

Dendrite growth direction measurements: understanding the solute advancement in continuous casting of steel

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Abstract. Maintaining competitiveness in steel manufacturing requires improving process efficiency and production volume whilst enhancing product quality and performance. This is particularly challenging for producing value-added advanced steel grades such as advanced high strength steels and electrical steels. These grades due to higher weight percentage of alloying elements cause difficulties in various stages of upstream and downstream processing, and this includes continuous casting, wherein high solute levels are critical towards macro-segregation. Interface growth direction in systems with more than one component is dictated by the solute profile ahead of the moving solidification front. Understanding the profile of growth direction with casting process parameters during the progress of casting will provide an important perspective towards reducing the macro-segregation in the cast product. In the present study, two steel slab samples from conventional slab caster under the influence of electromagnetic brake (EMBR) at Tata Steel in IJmuiden (The Netherlands) have been investigated for dendrite deflection measurements. The samples showed a transition zone where a change in the deflection behavior occurs. Also, the magnitude of the deflection angle decreases away from the slab surface. Correlating these experimental data with modeled fluid flow profile will help in improving the understanding of the dynamic nature of the solute advancement so that the casting parameters can be optimized to improve product quality.

1. Introduction

It is well known that the change of state of a system is governed by the systems thermodynamics^[1] which is based on the fundamental principle of Gibbs's free energy minimization and isolation criterion. The growth direction of a solid phase during the process of solidification indicates the direction of the interface movement between solid (S) and liquid (L) phases. The growth kinetics of the solid phase is governed by thermodynamic equilibrium and diffusion processes occurring at the interface, primarily in the liquid phase. Bulk fluid flow can enhance the diffusion processes in the liquid phase. For solidification in single component metallic systems, the driving force is entirely of thermal nature^[2] while in multi-component systems, the driving force for the S/L interface motion is also influenced by the solute transport. Thus the morphology and the distribution of the solid phase typically called the "microstructure" in the cast-product of the industrial alloys (mostly multi-component) will depend on the evolution of the solute profile in front of the moving interface. Forced convection due to bulk fluid flow^[3] (also called macro-scale flow) within the liquid melt will further enhance the kinetics of the solute transport process which might have an additional influence on the interface growth direction.



Dendritic solidification^[1] structure is quite common among the majority of metallic alloys. Due to the nature of their preferred crystallographic growth direction, dendrites are observed to grow in the form of branched tree-like morphology. In the continuous casting process, liquid steel transforms into solid, due to cooling, in a process wherein a liquid feedstock is continuously fed to an oscillating mold and a semi-solid product is extracted at the outlet. It is a quite complicated process where the phenomena of heat transfer and mass transfer take place simultaneously in presence of the incoming turbulent liquid jet, which after entering the mold creates a high degree of bulk convection. This incoming liquid stream on its way from the submerged entry nozzle (SEN) towards the mold exit takes away the rejected solute (rejected by the growing solid phase) thereby changing the local chemical driving forces and creating a washing effect. The liquid flow sweeps away the solute ahead of the growing interface from the upstream side to the downstream side. Thus it lowers the degree of undercooling on the downstream side (i.e in the direction of the outgoing fluid flow from SEN to the mold exit in the casting direction in **Fig. 1**) and promoting the driving force for solid growth on the upstream side (i.e towards the incoming fluid flow from SEN in **Fig. 1**). This has a direct effect on the evolving solidification microstructure. As the amount of solid fraction increases, the magnitude of the convection effect of the bulk flow decreases, thereby decreasing the effectiveness of the washing effect. During the process, if after a certain extent of time there exists a region with excessive solute accumulation, the undercooling will reduce drastically. This excess solute, if not further washed away, will lead to macro-segregation in the cast product. This macro-segregation is the inhomogeneity in the chemical composition when allowed to extend over large distances will lead to undesirable mechanical properties of the end product. Chemically driven precipitation can occur in this region between reactive metallic alloying additions and interstitial solutes. Thus the interface growth direction depends on the solute profile in front of the moving interface - which in turn depends on the casting process parameters. Hence to maintain the quality of the cast steel slab, it would be beneficial for the casting operators to have a good estimate about the interface growth direction and its dependency on the combination of heat transfer, mass transfer, and fluid flow. This will help to dynamically re-adjust the casting process parameters in order to minimize the degree of macro-segregation.

