Effect of Some Technological Parameters on the Macrosegregation of CC Slabs

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Abstract:The inner structure of the continuously cast semis has a great importance from the point of view of further processing and application. The main reason for this is the very direct effect of the inner structure's features (ie. porosity, macrosegregations, geometry of primary dendrites) on the technological characteristic features of the semis during further processing (ie. crack sensitivity, formability, etc.). The paper deals with the possible ways of macrostructure determination on the basis of the results of mathematical modeling of continuous casting process. We pay a special attention to the columnar-equiaxed transition as a function of heat parameters of the casting process and to the macrosegregation formation caused by the motion of solute enriched interdendritic liquid in the mushy zone.

Keywords: continuous casting, steel, modeling, columnar to equiaxed transition, fluid flow, macrosegregation

1   Introduction

In the continuous casting shops an obvious way to set up the production is the increase of the casting rate. In general, in order to realise the higher rate the rise of secondary cooling intensity is required. In turn, the cooling circumstances have a direct effect on the quality parameters of cast product, ie. on the surface and subsurface crack susceptibility, the geometrical parameters of the primary structure, and on the position of the columnar to equiaxed transtition (CET).

The last factor mentioned above is the solidification pattern (columnar or equiaxed), which has its effect mainly on the macrosegregation, ie. on the distribution of the impurity enriched melt. In the continuous casting process the appearance of macrosegregation is inevitable, and in some cases it can result in very serious centreline segregation. If mainly columnar dendritic growth takes place, the solute enriched liquid flows towards the centre of the slab and centreline segregation increases. In the other case, if equiaxed dendrites are growing, the

enriched melt can remain at the surface of individual dendrites and less solute enriched liquid will reach the centreline. The distribution of enriched melt can be changed also by melt flow. For example the imperfections of roll's adjustments, the eccentricity of the individual rolls and the bulging between them can pump the solute enriched liquid among the columnar or equiaxed grains to be moved towards the centreline. The chemical composition of the steel and a lot of technological parameters (superheat, casting speed, distribution of the secondary cooling intensity, the shape of the liquid pool, melt flow due to natural convection, rolls' adjustment, etc.) are contributing to the formation of the final macrosegregation pattern.

According to the above mentioned effect the macrosegregation can be decreased in the following manners: decreasing the concentration differences during solidification (ie. lowering the amount of impurities), controlling the dendritic pattern and reducing the melt flow in the mushy zone. This paper deals with the effect of the last two factors.

2   Thermal field, calculation of thermal parameters

Besides the steel composition the temperature field affects basically the solidification structure and through this the distribution of the solute enriched melt. On the basis of temperature field the mode of dendritic solidification and the quality of the dendritic structure can be estimated. These latter parameters give the possibility to predict indirectly the macrosegregation pattern. For describing the thermal field inside the strand, heat transfer model, Tempsimu [1], developed at Helsinki University of Technology, Finland was used. This finite element model is suitable for 3D steady state thermal modeling of solidification of a continuously cast strand. The thermophysical parameters of the cast steel were taken into account by IDS software [1]. The calculation results are the temperatures of each node along the whole strand. From this temperature field the actual temperature gradient and cooling rate can be derived.

3   Industrial experiment and its evaluation for CET determination

In order to clarify the situation chiefly around the CET formation under industrial conditions, casting experiments were performed. Different heats and slabs were cast under controlled circumstances close to the steady state casting conditions both in Hungary and in Finland. The caster in Hungary is a renewed vertical one, whilst in Finland a vertical-bending type was chosen. In Hungary there was a

series of experiments, in which radioactive isotope was added into 4 heats (6 strands). After solidification the distribution of isotope was investigated in cross-sectional direction by using sensitive photo paper. The macrostructure of the slab is revealed by the trace of the isotope. In these photos the CET position is clearly visible in the whole cross-sectional area. In the rest of Hungarian experiments and in Finland conventional metallographic technics were used to reveal the macrostructure. The isotopic investigations gave us a more precise and global picture both about the primary structure and CET position. The detailed description of industrial experiments was published earlier [2,3].

