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The influence of liquid steel level fluctuations on the formation of oscillation marks

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Abstract
In continuous casting molten steel flows through a submerged nozzle into a chilled mould. There the steel solidifies and forms a shell which is withdrawn downwards. In order to lubricate the passage of the steel shell through the mould flux powder is added on top of the molten steel. The powder melts and is drawn into a narrow lubrication gap between the mould and the strand surface. The mould oscillates vertically to prevent freezing of the steel onto the mould. However, the oscillation of the mould causes more or less regular depressions in the strand surface so called oscillation marks. In this investigation the influence of the liquid steel level fluctuations on the formation of oscillation marks will be investigated. It turns out that the depth of the oscillation marks and, the distance between two consecutive marks depend strongly on the motion of the steel level. More over the thickness of the the strand shell is effected too. This may trigger further liquid steel level oscillations caused by bulging of the strand shell below the mould.

1 Introduction

Continuous casting is a method of producing an infinite solid strand from liquid metal by continuously solidifying it as it moves through a casting machine (fig. 1). Linking steel making and hot rolling, it has become the predominant process route in modern steel production.

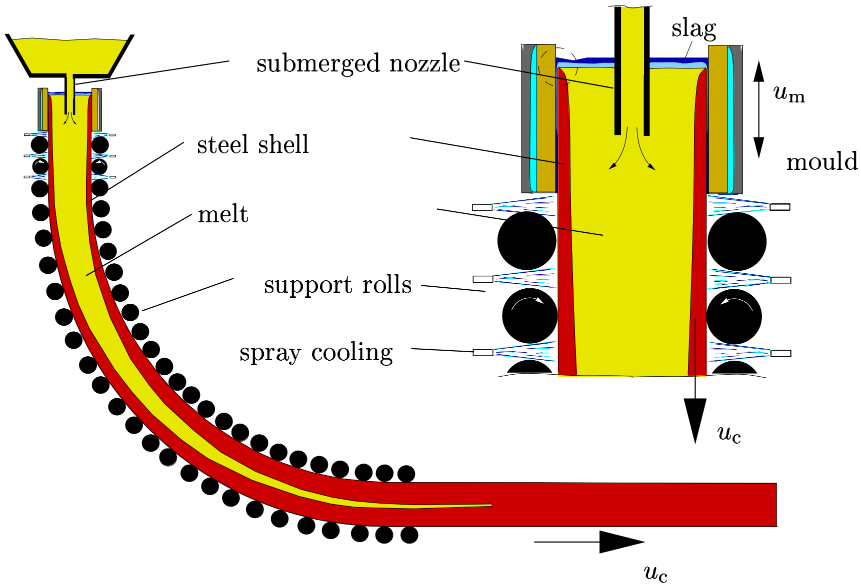

Figure 1: Continuous casting machine

Liquid metal is continuously fed into a copper mould through a submerged nozzle (fig. 1). Intense water cooling causes the metal to solidify, and by the time the metal strand leaves the mould vertically, a solid shell thick enough to withstand the ferro-static pressure of the liquid core must have formed. Outside the mould the shell is supported by support rollers. It is bent via an arc with a radius of about 10m into horizontal direction. Cooling is accomplished by water sprays and final solidification is achieved at the end of the arc.

The initial stages of solidification are crucial for the stability of the process and the quality of the strand surface. One measure to achieve that goals is to add casting powder *(flux, slag)* (fig. 2) at the top of the mould. It melts and fills a thin gap between the mould and the metal strand. This serves to lubricate the passage of the metal through the mould and to prevent direct thermal contact between the two, which would cause the strand to freeze onto the mould and consequently lead to shell rupture and liquid metal being spilt below the mould. Reciprocation of the mould has turned out to improve the reliability of the continuous casting process, but it also causes unwanted dents in the strand surface *(oscillation marks)*. The mechanisms of these two effects are still not completely understood.

Metallurgical examinations have shown that there are at least two fundamentally different ways in which oscillation marks can form [7]: A pressure difference between the molten flux and the melt can bend the solidified meniscus cusp, leaving a depression in the strand shell. Alternatively, the solidified meniscus can be overflowed by liquid metal and remain as a thumb nail trace microstructure. Both types of oscillation marks are distinguished from *ripple marks*, which are not directly related to the mould oscillation and can also occur with a static mould.

The *meniscus bending*-type oscillation marks are strongly affected by the fluid flow in the flux gap.

