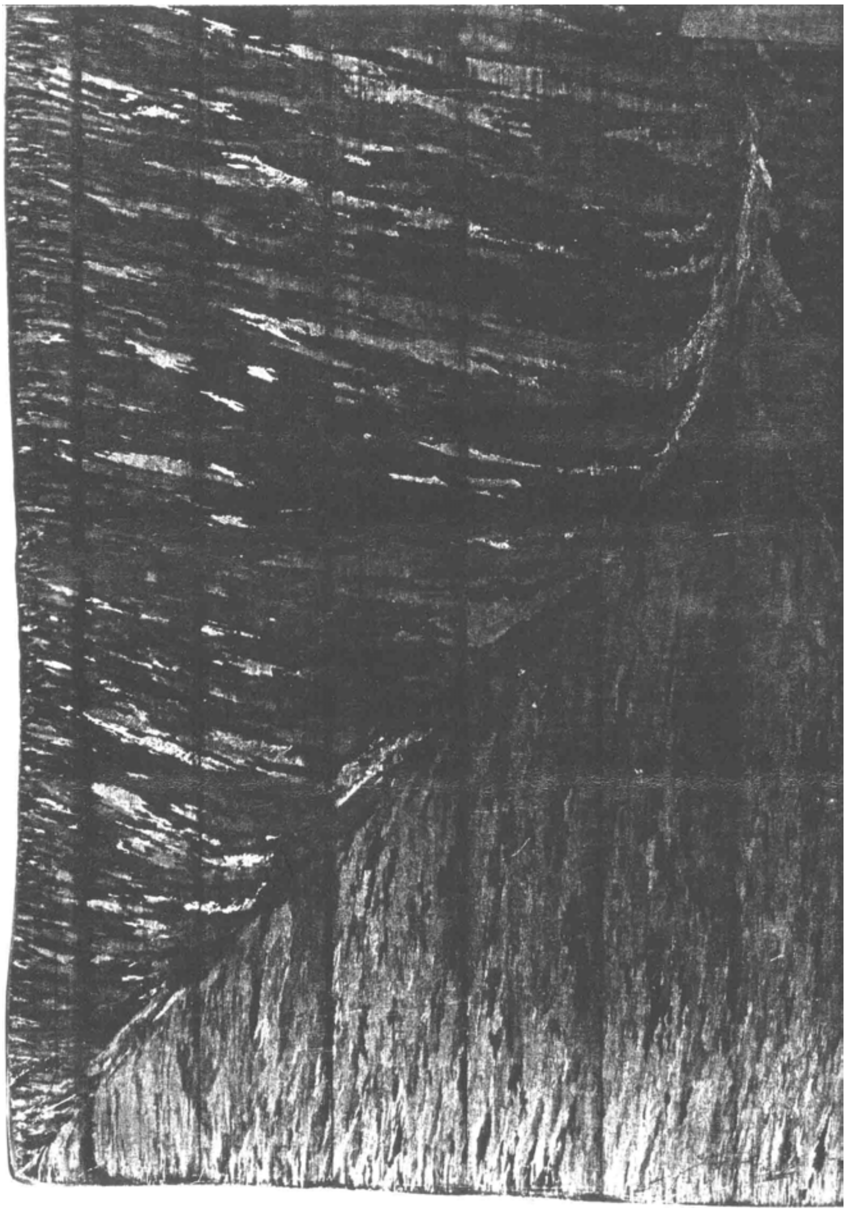


Fig. 2 Example of longitudinal off-corner surface depression or *gutter* on the wide face of a 304 stainless steel slab (transverse section near corner on inner radius).

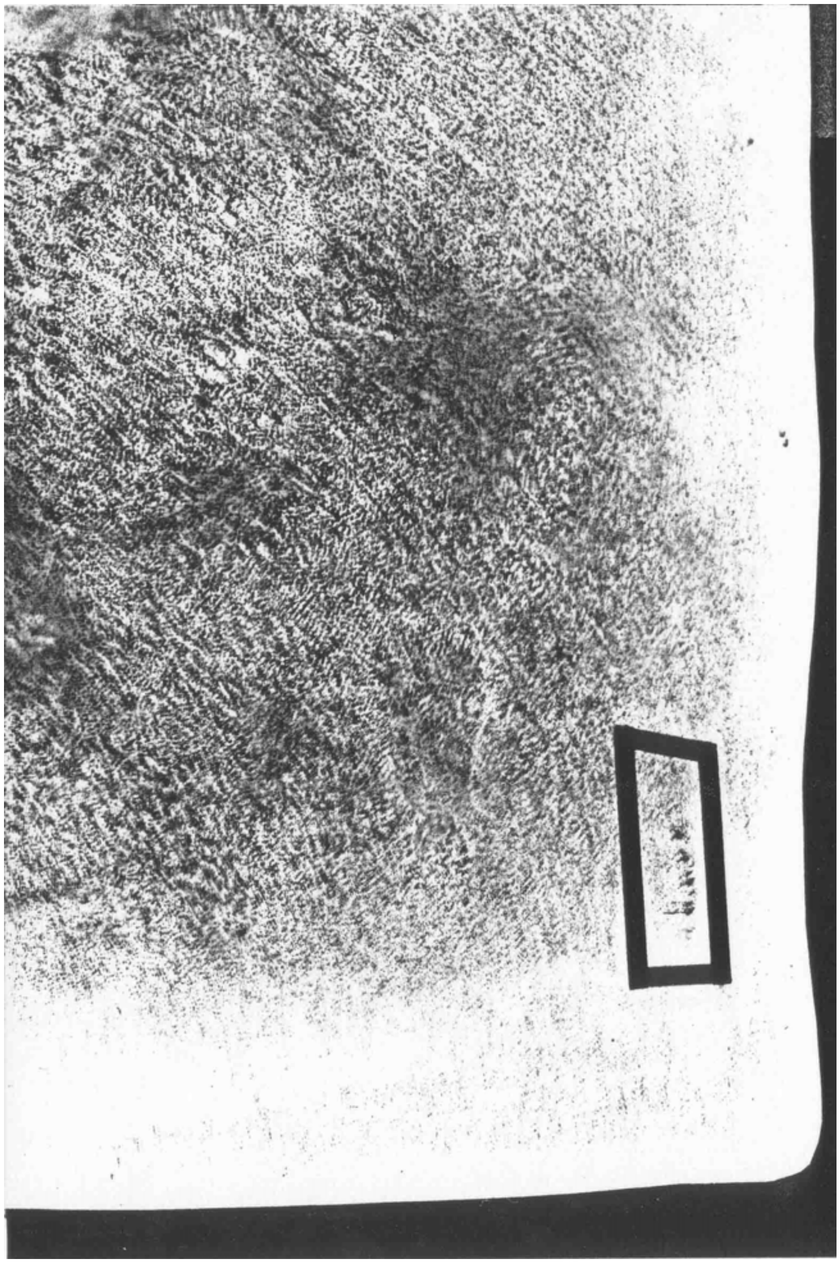


Fig. 3 Example of subsurface cracks beneath gutter (outlined in black box on outer radius sulfur print).

