# Thoughts about the initial solidification process during Continuos casting of steel

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## Abstract

The initial solidification process in a continuos casting process are very important for the surface quality of the strand. Oscillation marks are formed by the mould oscillation. One mainly distinguishes between two different types of marks namely folding marks and overflow marks. The heat flow and the surface tension balance can describe the formation of these two types. A theoretical analysis is presented to line out the most important parameters describing these two types of marks.
A metallographic analysis of the formation has also been performed. The theory and the observations are used to analyse the effect of the casting speed and the oscillation frequency on the formation of the different types of marks. It is shown that a meniscus is formed at the top of the growing shell. The maximum height of the meniscus is determining the ideal distances between the marks. The mould frequency is related to this height. A frequency not related to the ideal one gives rise to overflow marks and folded marks with macrosegregation and cracks. The distances between the marks will in such a case not be constant. The depth of the marks is calculated by the heat flow and the surface tension balance. It is discussed that the depth of the mark decreases with increasing superheat and decreasing surface tension of the meniscus. The crack formation in the folded mark and the segregation in those marks are discussed. Segregation is also formed together with the overflow marks. The formations of these types of segregations are as well discussed.

## Introduction

The most critical zone in continuous casting is in the upper part of the mould. Here the liquid metal forms a meniscus in contact with molten, and solidified, casting powder and the surface of the strand is created as the solidification of the metal starts. The most common defects on continuously cast material, the oscillation marks, are formed in the meniscus region. For some materials these marks must be grinded away before the material can be allowed to go to the next manufacturing step. In some cases there are deeper defects, e.g. cracks, but those kinds of defects are usually very local while the oscillation marks covers all surfaces of the cast strand. The necessary grinding step is an extra cost, and an extra time step in the production line, that could be saved if the surface was good enough directly after the casting process. The formation of oscillation marks has been well examined. There are several models describing the formation of oscillation marks in continuous casting [1]. The models are based on some kind of force balance and it has been assumed that it is the oscillation that causes the marks. This explanation is insufficient since the same kind of marks has been observed in statically cast products as well. To be able to control the formation of marks, the mechanism of the formation must be fully known. In this work the instabilities at the meniscus are considered to be connected to the surface tensions between the different phases. The meniscus has a maximum height, above which the surface tension balance collapses and thereby the meniscus itself. This maximum height will determine the oscillation frequency of the mould.

## Experimental observation

A number of break throughs have been analysed. Mainly two different types of oscillation marks were observed. In the literature those marks are defined as overflow marks and folding marks. The formation of overflow marks can be described in the following, simplified, way. The solidified shell are growing upwards and inwards and form a curvature inwards. Liquid flows over this solidified shell and fills up the space between the solidified curved shell and the mould. Sometimes melt is drawn downwards and a hook is formed in the bottom of the mark. Macrosegregations are formed in the mark and at the volume just above the first formed curved shell. The crystal structure in the overflow and downdrawn liquid is often equiaxed.
The structure in the folded mark is often described in the following way. The same curvature surface of the solidified shell is formed but no overflow will take part, instead the front is bent backwards and grows towards the mould. A bay is formed on the surface. Cracks are often seen in the bottom part of the bay and macrosegregated liquid is often found in the bottom part of the bay.
It was further on observed that the two types of marks are not related to a single casting but are mixed at the surface of the same casting. Both overflow marks and folded marks are repeated in a regular pattern. There are regions with shorter and longer distances between the marks. It was observed that the overflow marks dominated in the part where the mark distances was smaller than the average distance. The folded marks were observed in the parts where the distance was longer than the average one. In some cases it was observed two types of folded marks, deep ones with shallow ones there between.

The microstructure of shells from break throughs was also analysed. Figure 1a shows the microstructure at the top in one of the shells. The figure shows a coarse and a fine dendrite structure. The coarse structure has been formed during the normal casting conditions and the fine structure reveal the thin layer of liquid left at the shell when the bulk liquid is drained. It is interesting to note that the remaining liquid forms a thin layer at the top and form a bay against the mould. The solid never forms a continuos layer against the cold surface. The surface tension will in this case draw the liquid over the solid shell. The surface tension balance is as is illustrated in figure 1b. It has further on been observed that the top shell not form a continuos even line around the mould shell. Figure 2a shows one case where the layer forms a jog at the top. Observation perpendicular to this, figure 2b shows that the layer growth has occurred in steps. A thin layer of uniform thickness is formed at the top. This layer corresponds to the height of an oscillation mark.