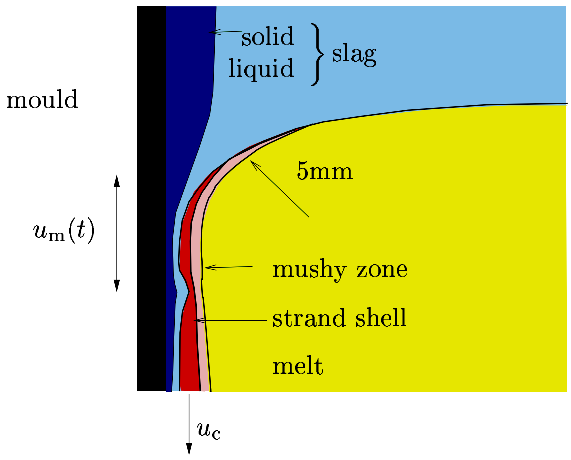

Figure 2: The meniscus region

Therefore, both analytical and numerical calculations [1, 3, 4, 5, 6, 8, 9, 10, 12, 11, 15] have been performed for quite some time to determine how changes in the flux properties or in the mould oscillation mode can improve the surface quality of the cast strand.

In a recent study [13, 14] a fully coupled, self-contained mathematical model for the formation of oscillation marks in continuously cast steel due to the *meniscus bending* mechanism has been presented. It comprises the interaction of fluid flow, heat transfer and solidification and requires only the knowledge of material properties and process parameters.

A major advantage of the model is that slag flow, heat transfer and solidification of the strand shell are solved simultaneously. Changes in the shell thickness and the position of the shell tip during each oscillation cycle turn out to have substantial influence of the formation of oscillation marks.

In the present study we will focus on the influence of fluctuations of the level of liquid steel on the formation of oscillation marks. We first review the the ingredients of the underlying model sections 2-5 and discuss the results in section 6 and 7.

2 Slag fbw

To understand the fluid flow in the slag gap, a simplified problem without solidification can be studied. This problem is closely related to *free coating*, which is applied in many industrial processes such as the production of photographic film and has been studied extensively. The theory of free coating needs to be extended to the case of an oscillating wall. Thus the Laplace Capillary length

$$L = \sqrt{\frac{\gamma}{g(\rho_{\mathrm{st}} - \rho)}}, \tag{1}$$

where γ, g and ρ_{st}, ρ are the interfacial tension between slag and steel, the gravity acceleration and the densities of steel and slag, respectively, serves as a reference length.

In this study we assume for sake of simplicity that all material properties of the liquid slag to be constant, although they depend strongly on temperature. The capillary numbers *Ca* $= \mu u_{\mathrm{m}}/\gamma$ based on the mould velocity u_{m}, the slag viscosity μ and the interfacial tension γ describes the influence of the interfacial tension compared to the viscosity effects. An asymptotic analysis for small capillary numbers identifies three distinct regions: In the *meniscus region* the pressure in the slag is dominated by the hydrostatic part. The shape of the meniscus is therefore de-coupled from the fluid flow. In the *flux gap* the pressure is essentially equal to the ferro-static pressure of the adjacent melt. The velocity of the slag is constant across the gap *(plug flow)*, and the shape of the flux gap can be described by a kinematic wave equation. Note that there is no solid strand shell in this simplified problem. Finally, a short *intermediate zone* connects the meniscus region to the slag gap. It accomplishes the rapid rise of pressure from the hydrostatic value in the meniscus region to the higher level in the gap. In this intermediate zone the direction of the mould wall motion is crucial. In the case of the mould wall moving downwards, the problem is quasi-steady, and the gap width can be expressed by simply scaling a reference solution. Near the turning point of the mould, the problem is no longer quasi-steady, and a special scaling of coordinates — including time — is necessary. In the case of the mould wall moving upwards, the width of the flux gap is governed from the bottom part of the mould, which is not part of this model. However, any effects which might propagate upwards cannot — in a first-order approximation —- affect the meniscus region, nor do they leave any trace to the next downstroke phase. All terms occurring in the asymptotic approximations are contained in a uniformly valid equation for the dimensionless gap width $\bar{w}$ which can be directly obtained using the lubrication approximation.