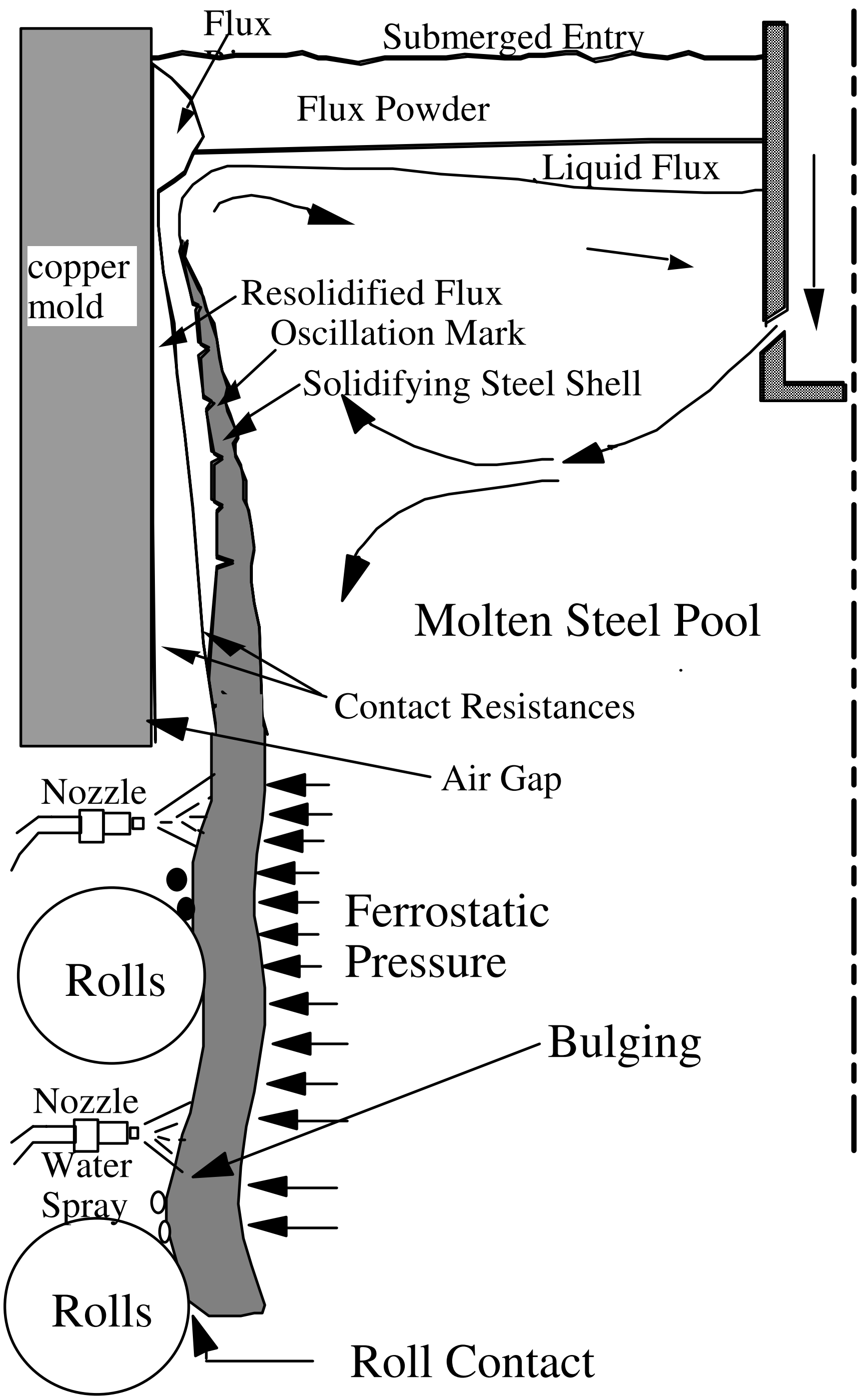


Fig. 4 Schematic of continuous casting process showing phenomena important to gutter formation (not to scale)

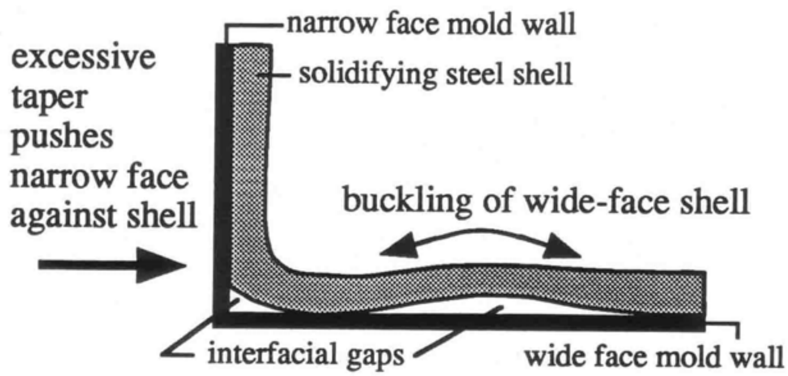


Fig. 5 Mechanism of gutter formation near mold exit due to excessive narrow face taper5