Due to stringent quality requirements, continuous casting of commercial advanced steel grades can be at the risk of having macro-segregation due to addition of a wide variety of alloying elements in higher proportions, and some of these very reactive elements are Al, Si or Ti. Thus it is important to find out the linkages between the fluid flow and the transient nature of the interface growth evolution from the fundamental principle of thermodynamics. The solidification microstructure consists of micron-scale dendrites spread over relatively large distances (of the order of several mm's). Under typical casting conditions, one can observe an almost fully columnar dendritic structure extending from the slab surface to the slab center. Experimentally^[2,3,4] it has been observed that the dendrites in presence of melt convection, have a biased growth direction towards the upstream side. This phenomenon is called dendrite deflection. The variation in the angle of deflection from the slab surface towards the centre represents how the dendrite growth direction dynamically changes during casting. It is of scientific relevance how the solute is rejected ahead of the moving solidification front as Takahashi^[3] showed that the distribution coefficient depends on solidification rate and bulk flow velocity. This mostly depends on the flow velocity, growth rate / undercooling and the solute content of the alloy. Very limited quantified experimental evidence^[2-4] of the phenomenon of dendrite deflection is available in literature and the information on steels cast under industrial conditions is even more scarce. From his experimental data on steel ingots, Takahashi et al^[3] proposed an empirical correlation, showing the dependency of the interface growth direction on the solidification rate and the bulk flow velocity. With steels of different carbon contents, Esaka et al^[2] modified Takahashi's relation by adding a carbon concentration based pre-factor. The present work involves the measurement of dendrite deflection in industrially cast steel slab samples. The objective of this paper is to establish whether differences in casting conditions will result in different dendrite deflection angles, with the underlying hypothesis that this is caused by differences in convective flow causing differences in solute distribution. Higher casting speed increases the degree of convective flow while higher mold width would tend to provide more time

for liquid steel to flow laterally towards the narrow face walls after it exits from the SEN nozzle. Convective flow influences the superheat dissipation, which would affect the mold temperature distribution. However, the thermal diffusion coefficient being orders of magnitude higher than the solute diffusion coefficient, flow driven mass transport will be more critical than flow driven temperature towards macro-segregation.

2. Experimental Methodology

Two steel slabs namely – sample A (LCAK : low carbon aluminium killed) and sample B (LAP: low alloyed peritectic steel) from the conventional slab caster were used in the present study. The chemical composition of the slabs are given in **Table 1** and the casting process parameters are given in **Table 2** respectively.

Table 1. Chemical composition of the steel grades.

| Steel | C, wt% | Mn, wt% |
|--------------------|-------------|-----------|
| Sample A (LCAK) | 0.06 – 0.08 | 0.2 – 0.4 |
| Sample B (LAP) | 0.11 – 0.14 | 0.5 – 0.8 |

Table 2. Casting process parameters.

| Steel | Casting Speed, m/min | Superheat, °C | Slab thickness, mm | Width, mm |
|------------|----------------------|---------------|--------------------|-----------|
| Sample - A | 1.7 | 23 | 225 | 1300 |
| Sample - B | 0.76 – 1.55 | 16 | 225 | 1600 |

It can be seen that sample A had a stable casting speed of 1.7 m/min^[6] while sample B had a wide variation in casting speed. This is because sample B was collected during the ramp-up period, i.e with continuous increase in casting speed. Both the slabs were cast under the influence of EMBR. **Fig. 1** shows the portion of the slab from where the samples were taken with the sample cutting plane shown as a green dotted line.