$$\bar{Q} = \bar{u}_{\rm m}\frac{1+\zeta_{\rm s}}{2}\bar{w} + \bar{u}_{\rm sh}\frac{1-\zeta_{\rm s}}{2}\bar{w} - \frac{(1-\zeta_{\rm s})^3\bar{w}^3}{12Ca}\left(\frac{\partial\bar{p}}{\partial\bar{x}}+1\right) . \tag{2}$$

The continuity equation over a cross section reads

$$\frac{\partial\bar{Q}}{\partial\bar{x}} + \frac{\partial\bar{w}}{\partial\bar{t}} = 0 . \tag{3}$$

Here $\bar{Q}$ denotes the dimensionless mass flow rate of flux, $\bar{p}$ the pressure in the flux gap, and $\bar{u}_{\rm m}$, $\bar{u}_{\rm sh}$ the velocity of the mould and strand shell, respectively. Due to the cooling of the mould the slag will freeze onto the mould wall. The width of the solidified slag layer is denoted by $\zeta_{\rm s}\bar{w}$.

In absence of a solidified strand shell the dimensionless pressure $\bar{p}$ is given by

$$\bar{p} = -\bar{\kappa} \tag{4}$$

where $\bar{\kappa}$ is the dimensionless curvature of the interface steel/slag.

The equations (1)-(3) are uniformly valid and therefore give a correct first-order approximation for the meniscus shape, even though the assumption of a thin layer is violated in the meniscus region.

3 Mechanical properties of the strand shell

The solid steel shell is treated as a thin plate under a transverse load due to the pressure difference between the flux gap and the mushy zone. A simple elasto-viscoplastic constitutive model is used, taking into account the variation of mechanical properties with temperature. Using a two term 'Galerkin' method we obtain an equation for the deformation of the plate:.

$$\frac{\partial\bar{\kappa}}{\partial\bar{t}} + \bar{U}_{\rm cast}\frac{\partial\bar{\kappa}}{\partial\bar{x}} = \frac{12}{\bar{E}\bar{d}_{\rm s}^3}\left(\frac{\partial\bar{M}}{\partial\bar{t}} + \bar{U}_{\rm cast}\frac{\partial\bar{M}}{\partial\bar{x}}\right) + \frac{6^{n+1}}{n+2}\frac{\bar{C}}{\bar{d}_{\rm s}^{2n+1}}\bar{M}|\bar{M}|^{n-1} . \tag{5}$$

The dimensionless material properties $\bar{E}$, n and $\bar{C}$ are taken at the interface temperature $\vartheta_{\rm if}$. The bending moment is denoted by $\bar{M}$ and the thickness of the solid shell by $\bar{d}_{\rm s}$. The strand shell moves with the casting speed $\bar{U}_{\rm cast}$ downward. The dimensionless pressure in the flux gap is given by,

$$\bar{p} = \frac{\partial^2\bar{M}}{\partial\bar{x}^2}. \tag{6}$$

The mushy zone is split into two parts: The part with a solid fraction of 40 % or more is treated in the same way as the solid shell. The rest is modeled as a thin layer of a Newtonian fluid with large (dimensionless) viscosity $\bar{\mu}_{\rm mz}$. The shell tip $\bar{x}_s$ separates these two parts of the mushy zone. An asymptotic analysis with respect to the aspect ratio of the viscous layer yields the equation for the strand velocity $\bar{u}_{\rm sh}$:

$$
\begin{aligned}
\bar{x} < \bar{x}_{\rm s}: \quad & \frac{\partial}{\partial \bar{x}}\left(\bar{\mu}_{\rm mz}\frac{\partial \bar{u}_{\rm sh}}{\partial \bar{x}}\bar{d}\right) = \frac{\bar{\mu}_{\rm sl}}{2(1-\zeta_{\rm s})^2\bar{w}}\left(\bar{u}_{\rm m}(1+2\zeta_{\rm s}) + 2\bar{u}_{\rm sh}(1-\zeta_{\rm s}) - \frac{3\bar{Q}}{\bar{w}}\right) \;, \\
\bar{x} \geq \bar{x}_{\rm s}: \quad & \bar{u}_{\rm sh} = \bar{U}_{\rm cast} \;.
\end{aligned}
\tag{7}
$$

4 Heat transfer

Heat transfer through the mould is governed by conduction from the hot face of the mould wall to the cold face and by forced convection flow in the cooling water. Using constant material properties of the copper mould and an approximation for fully developed turbulent flow, a heat transfer coefficient between the hot face and the cooling water can easily be calculated.