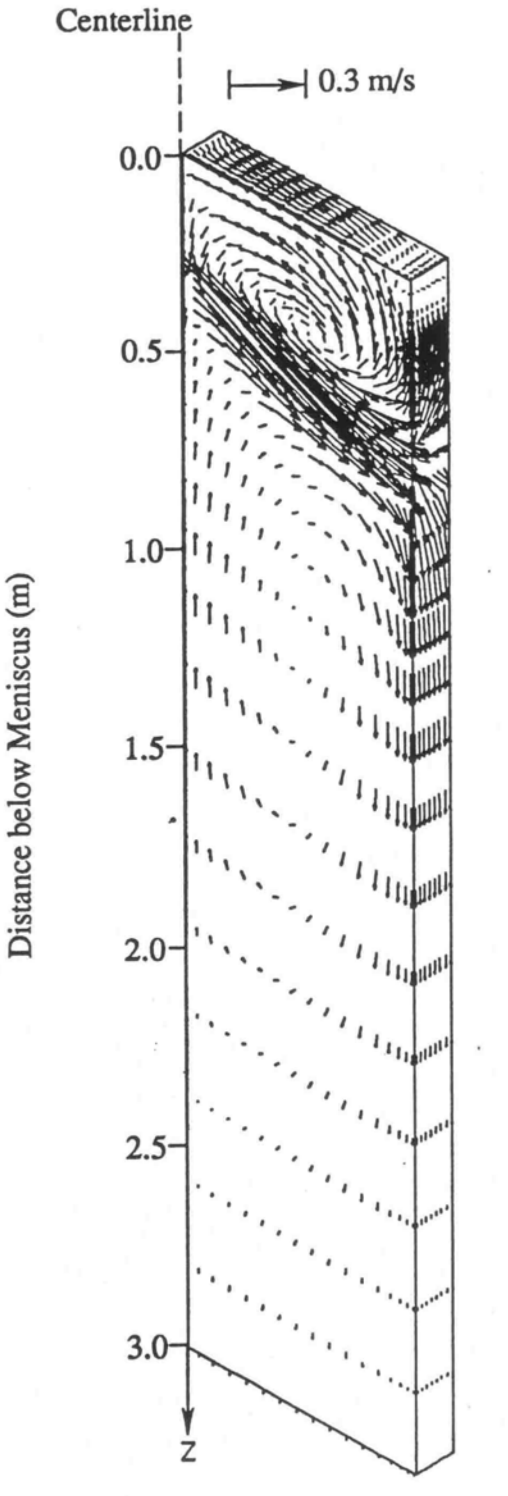


Fig. 6 Velocity pattern calculated in liquid steel pool

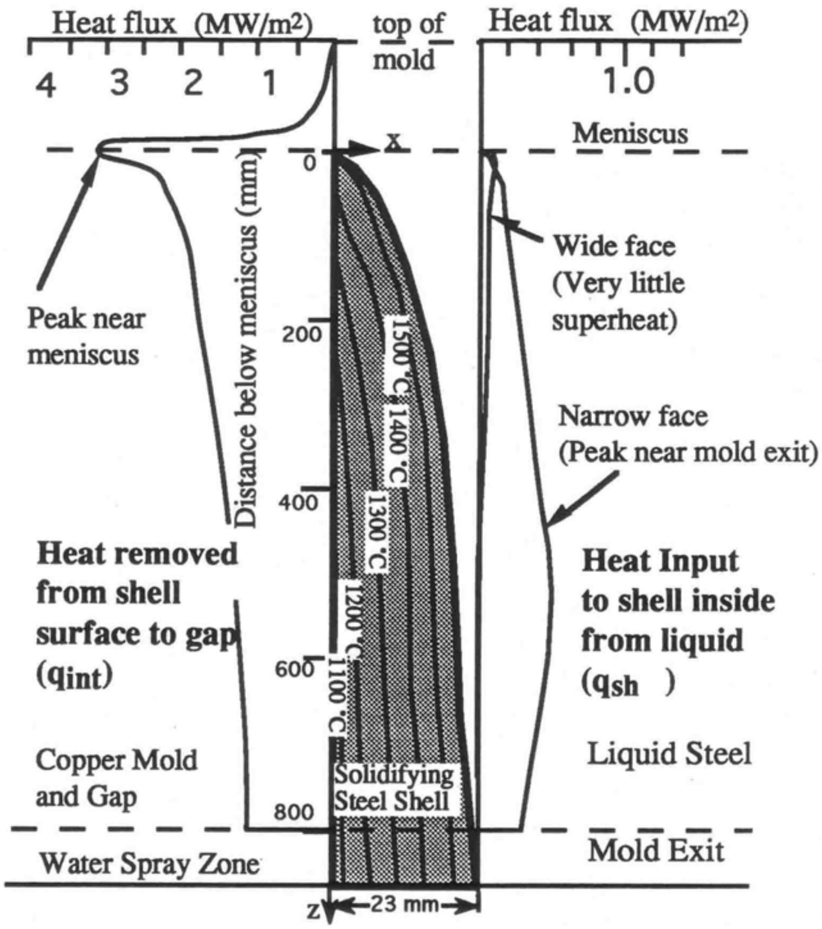


Fig. 7 Typical isotherms and boundary conditions calculated on shell solidifying in mold

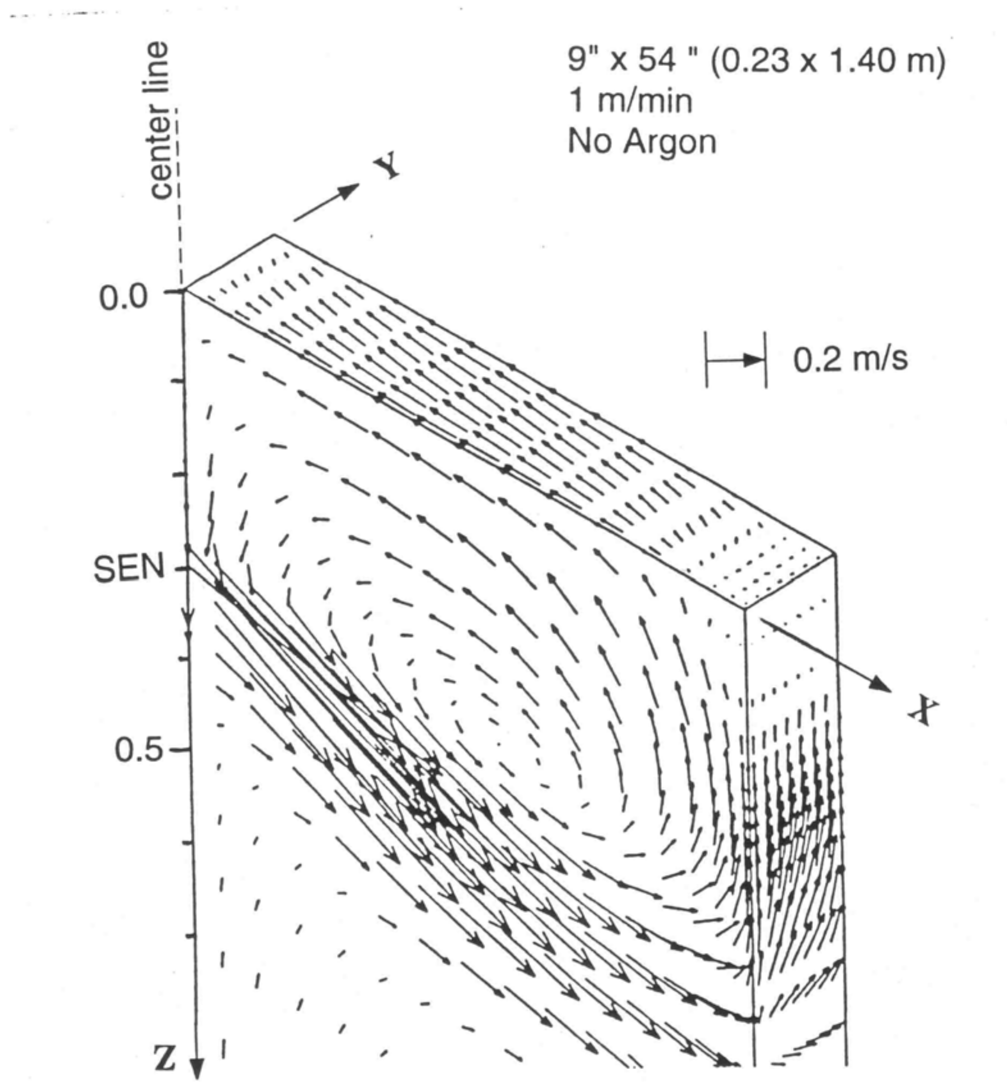


Fig. 8 Steel flow velocities calculated in upper recirculation zone (close-up of Fig. 6)