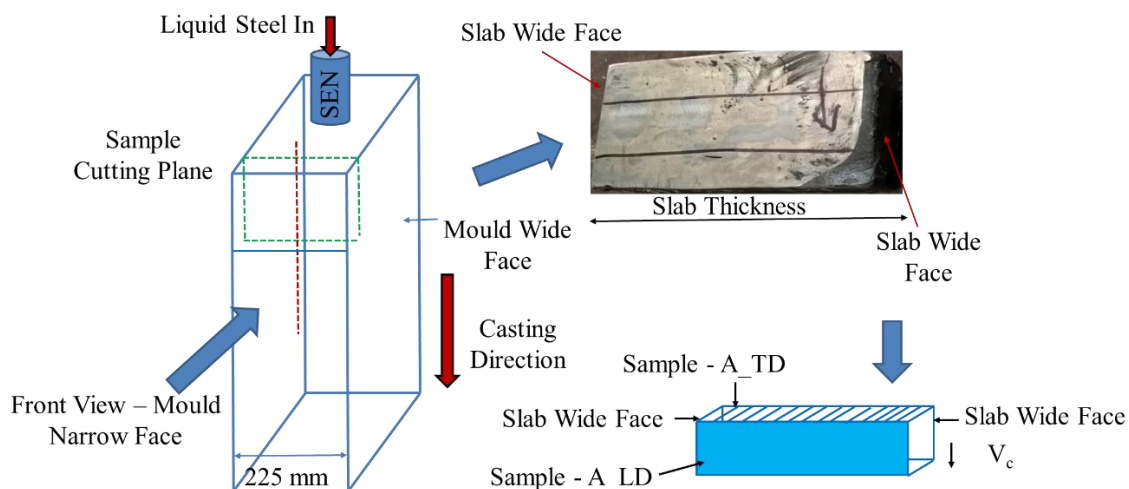


Figure 1. Collection and preparation scheme for continuously cast alloy samples.

The sample was cut approximately at a quarter distance inwards from one of the narrow face. Thus the sample cutting plane was parallel to the narrow face and the red dotted line in **Fig. 1** shows the slab centreline on the narrow face along longitudinal direction. Samples after cutting from the slab were cut further into small pieces of 35x35x10 mm. The area of the sample closest to the slab surface was selected for analysis and thus mounted as per the standard metallographic procedure so that it could be handled conveniently to be used for subsequent steps of metallographic sample preparation. Final samples for solidification structure analysis were prepared after coarse grinding and subsequent fine polishing with diamond abrasive particles followed by room temperature etching with Bechet–Beauchard etchant^[7] to reveal the dendritic structure. The etched sample was observed by optical microscopy for visualization of the solidification structure. The dendrite deflection angle was measured by individually selecting the dendrites and measuring the height and width of the rectangle with dendrite as the diagonal. **Fig. 2** shows the convention of measuring the bending angle of a dendrite originating from the mold wall in presence of fluid flow (bending angle denoted as θ). Starting from the slab surface, the bending angle was measured at perpendicular distances. At each distance, the bending angle was measured at various points.

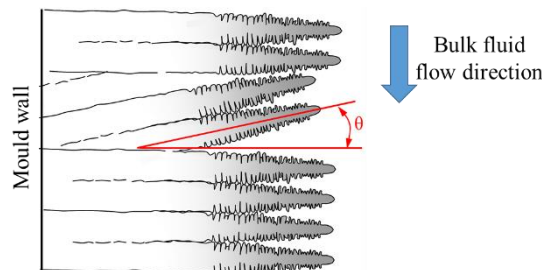


Figure 2. Schematic representation of the definition for the bending angle θ ^[7], used in this study.

3. Results and Discussion

Fig. 3 shows the variation of the dendrite growth direction from slab surface towards the slab center for sample - A solidified under a constant casting speed. It can be seen that near the surface, all primary dendrites (shown as white dotted lines) are oriented in the same downward direction. A small distance away from the slab surface, the primary dendrites undergo a change in growth direction from downwards to upwards. Some primary dendrites are seen to follow their original downward growth direction, while other dendrites are seen to have an upwards growth direction. Further away, it can be seen that all primary dendrites are oriented in the upward direction, which is exactly opposite in close proximity to the surface. Thus, it seems that the observed change in the dendrite growth direction might be due to a change in the fluid flow direction ahead of the moving front. Generally, a portion of the liquid steel after exiting from the submerged entry nozzle with relatively high flow velocity directly hits the narrow face mold walls^[8]. After striking the mold walls, a portion of the liquid steel may travel upwards towards the meniscus and creating a recirculation loop at the top of the mold. The rest of the liquid steel travels down towards the mold exit after striking the moving solidification front. Thus at a particular distance away from mold walls, a change in the flow direction may occur, which is responsible for the experimentally observed change in the dendrite growth direction mentioned before. The transition in the preferred growth direction can be compared with the transition in the fluid flow profile and is thus helpful to study how this transition varies with casting process parameters.