Heat transfer between liquid steel and liquid slag is controlled by the fluid flow on both sides of the interface. Since the inherently three-dimensional, turbulent flow of the melt cannot be adequately described by a two-dimensional model, a non-dimensional heat transfer coefficient (Stanton number) is introduced. This Stanton number mainly depends upon the geometry of the casting mould and the entry nozzle. It can therefore be viewed as a machine-specific parameter, which is obtained either from numerical simulations of the three-dimensional melt flow in a specific casting machine or from empirical data (e.g., measurements of mould temperature or oscillation mark depth).

Convection in the slag pool is calculated within the framework of the simplified problem described in the previous section (small capillary number, constant material properties, absence of solidification) using a finite-volume code. It turns out that despite the large influence of convection and the slag pool not being slim, a reasonable approximation for the temperature profile along the interface can be obtained from horizontal conduction alone.

Heat transfer in the liquid slag gap is also approximated by horizontal conduction, neglecting the heat capacity of the slag.

The energy balance for a cross section of the strand shell is

$$
\begin{aligned}
\bar{d} = 0: \quad & \bar{H}_{\rm sh} = 0 \;, \\
\bar{d} > 0: \quad & \frac{\partial \bar{H}_{\rm sh}}{\partial \bar{t}} + \frac{\partial(\bar{u}_{\rm sh}\bar{H}_{\rm sh})}{\partial \bar{x}} = \frac{1}{\mathit{Pe}_{\rm st}}\left(\bar{h}_{\rm st}\bar{\vartheta}_{\rm sup} - \bar{q}_{\rm if}\right) \;.
\end{aligned}
\tag{8}
$$

where $\bar{H}_{\rm sh}$ denotes the dimensionless enthalpy of a cross section of the strand shell.

5 Solidification

Slag in contact with the mould wall solidifies into a glassy or crystalline phase, depending on the cooling rate. For the sake of simplicity glassy solidification is assumed. In this case the effective thermal conductivity is similar to that of the liquid phase, and the latent heat of fusion can be neglected. This results in a linear temperature profile across the whole slag gap (solid and liquid phases). Between the solid slag and the mould wall a thermal contact resistance is introduced, representing the formation of an air gap.

This air gap has been observed to account for up to 50 % of the total thermal resistance in a continuous casting mould.

Solidification of the melt is described by an enthalpy method, assuming a piecewise linear dependence of the specific enthalpy of temperature in the solid, mushy and liquid phase, respectively. An integral method is applied to solve the energy equation for the strand shell. The temperature profile in the shell is approximated by a parabola satisfying boundary conditions at the strand surface and at the liquidus isotherm. Since the energy equation does not take a particularly simple form along any border, it is not used to impose further conditions upon the assumed temperature profile.

6 Numerical implementation

Based upon the ideas presented in the previous sections, a mathematical model comprising the interaction of fluid flow, heat transfer and solidification in the meniscus region is obtained. It consists of a mixed system of algebraic, ordinary and partial differential equation for fourteen non-dimensional solution variables and sixteen non-dimensional parameters. The solution variables are functions of a vertical coordinate and time. Boundary conditions at the surface of the melt are chosen to match the static meniscus. Since only the meniscus region of a continuous casting mould is being modeled, the lower boundary is an artificial one. Boundary conditions there are chosen that influence the solution as little as possible. Initial conditions can be chosen arbitrarily as long as a stable periodic solution is obtained.

The time derivatives are discretized using implicit first and second order schemes and a constant time step. This leaves a multi-point boundary value problem of ordinary differential and algebraic equations to be solved at each time step. The solution of this problem is performed in two parts. First, a *mechanical* sub-problem of six solution variables is solved by a collocation [2] method with automatic grid refinement. Then a *thermal* sub-problem consisting of a first-order differential equation and a number of algebraic equations in the remaining eight solution variables is solved iteratively using an implicit upwind scheme on an equidistant grid and a smaller time step.

The governing equations are integrated forward in time using a fixed time step size $\Delta\bar{t}$ and an implicit scheme for the discretization of time derivatives. Above the shell tip and in its vicinity, a first order scheme is applied for easy convergence. Sufficiently far below the shell tip, the oscillation marks are convected with the strand shell almost unchanged. This solution is particularly sensitive to numerical dissipation, therefore a second order scheme is applied in this region. In order to avoid numerical problems arising from the variation of the location of the shell tip x_s , the intervals $(\bar{x}_0, \bar{x}_\mathrm{s})$ and $(\bar{x}_\mathrm{s}, \bar{x}_\infty)$ are both mapped to the standard interval $(0, 1)$. This transformation maps the shell tip to $\xi = 0$ and both ends of the solution domain ($\bar{x} = \bar{x}_0$ and $\bar{x} = \bar{x}_\infty$) to $\xi = 1$.