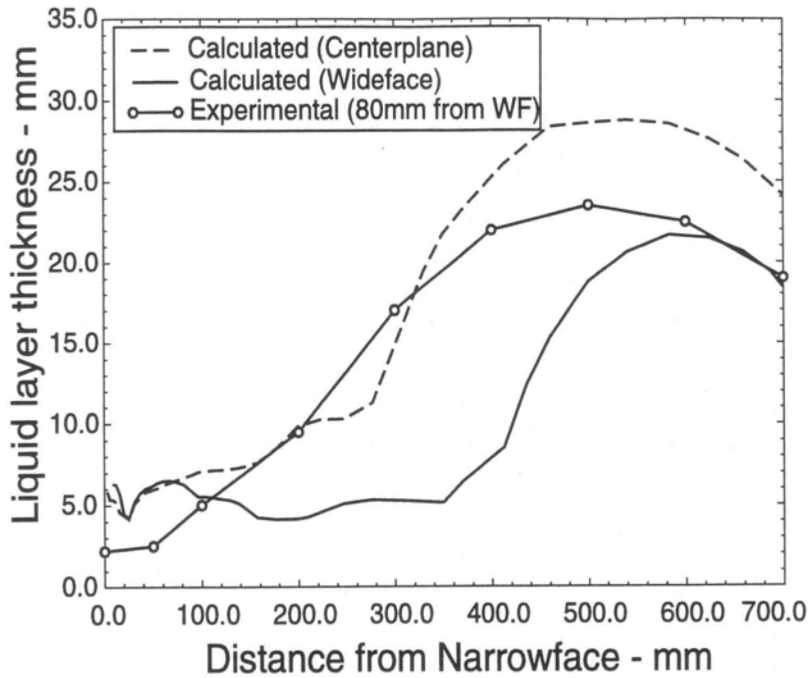


Fig. 9 Variation of liquid layer thickness across wideface

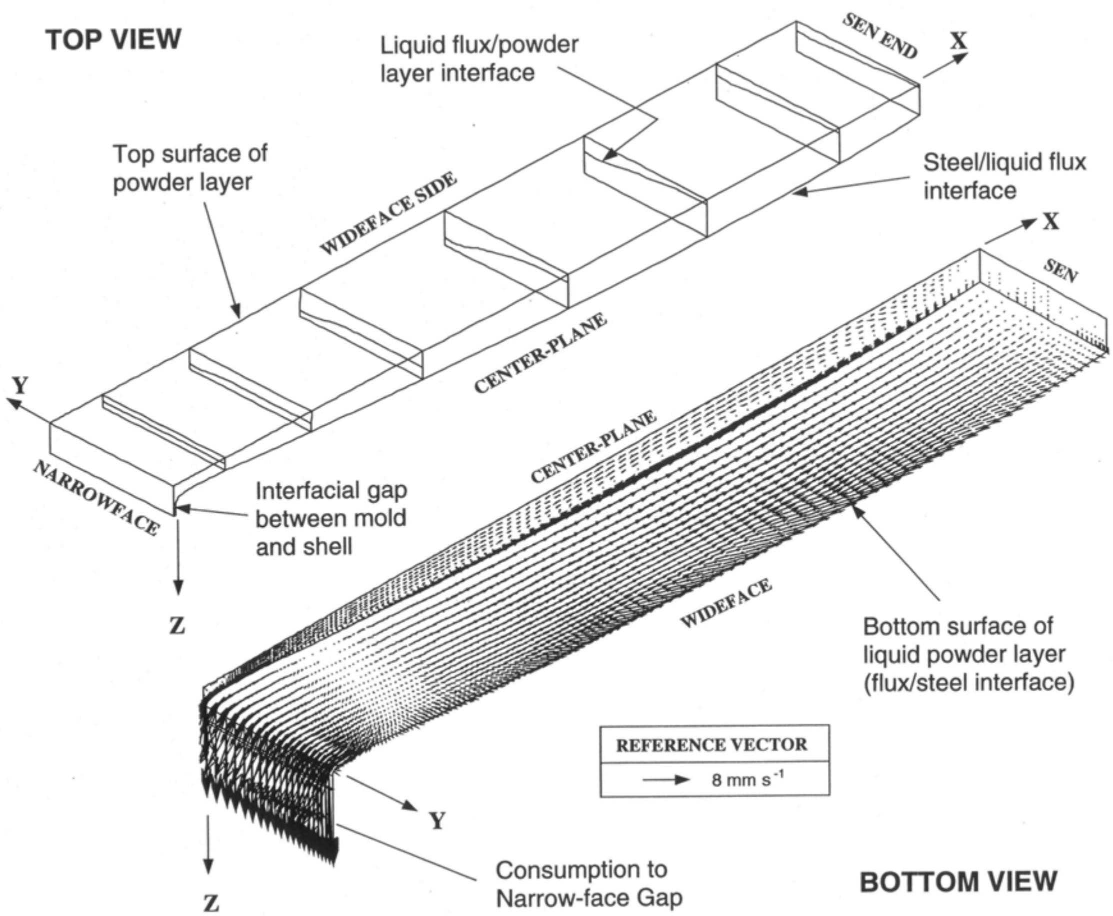


Fig. 10 Flow pattern and liquid layer interfaces calculated in top-surface flux layers

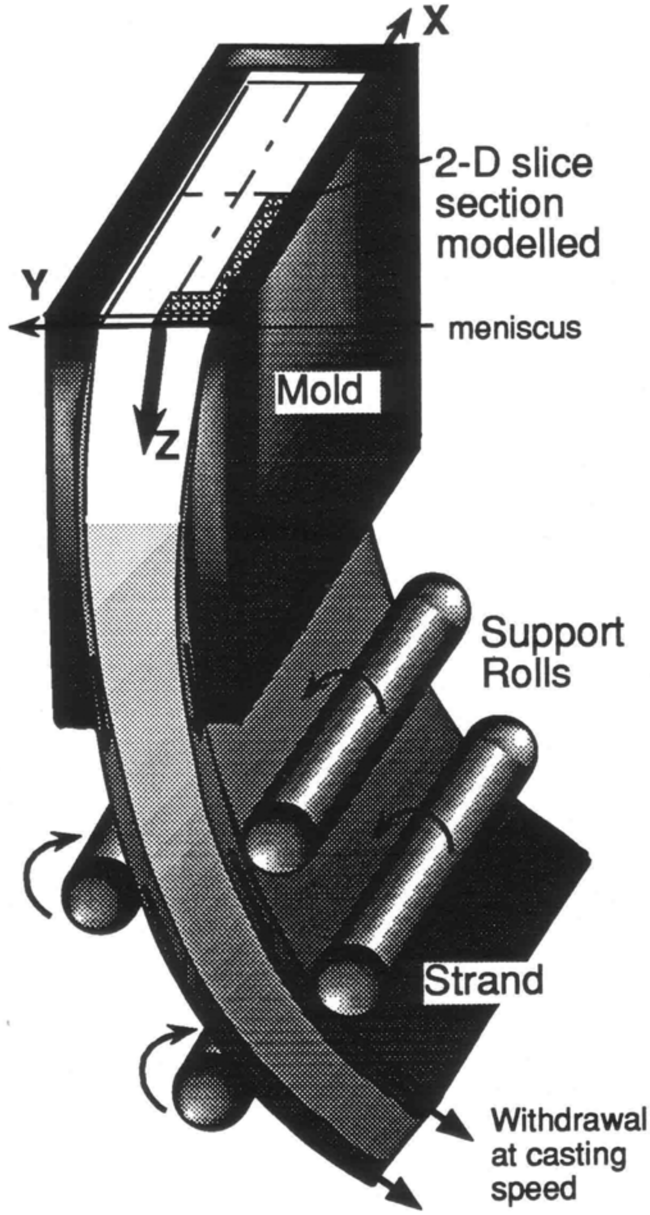


Fig. 11 Thermal-stress model domain: one quarter transverse section through strand moving down at casting speed