## Model Description

The observations described in figure 1 and 2 gives the following explanation to the formation of the oscillation marks. Starting with a flat upper surface of a liquid in contact with a cold mould, illustrated in figure 3, a solid layer is formed against the cold surface. New liquid is filled in and the height of the meniscus, formed at the upper surface of the liquid, increases. The surface tension will now make the liquids upper surface rise but the solid layer only grow inwards and not much upwards. When the meniscus gets high enough it will overflow the shell and a mark is formed. This phenomenon will occur in all casting processes with a rising liquid and with a heat transport perpendicular to this surface such as in ESR-processes and in ingot casting processes. The oscillation of the mould in a continuos casting process will however effect the formation process and the relation between the oscillation frequency and the overflows will determine if the marks formed will be overflow or folding marks. This will be further on discussed below.

We will assume that a balance between the surface tension force and the gravity force describes the upper surface of the meniscus. The profile of this meniscus was analytically described by Bikerman [2]. His equation describes the shape of the upper surface of a melt in any kind of tube. Figure 4 shows the profile for iron in contact with its own vapour.

The idea of overflow of the meniscus was described in 1979 by Sato [3] but he connected it entirely to the oscillation of the mould while we suggest that the surface tension balance control the overflow. In that case the model can be used for explaining, not only oscillation marks in continuous casting, but also the formation of folding marks in static casting.

The distance between the collapses will be influenced not only by the surface tension but also by the metallostatic pressure, by the convection in the liquid metal as well as by the oscillation. The shape of the meniscus is influenced by the mould oscillation. Probably the height of the meniscus decreases during the downstrokes and increases during the upstrokes.

### Numerical model

We will now calculate the depth of a folded oscillation mark. At the upper surface the shape of the meniscus is described by Bikerman [2]:

$$x - x_0 = -\sqrt{2a^2 - z^2} + \frac{a}{\sqrt{2}} \ln \frac{a\sqrt{2} + \sqrt{2a^2 - z^2}}{z} \qquad (1)$$

x is the direction perpendicular to the mould wall and z is parallel to the wall, see figure 4.

$$x_0 = a - \frac{a}{\sqrt{2}} \cdot \ln\left(\sqrt{2} + 1\right) \approx 0.3768a \qquad (2)$$

$$a^2 = \frac{2 \cdot \sigma}{\rho_L \cdot g} \tag{3}$$

σ is the surface tension between the melt and the vapour (or the melted casting powder), $\rho_L$ is the density of the liquid metal and g is the gravitational acceleration. The equation gives the profile shown in figure 4.

Table 1. Data used in the Bikerman equation

| Metal | $\sigma_{l/v}$ [J/m$^2$] | $\sigma_{s/v}$ [J/m$^2$] | $\sigma_{s/l}$ [J/m$^2$] | $\rho_{liq}$ [kg/m$^3$] | (-ΔH) [kJ/kg] |
|---|---|---|---|---|---|
| iron BCC / own vapour | 1.880 | 1.930 | 0.204 | 7015 | 270 |
| iron FCC / own vapour | 1.880 | 2.100 | 0.204 | 7015 | 270 |

The interface tensions are from Machlin [4], the density from Smithells [5] and the heat of fusion from CRC [6].

According to this profile, the original height of the meniscus is the height where the distance between the meniscus and the wall is as small as possible. In the case of pure iron in contact with air, this height is 7.38 mm. It has been shown [1, 7] that the original height is somewhat smaller, about 5-6 mm.

By making a heat balance between the heat transported across the air gap and the heat of solidification, the growth rate of the shell can be found. The heat transported across the air gap is described by:

$$\frac{dQ}{dt} = h \cdot A \cdot (T_{shell} - T_{mould}) \tag{4}$$

and the heat of solidification can be written as:

$$\frac{dQ}{dt} = A \cdot \rho \cdot (-\Delta H) \cdot \frac{dx}{dt} \tag{5}$$

Assuming that all heat must be transported across the gap between metal and mould, we can put these two equations equal and obtain the following expression for the growth rate of the shell:

$$\frac{dx}{dt} = \frac{h \cdot (T_{shell} - T_{mould})}{\rho \cdot (-\Delta H)} \tag{6}$$

The assumption that all heat is transported across the gap between metal and mould can be questioned. Neither the heat loss from the upper surface of the liquid metal nor the conduction in the solidifying material might be neglectable. However the temperature gradient along the strand is very small and for simplicity we neglect those factors.