A detailed examination of the connection between the measured position of CET and the calculated thermal parameters was performed, in which also the chemical composition of the slabs was taken into account. During the preliminary analysis of the data it was established that the carbon and sulphur content can be regarded as very effective influencing factors. The mathematical analysis of experimental data gives us the possibility to create a general phenomenological description of CET. By multiple linear regression the individual effect of carbon and sulphur can be taken into account, and a third parameter was also introduced in order to describe the cross-effects. The final result can be given in the following form:

$$G_{Liq-1} = 0.166 - 0.398*[C] + 5.870*[S] - 17.797*([C]*[S]) \qquad (1)$$

where

- G_{Liq-1} is the threshold thermal gradient (calculated for the liquidus – 1 Centigrade), if the real thermal gradient during solidification reaches this threshold value columnar to equiaxed transition is expected,
- [C] and [S] are the carbon and the sulphur content in wt%, respectively.

Correlation analysis was performed between thermal gradients calculated from the thermal field of the slabs and calculated by Eq. 1. The correlation factor is 0.8, which is fairly good, taken into account the complexity of the columnar to equiaxed transition. Fig. 1 represents a nomogram calculated by Eq. (1) for different carbon and sulphur contents in the chemical composition range of experimental heats.

There were two slabs from the same heat without inner equiaxed zone in the experimental series. From the thermal field of the slabs thermal gradients of 0.4 and 0.45 were calculated for the centreline. The thermal gradient threshold which is necessary in this case for columnar to equiaxed transition calculated by Eq. (1) is 0.24 K/mm. It means that if the thermal gradient in the centreline is lower than 0.24 K/mm, equiaxed dendritic solidification can be expected. In these cases the

thermal gradient was two times higher than the threshold value. That is why no equiaxed dendrites were developed.
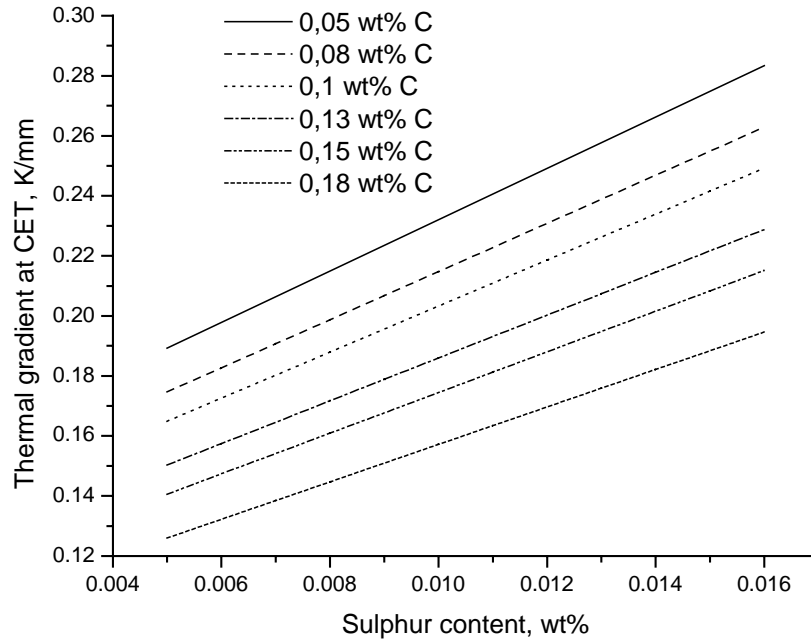

Fig. 1 Nomogram for determination of the thermal gradient threshold v

4 Motion of fluid inside the slab

A necessary pre-condition of the macrosegregation process is that the solute enriched liquid moves from the neighbourhood of that solid phase which is in equilibrium with the liquid. Fluid flow during solidification can result from the following reasons:

Fluid flow caused by feeding of molten steel: the fluid flow calculations and isotopic solidification experiments proved that fluid flow from this reason can be significant only in that part of the slab in which the centreline temperature is over the liquidus. If the mushy zones growing from both wide sides touch each other, the viscosity increases drastically and there is no significant fluid flow in the mushy zone.