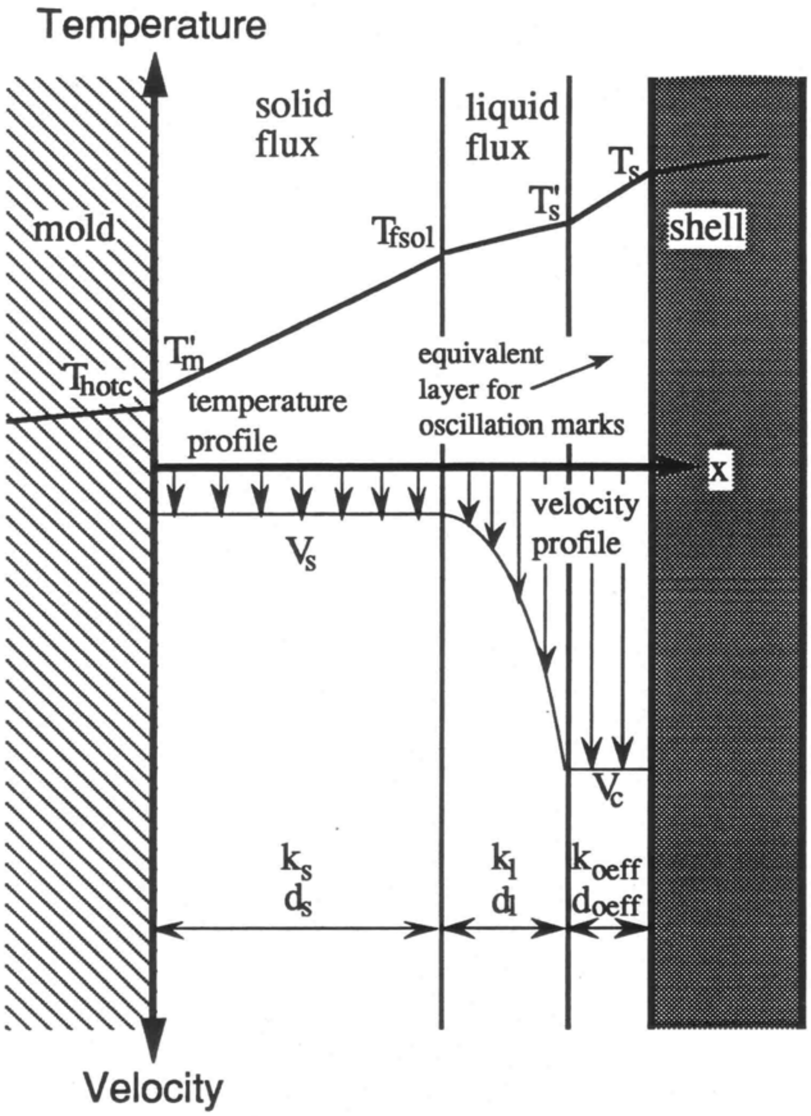


Fig. 12 Velocity and temperature profiles across interfacial gap layers (condition with no air gap)

