The formation of oscillation marks
in continuous casting of steel

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 steelmaking and hot rolling, it has become the predominant process route in modern steel production.

Liquid metal is continuously fed into a copper mould through a submerged nozzle (fig. 2). Intense water cooling causes the metal to solidify, and by the time the metal strand leaves the mould, a solid shell thick enough to withstand the ferrostatic pressure of the liquid core must have formed. This shell is extracted at constant speed, and spray cooling then completes the solidification process outside the mould. Casting powder (flux, slag) is added 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), see fig. 3. 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: 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. In any case, imperfections of the strand surface are a major obstacle to directly rolling the hot strand as it leaves the casting machine. Instead, the strand is cooled to ambient temperature, inspected for surface faults and treated appropriately (e.g., by grinding), and then re-heated for hot rolling. Direct rolling could save a substantial amount of energy.

The meniscus bending-type oscillation marks are strongly affected by the fluid flow in the flux gap. Therefore, both analytical and numerical calculations 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.

The different length scales in the fluid flow of liquid steel are the main obstacle for the simulation of the entire flow and solidification process. The longitudinal extend of the melt flow is about 10 m. The is the distance from the nozzle to the point where the strand is completely solidified. The height of the mold is about 1 m. In contrast to that the radius of curvature of the meniscus is about 5 mm and the width of the lubrication gap between the strand shell and the mould is below 1 mm. Therefore modelling of the interaction of the slag flow with the steel melt and the strand shell is unavoidable.

In this project a fully coupled, self-contained mathematical model for the formation of oscillation marks in continuously cast steel due to the meniscus bending mechanism will be presented. It comprises the interaction of fluid flow, heat transfer and solidification and requires only the knowledge of material properties and process parameters.
Starting from a two-dimensional view of the top part of the mould (the region near the meniscus), the theory of thin layers is applied. This approach is reasonable for the mould wall, the flux gap and the strand shell, not however for the turbulent flow of the melt (for which already the two-dimensional view would be an inappropriate simplification). Therefore, the melt flow is not covered by this model, and the heat transfer in the melt must be determined separately. This can either be done experimentally (e.g., by temperature measurements in the mould wall) or numerically (by some computational method suitable for three-dimensional turbulent flow). A second aspect not covered by the model presented here are differences between the broad faces, the narrow faces and the corner regions of the mould. Where those differences matter, this model best describes the centre of a broad face.

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.

2 Slag flow

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.

Near the meniscus, interfacial tension plays a dominant role. An asymptotic analysis for small capillary numbers identifies three distinct regions (fig. 4): 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 ferrostatic 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 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. Figure 5 shows the gap width in the intermediate zone during a short time slice around the lower turning point of sinusoidal mould oscillation. 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.

The equations obtained by this asymptotic analyses 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 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
Figure 5: Gap width in the intermediate zone at the lower turning point of sinusoidal mould oscillation.

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. Figure 6 shows temperature profiles at the mould wall and at the slag–steel interface during a period of sinusoidal mould oscillation. 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.

4 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.

5 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. The deflection of the solid strand shell is calculated by a Galerkin method.

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 modelled as a thin layer of a Newtonian fluid with large viscosity. An asymptotic analysis with respect to the aspect ratio of the viscous layer shows that the pressure is equal to that of the melt. The velocity profile of the slag is affected by the mushy zone only near the tip of the solid shell, where the viscosity of the mush is much larger than that of the slag.

6 A mathematical model of the meniscus region

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 modelled, 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 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.

This solution algorithm is validated by solving the same physical problem with different time step sizes. Figure 7 shows the width of the flux gap evaluated after a fixed number of oscillation periods. Smaller time steps yield sharper oscillation marks and smaller numerical oscillations between the marks. For most calculations 128 time steps per oscillation period are a good choice, some sets of physical parameters however require a smaller time step.

### 7 Numerical results and experimental data

Figure 8 shows some results of the calculation for a representative set of physical parameters. The red line at the top shows the sinusoidal mould oscillation. Below are five snapshots of the meniscus region corresponding to the black dots along the mould oscillation line. The regions of solid and liquid slag are shaded in dark and light blue, respectively. The solid
strand shell is marked red, the mushy zone orange, and the steel melt yellow. The numerical results suggest that oscillation marks form by loose pieces of solid steel freezing onto the shell at the end of the upstroke phase, when the flux gap is very thin and the cooling from the mould very strong. This result is somewhat contrary to other authors considering the negative strip phase (when the mould velocity exceeds the casting speed) as crucial for the formation of oscillation marks.

A parametric study is performed to test the model against experimental data. The only parameter used for fitting is the Stanton number, which depends strongly on the geometry of the casting machine. Figure 9 shows that the results are in excellent agreement with the experimental data.
Figure 8: An oscillation cycle: a. sinusoidal mould oscillation and position of the shell tip, b. snapshots of the flux gap (blue) and the strand shell (red).
Other results from this numerical study are:

- Oscillation mark depth and specific powder consumption are very strongly correlated. This suggests that the slag trapped in the oscillation marks accounts for most of the consumption.

- Both oscillation mark depth and specific powder consumption decrease with increasing casting speed.

- The influence of oscillation stroke and frequency on oscillation mark depth and specific powder consumption is non-monotonic.

This last result is in agreement with the fact that contradictory trends have been reported in the literature: Most authors report a decrease in powder consumption and/or oscillation mark depth with decreasing stroke and increasing frequency. However, in some frequency regimes the adverse trend has also been found. Figure 10 gives a three-dimensional view of the relation between oscillation stroke, frequency, and powder consumption for a fixed casting speed.

8 Outlook

More extensive parametric studies based on the model presented here should be carried out. They could include non-sinusoidal oscillation modes as well as different casting temperatures and powder properties. All these factors are of great practical interest.

Further enhancements to the model should include crystalline solidification of the slag, a more sophisticated treatment of the convection in the slag pool, or possibly a coupled calculation of the melt flow. Also, an attempt could be made to describe the formation of oscillation marks due to the overflow mechanism.
specific powder consumption $m_{sl} \, / \, \text{kg/m}^2$

Figure 10: Calculated powder consumption for various oscillation parameters.