The pulling rate, $\frac{dz}{dt}$, of the strand is known and by the assumptions given above this gives z as function of time in equation 1. By putting z into equation 1 and derivate it, the angle $\alpha$ in figure 1c is determined. By using a surface tension balance, the Dupré equation, [2, 8], the other angles in the figure can be found.

By comparing the angle from the surface tension balance with $\frac{\Delta \text{airgap}}{\Delta \text{height}}$ from the Bikerman profile the height of the meniscus and the air gap can be determined for each step.

## Results from Calculations

In the calculations we assume that the upper surface is close to flat when we start the calculations, Fig 3a. The shell is growing inwards. Surface tension balance is established between the solid and the liquid as is seen in figure 3b and c. The heat flow will be perpendicular to the mould surface as discussed above. By derivating equation 1 and by solving the other equations numerically by stepping in time, the depth of an oscillation mark was calculated. The result is presented in figure 5.
The temperature of the melt will have a large effect on the depth of the mark. The surface tension will decrease with increasing temperature, which will result in a lower maximum height on the mark and shorter time for shell growth which gives a less deep mark. However there is another effect as well. Since the natural convection at the meniscus is driven by the temperature difference between the solidification front and the free liquid, the convection will increase with increasing temperature of the liquid. The increased convection will slow down the growth of the solidifying shell. As the growth rate decreases the depth of oscillation marks decreases.

## Oscillation of the mould

The mould normally oscillates in a sinusoidal way, as is described in figure 6. The frequency and the stroke are normally varied. By increasing the stroke the relative velocity between the mould and the strand is increased. One often has a part of the movement of the mould where the mould moves faster than the strand. This period normally is called the negative strip period. Both the frequency and stroke do have an effect on the shape and the depth of the oscillation mark.

Equation 1 shows that the shape of the meniscus is related to the capillary constant, a. The height of the meniscus is determined by this constant. As was discussed earlier an overflow of the liquid will take place when the height is close to the maximum height. The frequency should thus be related to the maximum height of the meniscus. The following relation will thus give the relation between the velocity and the frequency:

$$f = v/A$$

Where A is the distance between the oscillation marks and should in the ideal case, correspond to $\sqrt{2} \cdot a$ , where a is the capillary constant in equation 3. This means that the frequency should increase with decreasing height of the meniscus. One way to do this is to decrease the surface tension, which also will decrease the depth of the oscillation marks. An increase of the carbon content as well as an increase of the melt temperature in a steel alloy will for instance decrease the surface tension. The surface tension between the steel and the slag is also depending on the composition of the slag. A casting slag will also have another effect on the frequency since the capillary constant should be divided by the difference in density between the melt and the slag and not only by the density of the melt. A decreasing density difference requires an increasing oscillation frequency. The time for the growth of the solid shell will increase with decreasing casting rate. Thus the depth of the marks will increase with decreasing casting rate.

If the frequency is chosen in another way than as in the relation given above the following will be found:

If the frequency is much smaller than half of the ideal value one will find two types of oscillation mark just as was observed in some castings. In this case one deep mark is formed when the mould turns towards down movement and one formed when the overflow takes place close to the start of the upwards movement.

If a frequency slightly lower than the ideal one is selected there will be formed different types of marks in a periodic pattern. Folding marks are formed when the distance between the marks is larger than the ideal one and overflow marks are formed when the distance is shorter. The formation of this type of pattern is illustrated by the drawing presented in figure 6. The first two marks formed will be of overflow type. The next two marks formed will be of folded type. A suggestion is now that the forth mark will contain cracks in the bottom of the oscillation mark. Another comment is that the second mark probably will contain a macrosegregated area in the mark. However this type of faults has to be investigated more carefully with new experiments.