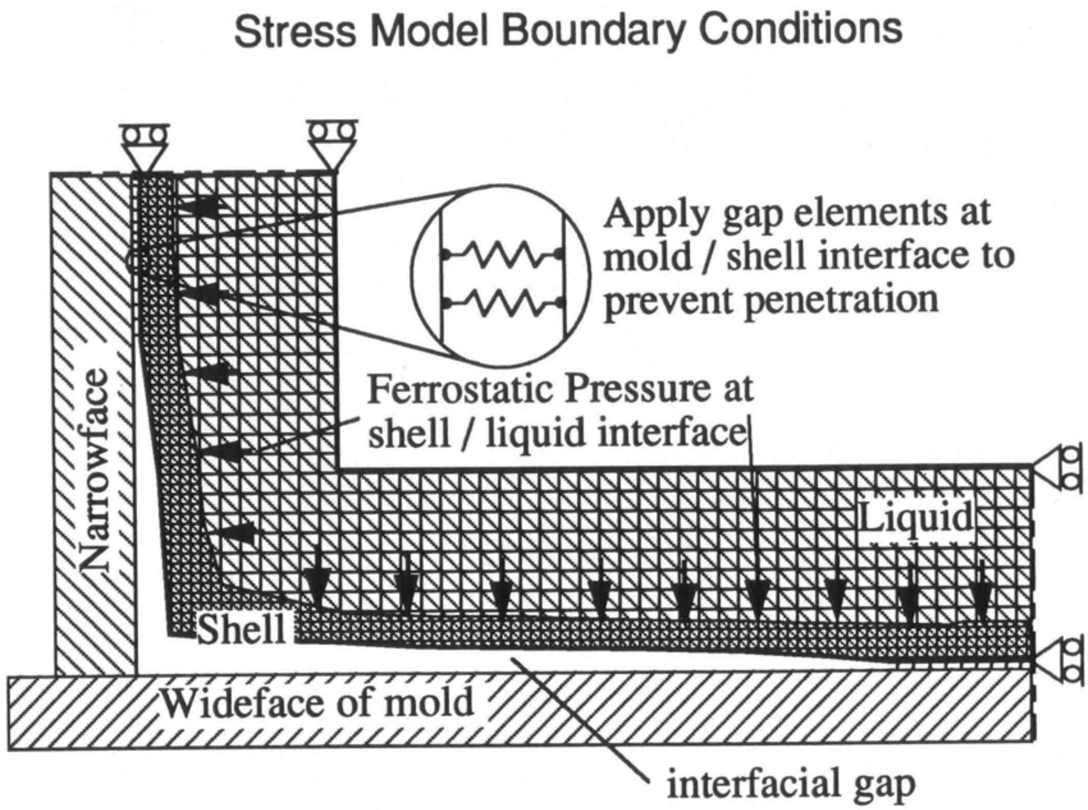


Fig. 13 Stress model boundary conditions

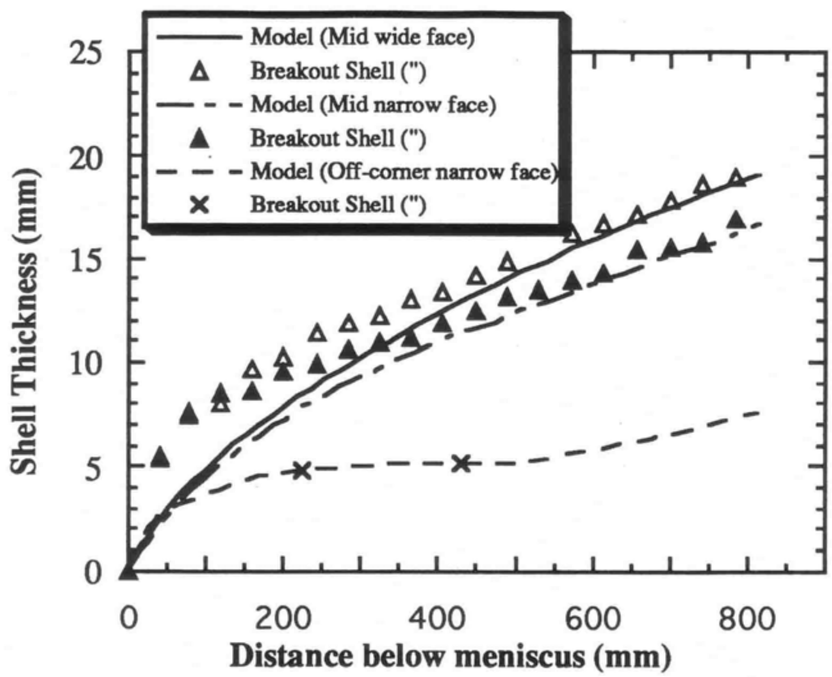
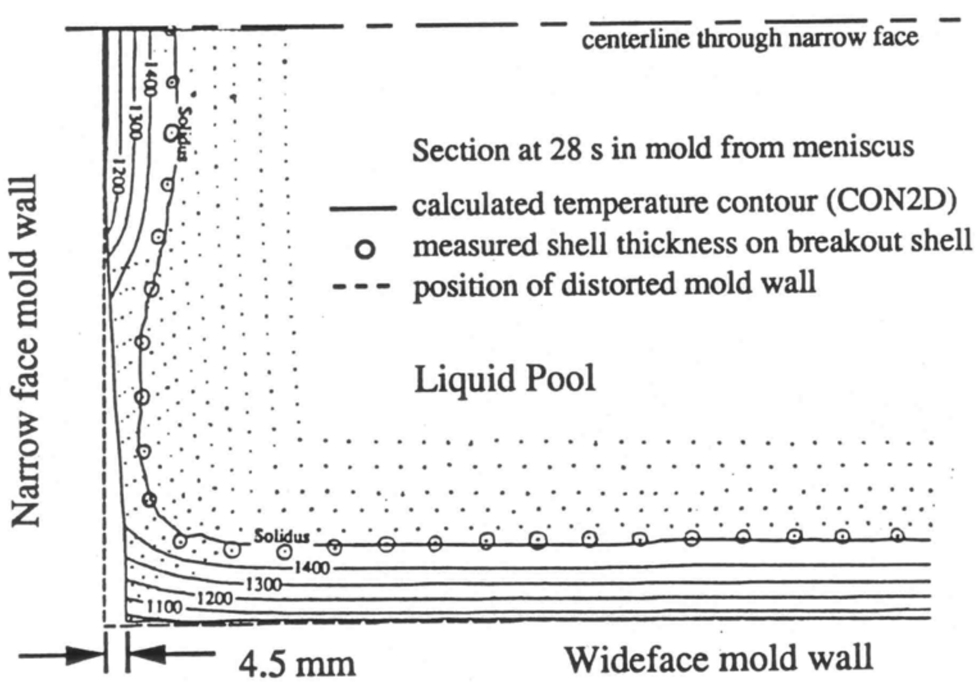


Fig. 14 Comparison of predicted shell thickness down the mold with breakout shell measurements.



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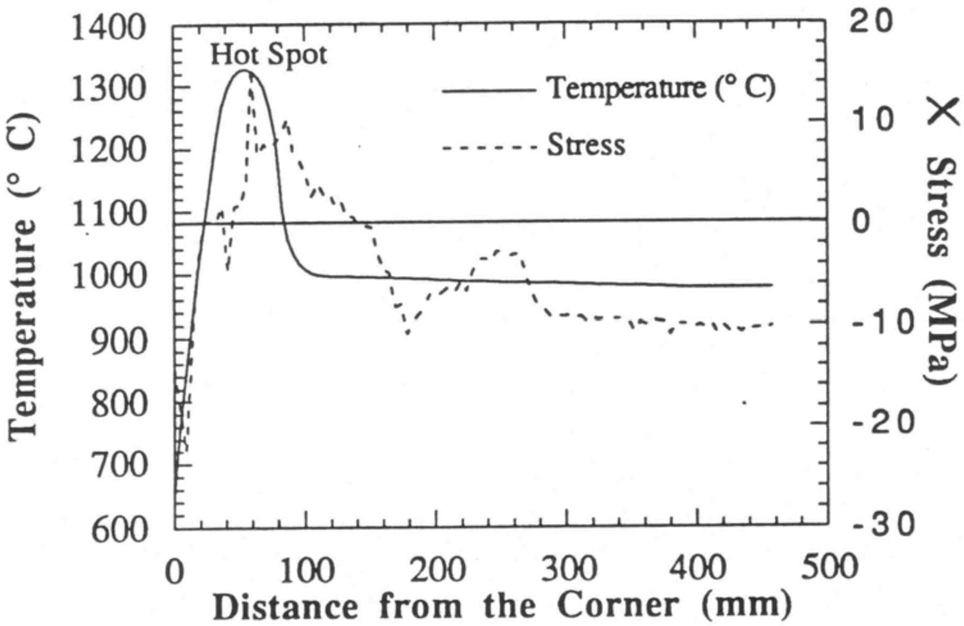


Fig. 16 Variation of temperature and tangential stress along wideface surface at mold exit showing hot spot

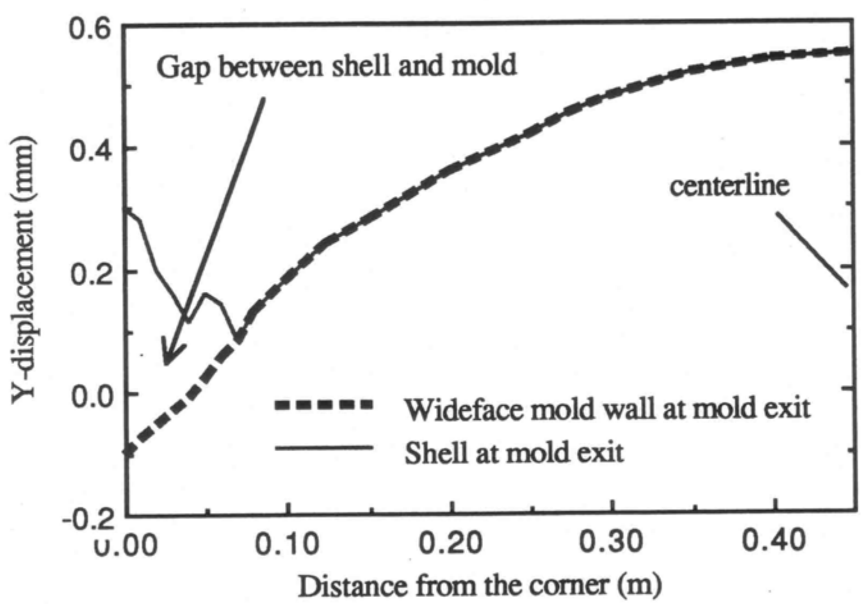


Fig. 17 Distorted position of shell / mold interface calculated along wide face at mold exit