Additional boundary conditions at $\xi = 0$ ensure the continuity of $\bar{w}$, $\partial\bar{w}/\partial\bar{x}$, $\bar{Q}$ and $\bar{p}$. The resulting multi-point boundary value problem is solved by a collocation method [2].

7 Moving liquid steel level

If the liquid steel level and all other casting conditions are constant a more or less periodic surface structure forms. The oscillation marks have a constant spacing and depth. However, in practice the casting conditions cannot be kept constant. There will be fluctuations in the liquid h level due several causes: non constant supply of liquid steel, surface waves or bulging of the strand shell between the support rolls. That is the following phenomenon: Assume the strand shell is at a certain position a little bit weaker than usual. If this weaker part of the strand shell is between two support roller the strand shell will deform outwards which creates an additional volume for the liquid steel and thus the bath level sinks. On the other hand if the weak part of the shell is approaches a support roll the volume for the liquid steel is reduced and the bath level rises again. It has been observed that the fluctuations of the liquid steel level may lead to weaker sections of the strand shell which in turn cause via bulging and steel level oscillations. Thus there may be a feed back mechanism which may lead to unstable operating conditions.

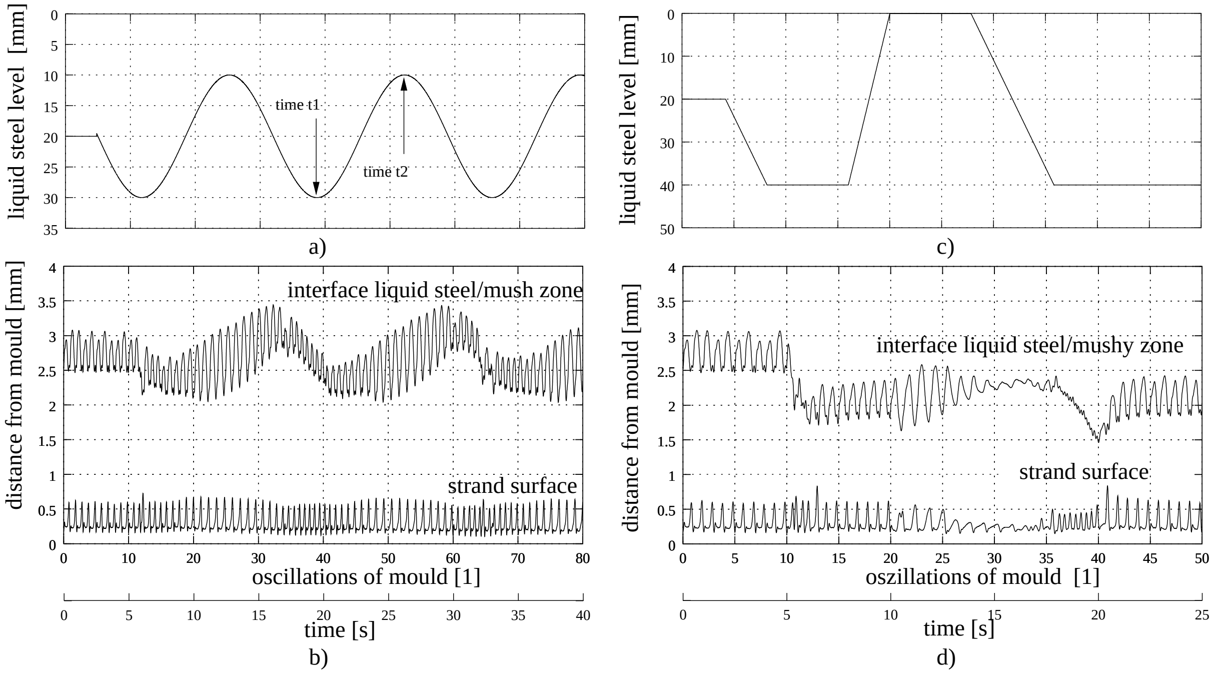

Figure 3: Influence of bath level oscillation on the formation of the strand shell. Shell surface and Interface liquid steel/mushy zone at fixed reference point 80 mm below origin of coordinate system. Sinusoidal bath level fluctuations: a) position of bath level, b) strand shell at reference point; arbitrary bath level fluctuation c) position of bath level, d) strand shell at reference point.