Fluid flow caused by density differences: there are two main reasons, the temperature and concentration differences, which play a role in the development of density changes. It cannot be influenced by technological methods.

Fluid flow caused by outer factors: we have to mention here all the factors which effect the strain of the cast strand and hereby result in the movement of the liquid inside the strand. The most important factors are adjustment, eccentricity and wear of supporting rolls. Bulging of the strand has to be mentioned here too, because it depends primarily on the distance between successive rolls. The enhancing effect of outer factors on macrosegregation must be taken into account only in that part of the strand in which only mushy zone can be found behind the solid shell. It means that the temperature of the centreline is in-between the liquidus and solidus temperatures. This distance is around 4-5 m in case of vertical casting machines.

In the development of macrosegregation, fluid flow caused by the last reason plays the governing role. Earlier industrial experiments performed under normal production circumstances proved the cyclic fluctuation of roll gaps because of the eccentricity of individual rolls [4]. In this case the constrained motion of fluid is inevitable.

The mathematical model for describing the effect of outer factors on the macrosegregation severity is under development. The theoretical background of this model is the following. If the exact geometry of rolls (adjustment, eccentricity, wear) is known, the roll gaps and their change depending on time can be determined. The shape of gap between a given pair of rolls is assumed to be a rectangular and its area is changing as a function of time because of eccentricity. This fluctuation characterises the fluid pumping effect developed in this gap. The sum of fluctuations of individual gaps characterises the fluid flow inside a given part of the strand in a given period of time. In the present model the fluctuation is defined by the scatter of the roll gap's areas.

On the basis of preliminary calculations the effect of eccentricity seems to be the most important between the above mentioned factors. Fig. 2 summarises the results, which shows the difference between the nominal and real individual gap sizes along the length of the casting machine.

The displayed differences result from the bulging of the solid shell, from the solidification shrinkage and from the eccentricity of the rolls. On the basis of technical literature in this calculation 0.5 mm eccentricity was supposed for each supporting roll. The governing parameter is the effect of eccentricity on the area change (Fig. 2), especially in the lower part of the strand. It must be noticed that the curve characterising the eccentricity effect in Fig. 2 is valid for a given moment in time.

The first calculations proved the correlation between the Baumann prints of slabs produced in the frame of industrial experiments and the scatter of roll gap's fluctuation caused by outer factors. Fig. 3 shows the representative Baumann

prints and the proper scatter values. In the near future it is necessary to express the information content of macrostructure picture in a numerical way by using image analysis methods.
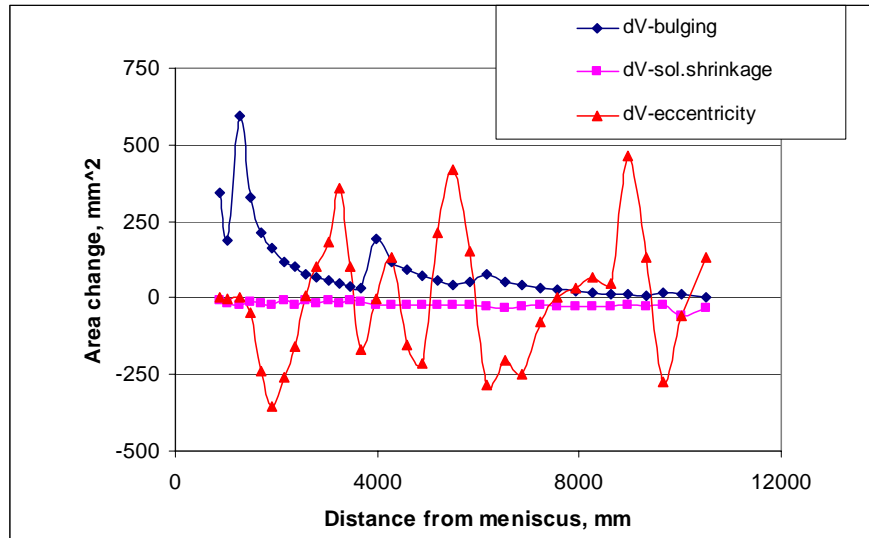