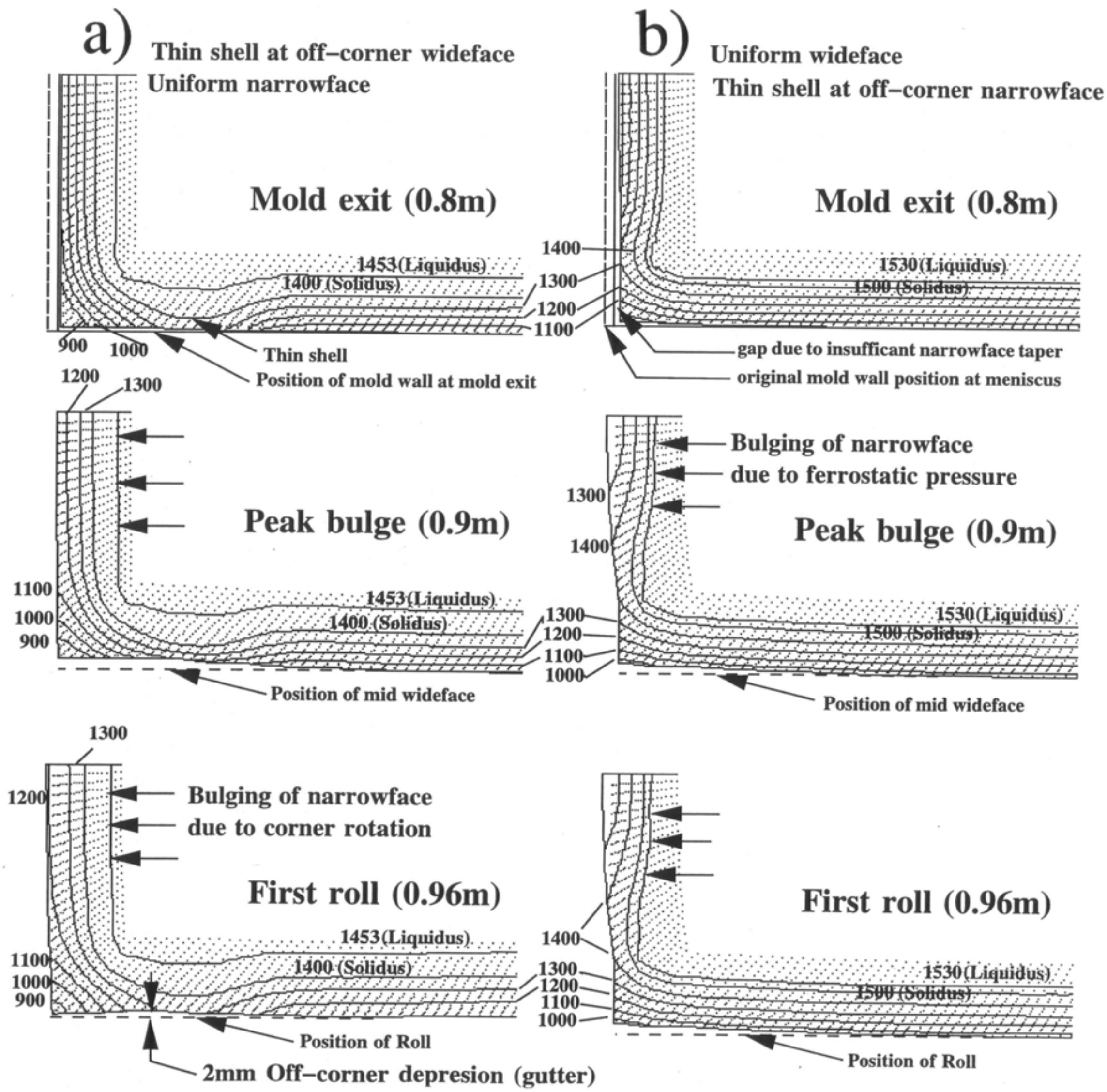


Fig. 18 Calculated evolution of shape of shell below mold with isotherms (to scale)