## Concluding remarks

The oscillation frequency should be selected in relation to the capillary constant given by a balance between the surface tension and the gravity force. The depth of the oscillation mark is also related to the shape of the meniscus. The depth will be decreased by a decreasing surface tension as well as by an increasing temperature of the melt. However it will be difficult by the theory to adjust the frequency in a strand process but a lot of help will be given by the theory in order to optimise a continuous casting process.

## References

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## Figure caption

1. a. The microstructure at the top of a shell.

   b. The surface tension balance.

   c. The angles between the phases.

2. a. A jog has been formed at the top of the shell.

   b. A picture perpendicular to 2a shows that the layer growth has occured in steps.

3. The height of the meniscus increases until the meniscus collapses as the surface tension balance gets unstable. The melt will then flow over the shell tip and an oscillation mark is formed.

4. The Bikerman profile for iron in contact with its own vapour.

5. The calculated depth of an oscillation mark.

6. Formation of oscillation marks in relation to the overflow distance of the meniscus. The vertical lines indicate when the overflow takes place in relation to the oscillation.

## Figures

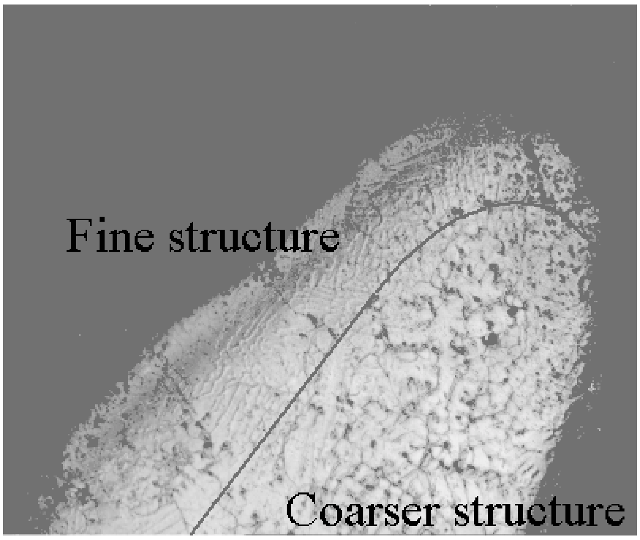


Figure 1a. The microstructure at the top of a shell.

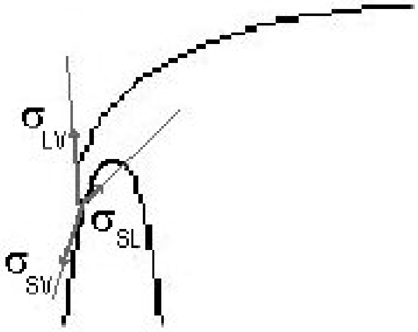

Figure 1b. The surface tension balance

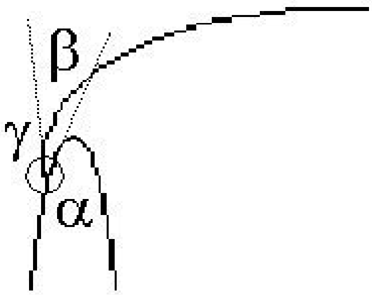


Figure 1c. The angles between the phases.

Figure 2a. A jog has been formed at the top of the shell.

Figure 2b. A picture perpendicular to 2a shows that the layer growth has occurred in steps.