Fig. 2 Area changes of roll gaps caused by the eccentricity of individual rolls (triangles) compared to area changes of solidification shrinkage and bulging between rolls

The effect of carbon content and superheat on the macrosegregation sensitivity is well known from industrial experiences and it is confirmed by the present mathematical model. The simulation results are summarised in Table I.

Table I Roll gaps scatter values for different carbon contents and superheats

Carbon content [wt %]	Superheat [K]	Scatter of roll gaps [mm^2]
0.05	30	280
0.10	30	517
0.15	30	319
0.20	30	680
0.10	20	340

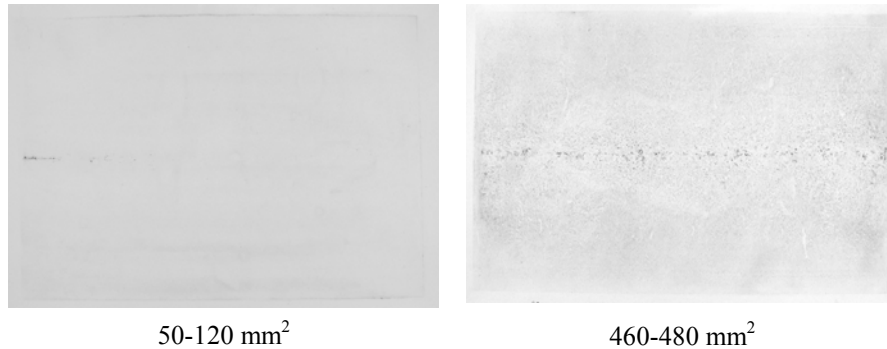|	
50-120 mm^2	460-480 mm^2

Fig. 3 Representative Baumann prints and area change scatter values of slabs with different chemical composition

In every case the chemical composition was the same, only the carbon content differed. For the solidification calculations real industrial data were used in the primary and secondary cooling zones, but in all cases the same casting machine geometry and roll eccentricities were taken into account. The scatters were calculated only for that part of the strand in which the centreline temperature was in-between the liquidus and solidus temperatures, ie. in the cross-sections of the slab only solid and mushy zones can be found. Comparing the second and last rows in Table I, the detrimental effect of superheat is obvious.

Conclusions

The primary structure of continuously cast products has a great importance from the point of view of the development of macrosegregation patterns. This primary structure mainly depends on the thermal parameters of solidification.

For CET position the governing role of thermal gradient can be observed, according to the literature. Among the constituents the carbon and sulphur content have a great effect on the formation of equiaxed dendrites.

On the basis of industrial experiments and thermal field calculations a phenomenological model has been developed for estimating the CET position and the equiaxed zone width in industrially produced slabs. Experimental results both from Hungary and from Finland have proved the validity of this model. The use of this model presumes the precise knowledge of thermal field of the slab during solidification in which the effects of casting parameters (ie. superheat, casting speed, cooling intensity distribution, thermophysical material parameters etc.) are taken into account properly. From this temperature field the thermal gradient distribution valid for the liquidus-1 Centigrade can be calculated as a function of the distance from the slab surface. Inserting the carbon and sulphur content of the steel into Eq. (1), a threshold value for the thermal gradient can be calculated. Where the thermal gradient distribution function reaches this threshold value,

columnar to equiaxed transition can be expected and presumable equiaxed zone will develop.

The second part of this paper gives a short overview on the theoretical background of the mathematical model, which was developed for describing the connection between fluid flow in the mushy zone and macrosegregation. The first results are in good accordance with industrial experiences and with literature. The further development of the mathematical model can only be based on the use of real roll gap geometries of the casting machine and on the numerical evaluation of macrosegregation.

Acknowledgements

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