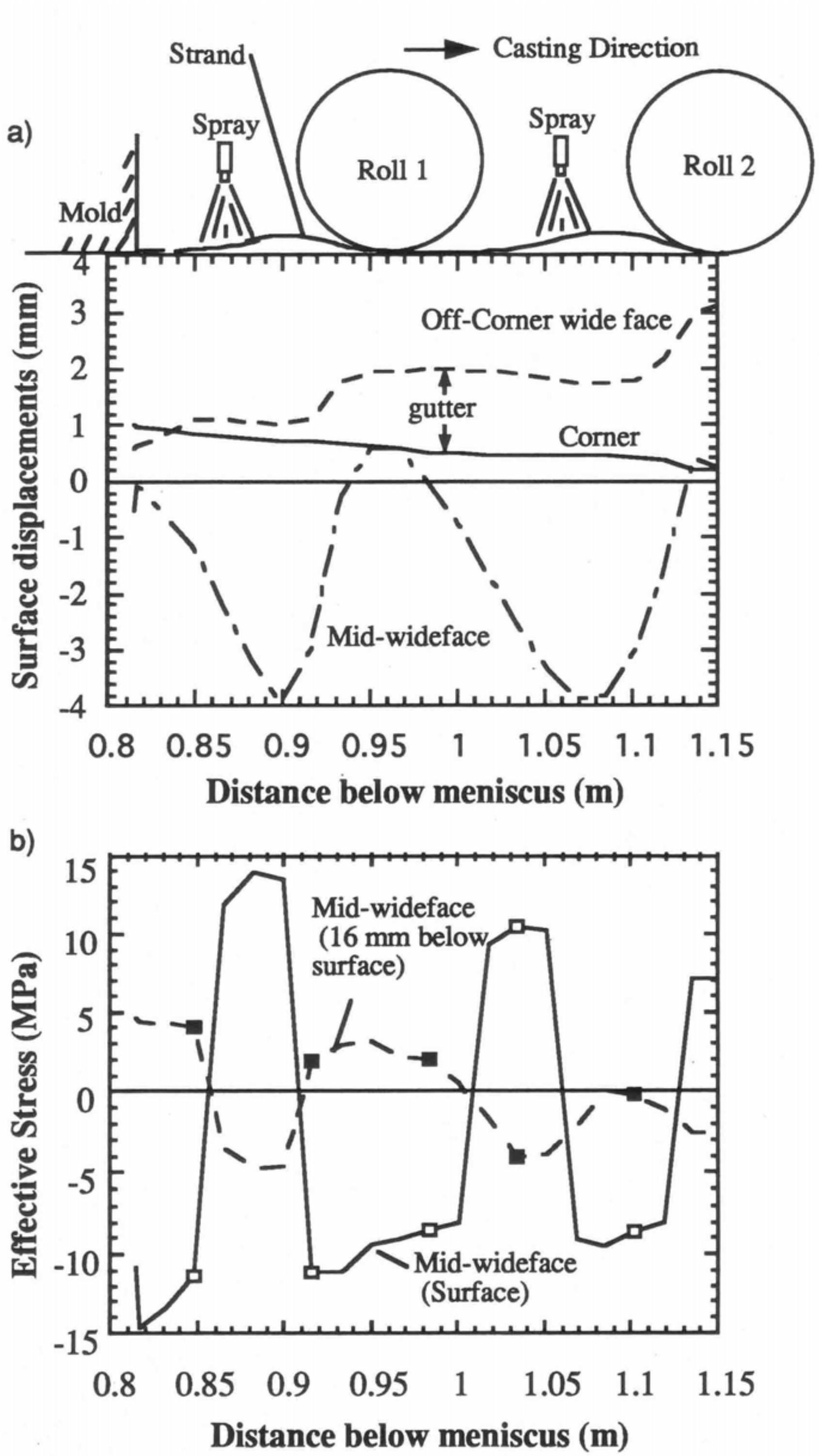


Fig. 19 a) Calculated evolution of off-corner depressions below the mold.
b) Effective stress histories along surface and subsurface (16-mm deep) of strand at mid-wide face

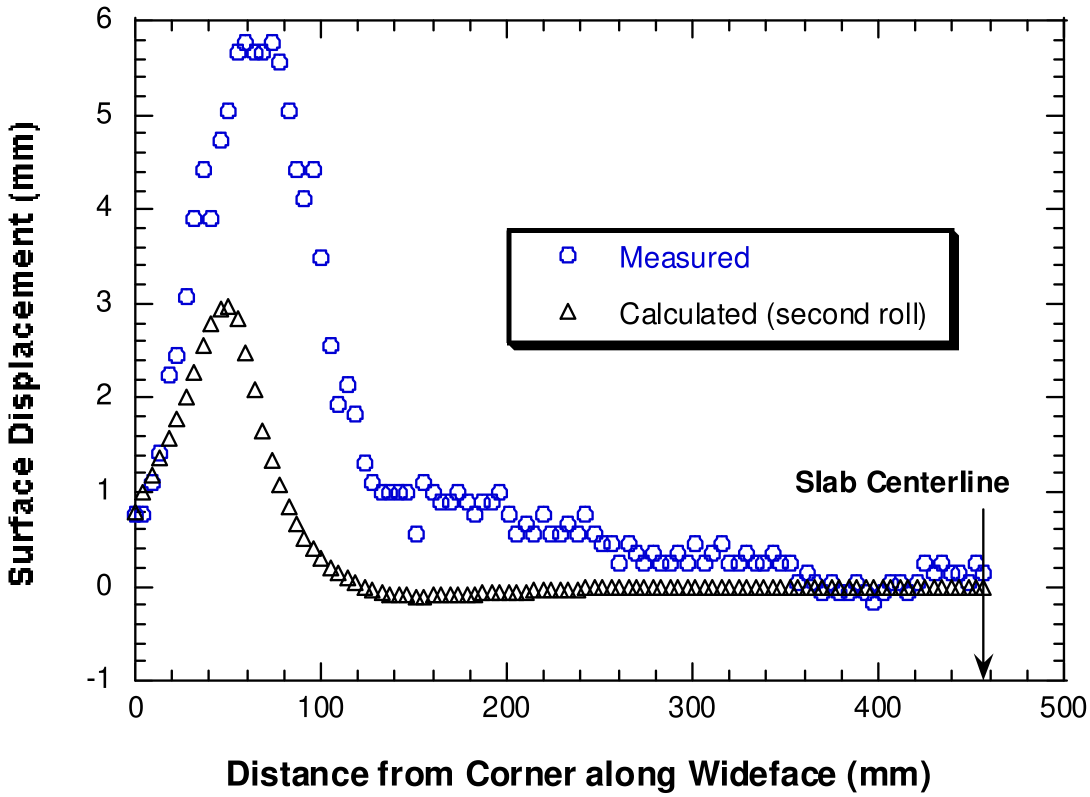
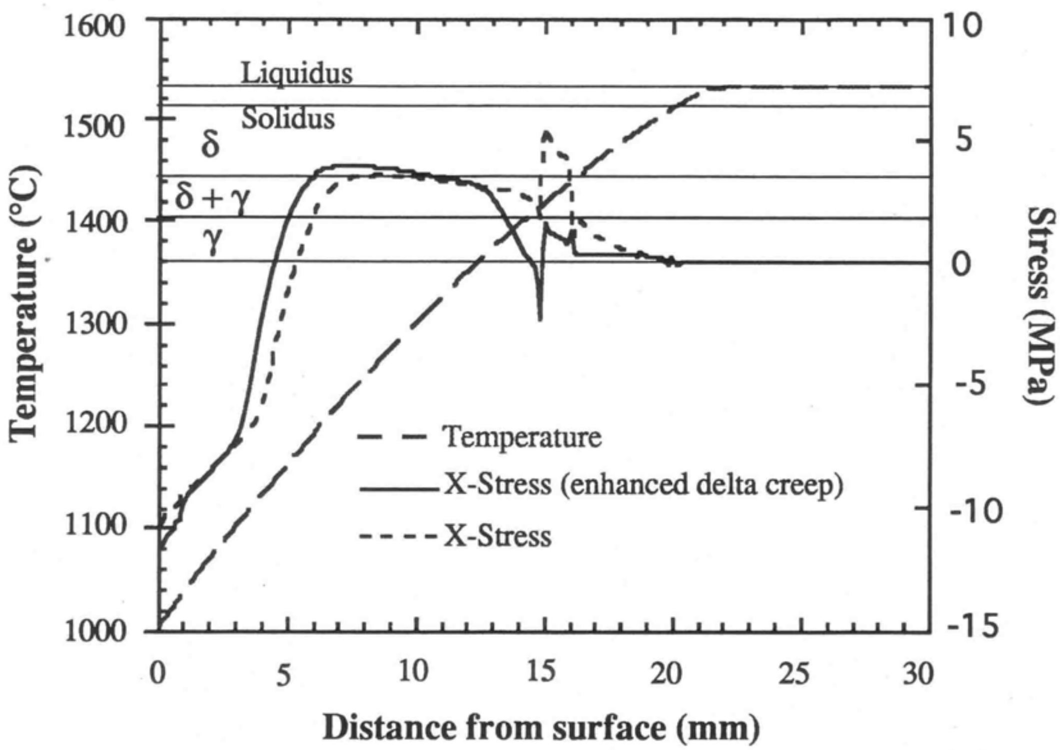


Fig. 20 Comparison of calculated and measured surface shape profile across wideface, showing gutter



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