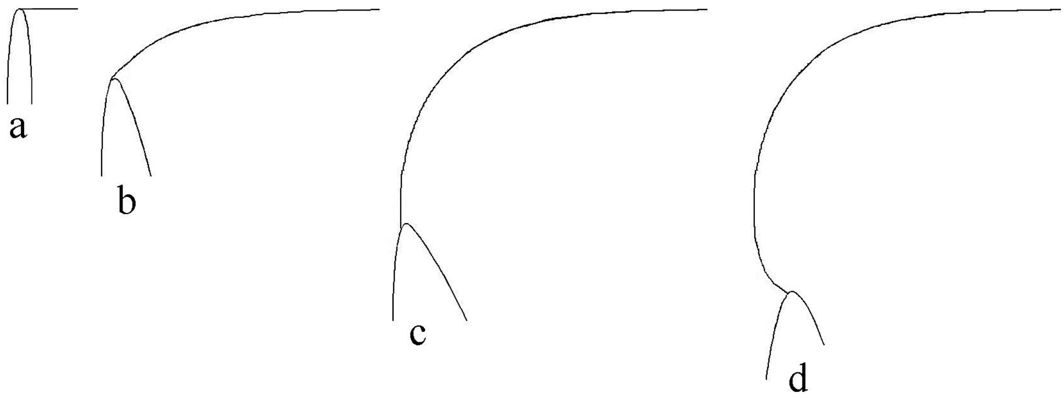


Figure 3. The height of the meniscus increases until the meniscus collapses as the surface tension balance gets unstable. The melt will then flow over the shell tip and an oscillation mark is formed.

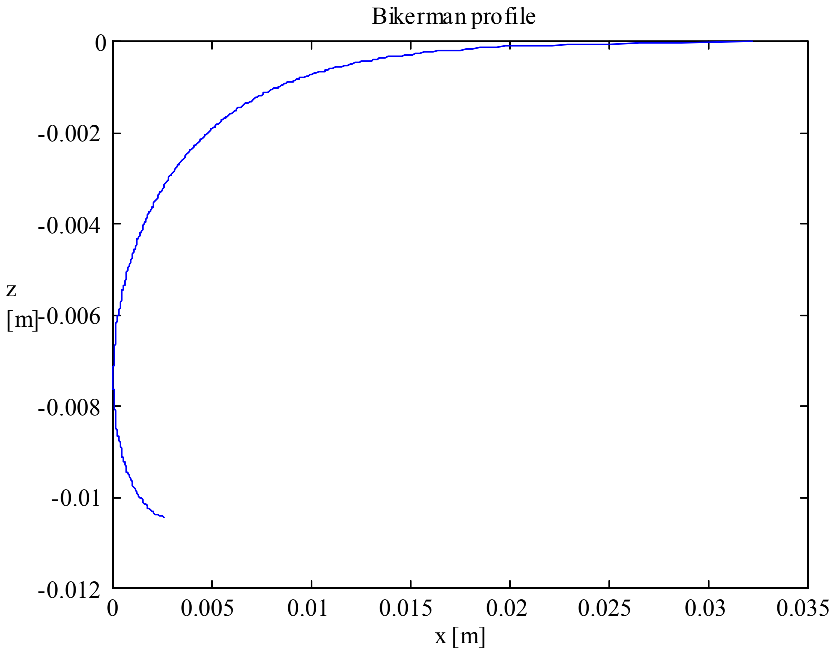


Figure 4. The Bikerman profile for iron in contact with its own vapour.

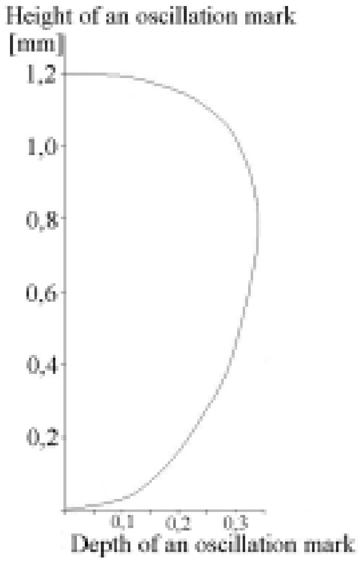

Figure 5. The calculated depth of an oscillation mark.

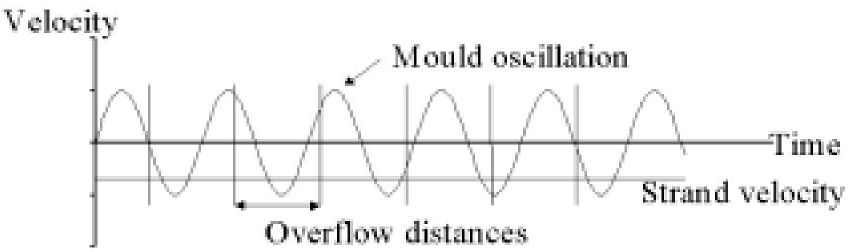

Figure 6. Formation of oscillation marks in relation to the overflow distance of the meniscus. The vertical lines indicate when the overflow takes place in relation to the oscillation.