In the following we will prescribe the steel level as function of time. We consider two examples: a periodic (sinusoidal) and piecewise linear changes of the melt level.

7.1 Sinusoidal level fluctuations

Here we assume a sinusoidal motion of the steel level with a frequency of $f = 4.4\,\mathrm{min}^{-1}$ an amplitude of$s = 10\,\mathrm{mm}$ (figure 3a). At a fixed reference point x_{ref} the distance of the strand surface and the interface solid/liquid steel from the mould wall are shown, respectively. In figure 4 the snap shot of the strand shell is shown at two different times: At t_1 the steel level is at its lowest position and at t_2 it is at the highest position. We can see clearly the oscillation marks as indentations in the shell surface. Due to the worse heat transfer at the oscillation marks the solidification speed is there locally slower producing a mirror of the oscillation marks at the interface solid/liquid steel. The distance between oscillation marks at t_1 is markedly smaller than at t_2. the marks at t_1 have been produced during a lowering of the steel level, the marks at t_2 during a rise of the steel level. To some extend the motion of the steel level has a similar a effect than the change of casting speed, since the relative speed of the meniscus to the mould is primarily responsible for the formation of oscillation marks. Thus a falling level corresponds to a slower, a rising level to faster casting speed.

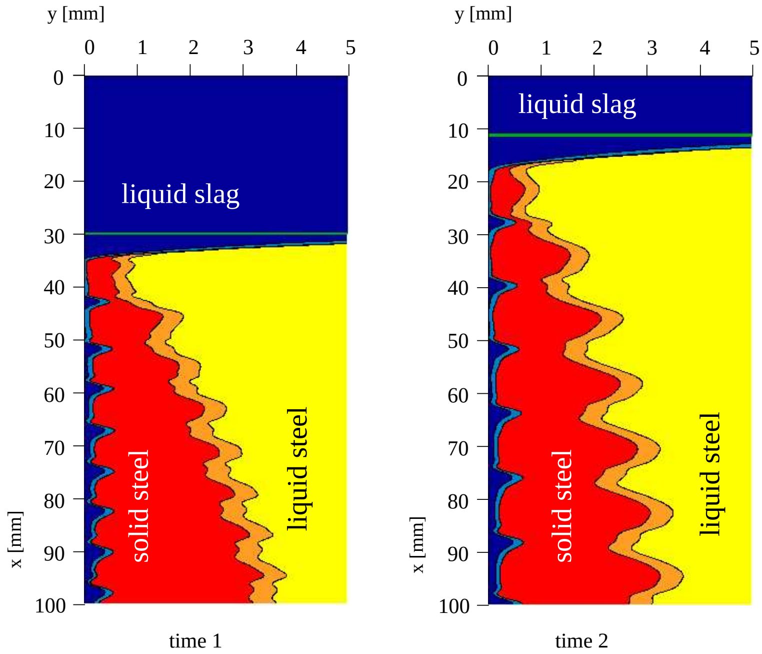

Figure 4: Sinusoidal fluctuations of bath level, oscillation marks at time t_1 lowest and t_2 highest level of liquid steel

Moreover, in figure 3b we see that the averaged strand shell thickness varies with the same frequency as the steel level, but the maximum of the strand shell thickness occurs later than that of the steel level. The time difference corresponds to the time needed for a cross section of the strand to move from the meniscus to the reference point.

If the frequency of the level oscillation is such that the distance between two (averaged) shell thickness minima is close to the spacing of the support rollers below the mould bulging of the the strand shell may amplify the steel level oscillation.

7.2 Arbitrary bath level fluctuations

In a second example we investigate an arbitrary steel level fluctuation. We start with a constant bath level at $x = 20\,\mathrm{mm}$ below the origin of the coordinate system. Then the level is linearly (with time) lowered to $x = 40\,\mathrm{mm}$ for 8 mould oscillations. During another 4 mould oscillations the bath level rises rapidly to $x = 0$, where it is again constant for 8 mould oscillation and finally drops slowly to $x = 40\,\mathrm{mm}$ during 8 mould oscillations (fig 3c).