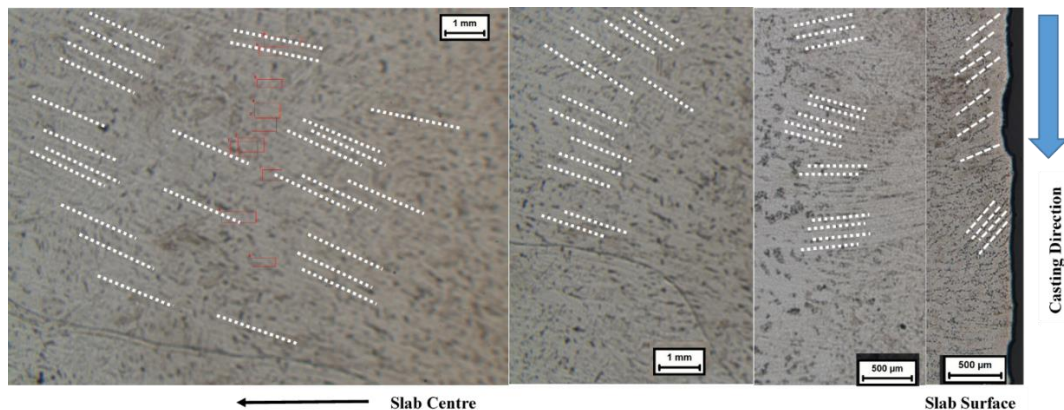


Figure 3. Variation in dendrite growth direction from the slab surface (right) towards the slab centre (left) for a low carbon aluminium killed steel (sample A).

Fig. 4a shows the variation in the bending angle from slab surface towards the center for both samples. Sample - A_LD represents the bending angle for sample A on the plane parallel to one of the narrow face walls (as shown in **fig. 1**). Sample - A_TD represents the bending angle on a plane perpendicular to the narrow face side (i.e along transverse direction) (as shown in **fig. 1**). Liquid steel, after exiting from the SEN port, travels towards the narrow face walls along width direction. It can be seen that for all the three samples, the magnitude of the mean bending angle near the surface is similar but within a wide variation of values. For the sample - B_LD, the mean deflection angle decreases up to 3 mm, after which the sign of the bending angle changes from positive to negative, indicating the change in the growth direction. This is likely caused by the change in the flow direction. For sample - A_LD, at about 1 mm from the surface, the bending angle is both positive and negative which again indicates a transition region where the bending angle is both positive and negative. Similarly for sample - A_TD, at about 9 mm from the surface, the bending angle is both positive and negative indicating a similar transition region of preferred dendrite growth. For sample - A_LD from 6.5 mm onwards, the bending angle is negative, which is opposite compared to near the surface. For all samples, the absolute value of the mean value and its standard deviation decrease from the surface towards the centre of the slab. This may be due to decrease in the magnitude of the flow velocity from surface towards the centre. Okano^[9] also observed this decrease in the bending angle across the slab width. Though the sample - B_LD had a wide variation in casting speed, the variation in the bending angles are similar to the case of sample A. This may be due to EMBR^[8], which tries to stabilize the turbulent flow within the mold region. Also, the slab thicknesses are same for both slabs and there is not much difference in the chemistry as well. For the sample - A with stable casting speed, the solidification rate within the mold region was estimated using the CON1D model^[10]. The obtained solidification rate and the experimental bending angle was put into the Takahashi^[3] correlation to estimate the fluid velocity. Only the maximum and minimum values of the bending angles at different positions for sample - A were used to get an idea of the range of the predicted flow magnitudes. **Fig. 4b** shows the range of the flow velocity magnitude at different distances from the slab surface for sample - A. The minimum predicted flow velocity was in the range 0.10 - 0.12 m/s. Many dendrites at the surface were found to have bending angles in the range of 40° – 45°. To get such high values, the corresponding estimated fluid velocity was found to be about 10 m/s even at a slower growth rate of 0.01 cm/s. Also at about 1 and 7 mm from the surface, the estimated maximum flow velocity was found to be in the range of 2 – 2.75 m/s. This extremely high flow velocity seems not realistic in a slab caster mold operating at a casting speed of 1.7 m/min with EMBR compared to what is reported in literature^[8]. Also, the fluid flow simulations performed at Tata Steel Research and Development, IJmuiden, The Netherlands with EMBR at a casting speed of 1.7 m/min revealed much lower values of maximum flow velocity. Thus it seems that the empirical correlations by Takahashi^[3] and Zhang^[11] are not applicable for the entire slab geometry and needs to be modified in order to predict