In figure 3d we show the shell thickness and the form of the strand surface and the interface solid/liquid steel at a reference point 8o mm below the origin of the coordinate system. As said above the change of the steel level will appear retarded at the reference point by $(x_{\mathrm{ref}} - x_{\mathrm{lev}})/u_c$ where x_{ref} and x_{lev} are the position of the reference point and the bath level respectively and u_c is the casting speed.

The first lowering of the steel level leads to smaller distances between the oscillation marks and a markedly thinner strand shell. The form of the oscillation marks become regular again after the steel level has reached a constant position at $x_{\mathrm{lev}} = 40\mathrm{mm}$. During the rise of the steel level the distance between oscillation marks first increase then there depth becomes significantly smaller and they almost vanish.

During the second lowering of the steel level small periodic oscillation marks form and the shell thickness decreases. After the constant position is reached periodic oscillation marks and a periodic interface solid/liquid forms after some relaxation time of 4 to 5 mould oscillations.

8 Summary

A model based on the lubrication approximation for the slag flow has been developed to describe the entrainment of flux into the lubrication gap between the strand shell and the mould. Coupling with the heat transfer problem and a model describing the deformation of the strand shell the early stages of solidification can be described.

The model equation are very sensitive to perturbation and thus great care has to be taken by the numerical evaluation. At two examples it has been shown that the form and spacing of the oscillation marks and the shell thickness is very sensitive to changes in the level of liquid steel.

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References

[1] E. Anzai, T. Ando, T. Shigezumi, M. Ikeda, T. Nakano, *Hydrodynamic behavior of molten powder in meniscus zone of continuous casting mold*, Nippon Steel, Technical report 34, (1987), 31-40.

[2] U. Ascher, J. Christiansen, R. D. Russell, *Collocation software for boundary-value ODEs*, ACM Trans Math Software, 7, (1981), 209-222.

[3] T. J. H. Billany, K. C. Mills,*Mould flux performance during continuous casting*,Commission of the European Communities,Directorate-General Science, Research and Development,EUR 12140 EN (1989).

[4] D. R. Bland, *Flux and the continuous casting of steel*, IMA J. Appl. Math., 32, (1984), 89-112.

[5] J. K. Brimacombe, I. V. Samarasekera, *The thermal field in continuous casting moulds*, Iron&Steelmaker Magazine, 6 (10), (1979), 20-27.

[6] J. A. Di Lellio, G. W. Young, *An asymptotic model of the mold region in a continuous steel caster*, Metal. Mater. Trans. B, 26B, (1995), 1225-1241.

[7] J. Dixon, A. A. Howe, I. Stewart, P. Jervis, *Reduction of reciprocation marks by high frequency vibration of the continuous casting mould*, Commission of the European Communities, EUR 10499 EN, Directorate-General Science, Research and Development, (1986).

[8] I. A. Frigaard, *A mathematical model of the mould-strand gap in a steel continuous casting machine during normal operation*. Institutsbericht 490, Institut für Mathematik, Johannes-Kepler-Universität Linz, Austria (1995).

[9] J. R. King, A. A. Lacey, C. P. Please, P. Wilmott, A. Zoryk, *The formation of oscillation marks on continuously cast steel*, Math. Eng. Ind., 4 (2), (1993), 91–106.

[10] O. Pütz, O. Breitfeld, S. Rödl, *Investigations of the Flow Conditions and Solidification in Continuous Casting Moulds by Advanced Simulation Techniques*, Steel research, **74**, (2003) 686-692.

[11] I. B. Risteski, *A mathematical model of the conduct of the molten powder in the gap between the mould and the slab in the vicinity of the meniscus,* Steel & Metals Mag., 28 (10), (1990), 661–665.

[12] H. Sha, *Beiträge zum Entstehungsmechanismus der Oszillationsmarken beim Stranggießen*. Ph-D thesis, Technische Universität Clausthal (1997).

[13] C. Rudischer, *The interaction between fluid flow, heat transfer and solidification in a continuous casting mould.* Ph-D thesis, University of Technology, Vienna, Austria (2001).

[14] H. Steinrück, C. Rudischer, *Mathematical Modeling of the Formation of Oscillation Marks in Continuous Casting of Steel*, in J.C. Misra ed., *Topics of Industrial Mathematics*, Narosa Publishing House, New Delhi, India, (2003), 1-62.

[15] E. Takeuchi, J. K. Brimacombe, *The formation of oscillation marks in the continuous casting of steel slabs*, Metals Tans. B. 15B , (1984), 493–509.