the high bending values obtained in the slab samples.

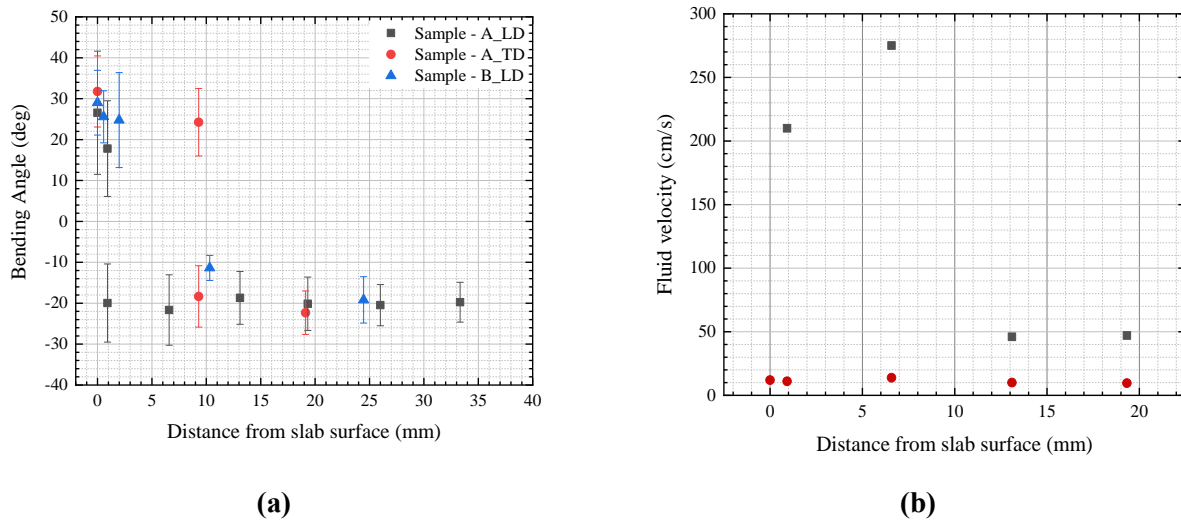


Figure 4. (a) Variation in bending angle from the slab surface towards the slab centre; (b) Minimum (●) and Maximum (■) Fluid velocity for sample - A as calculated from Takahashi equation^[3].

4. Conclusions

Two steel slab samples from an industrial thick slab caster were investigated for the variation in dendrite deflection from the slab surface towards the slab centre. Both alloys have a similar composition and casts were made under the influence of electromagnetic brake (EMBR). A clear change in the dendrite growth direction from surface towards the centre occurs, albeit over a wider zone, which can be correlated to changes in the fluid flow profile. Decrease in bending angle from surface towards the centre was observed. Takahashi relation needs to be revised to predict the high bending angle values. Correlating these deflection measurements with compositional analysis has been planned as a part of future activities, which would provide insight on the relation between the macro-segregation phenomenon and dendrite deflection. The transition area between downwards and upwards bending seems to be larger in the case of sample B, which fits qualitatively with the gradual increase of casting speed and the moving solid/liquid interface region.

5. References

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