Methods for Assessment of Slab Centre Segregation as a Tool to Control Slab Continuous Casting with Soft Reduction

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Slabs produced by continuous casting are characterized by macrosegregation in their central regions. The formation of this macrosegregation depends on many parameters, among others the state of the casting line and the casting technique used.

In order to minimize this slab centre macrosegregation for the various steel grades, appropriate samples cut from the slabs have to be subjected to a quantitative assessment. Optical methods of assessment are too inaccurate to serve, for example, as a useful index for controlling soft reduction. For this reason the centre of the slab was analysed using several physical and chemical test methods whose results were then cross-compared. In the process, a combination of ultrasonic porosity tests and spark analyses (OES-PDA) turned out to be the most informative, cost-effective and fastest method for assessing macrosegregations.

Thanks to the macrosegregation indexes elaborated on the basis of the test results for the individual slabs it is now possible to find optimum casting parameters such as casting temperature, casting speed etc. for the subsequent melts of the same steel grade and also to use soft reduction for the purpose of minimizing macrosegregation phenomena.

KEY WORDS: continuous casting; slab quality; macrosegregation; microsegregation; soft reduction; quality assurance.

1. Introduction

Being a cast product, a slab shows a cast structure consisting of primary dendrites and the solidified residual melt (microsegregation). The shape of the dendrites depends mainly on the carbon content of the steel,1,2 while the other alloying elements such as manganese, chromium, vanadin or molybdenum have only a minor influence on the dendrites’ shape and their respective distances.3

The orientation of the dendrites from the slab surface towards the slab centre is generally determined by heat extraction, i.e. by cooling. We distinguish four characteristic types of dendrite formation: strictly oriented, oriented, unoriented dendritic and globulitic.1,4

The centre of the slab contains the area of macrosegregation (centre segregation). Centre segregation is influenced by the cast structure (which in turn depends on the alloy content of the steel melt, on superheat, on secondary cooling) and the machine state.4,5–7 Oriented dendrites extending down to the slab centre make for pronounced centre segregation; by the same token the centre segregation increases with bulging.

To assess centre segregation, nowadays segregation coefficients or segregation indexes are used. In this process, samples are cut from the slab centre, etched with 38 vol% HCl and subsequently the segregation is assessed optically to establish the segregation coefficient. Figure 1 shows two types of segregation by way of example. Type A serves to assess an intermittent, type B to assess a continuous centre segregation. This optically determined segregation coeffi-

Fig. 1. Examples of the appearance of centre segregation.
cient is a measure of the slab quality. For many steel grades (St 52, sour gas resistant steel grades as well as multiphase steels) low segregation coefficients are a prerequisite for industrial use. Very pronounced segregations will lead to a banded structure in the hot rolled band or heavy plates.8–10)

Centre segregations tend to be irregular both across the slab and along the slab’s longitudinal axis. Figure 2 shows the slab samples taken from a slab for the purpose of comparing the segregation indexes. The results of the comparison are summarized in Table 1.

As can be seen in the Table 1, melt no. 739944 has a segregation coefficient after optical assessment that lies between 0.2 and 0.9. For this reason the question arises in each case whether such assessment results based on very few samples are truly representative. In the following report some test methods for determining the centre segregation are examined with regard to their information content, practical application and economic efficiency as well as their implementation in the continuous casting plant.

2. Assessment of Centre Segregation

Casting liquid steel with soft reduction requires precise adjustment of the casting machine to meet certain criteria. Whether such adjustment has been made with the optimum accuracy, is shown by the assessment of the centre segregation. There are several ways of doing this, which will be described below.

2.1. Optical Coefficient

The optical coefficient as a prerequisite for the segregation index is determined with the aid of a specially made etching plate. A longitudinal sample is cut from the slab centre and etched with 38 vol% HCl. Using this etching plate and a standard series the tester is then able to determine the segregation coefficient (index).

In the Linz works of voestalpine three standard series (type A, type B, type AB) are employed. The segregation coefficient is used to adjust the quality of the slab depending on customer specification.

2.2. Porosity

It can be presumed that between microcavities and macrosegregation there is a correlation.13) A large number of contraction cavities (high porosity) corresponds to a strong centre segregation in slabs cast without soft reduction. For this reason porosity is used for indirect segregation assessment. The method used in this context is the ultrasonic test. For the ultrasonic (US) test a 250×50×20 mm sample (Fig. 3) is taken from the slab, i.e. from the edge and the centre. This sample is subjected to a grid test in a US equipment at a frequency of 10 MHz. The minimum diameter of detectable pores with this method is 100 μm.

As pores reflect the ultrasonic waves, one obtains an indication of the number of pores. With the aid of an evaluation algorithm the porosity can then be calculated.

Porosity=\text{Number of pores/tested volume \left [ 1/cm^3 \right ]} \ldots (1)

Figures 4 and 5 illustrate the test results for slabs with high (Fig. 4) and low porosity (Fig. 5). Starting at the left side of the figure, one observes first of all a pore-free zone. Any US signal indicated here are due to larger grains or to macro-inclusions. After about 1/3 of the represented area a pore band appears reflecting the solidification triangle in the slab. This pore band is already considered in the evaluation. Subsequently, Figs. 4 and 5 give a graphic representation of the number of pores and their distribution.
2.3. OES-PDA Test

Taking into considerations the results furnished by the electron probe microanalysis, a spectroscopy PDA (pulse discrimination analysis) method was adapted for segregation assessment. The Optical Emission Spectrometry with Pulse Discrimination Analysis Mapping (OES-PDA) has the decisive advantage of supplying within an hour reproducible quantitative results.

Here, the centre segregation range is continuously sparked (six times) whilst moving, with a spark distance of 1 mm, over a length of 40 mm; see Fig. 6. The result is an element mapping of different intensities that shows the level of segregation in the probe. An advantage of this test method is that all chemical elements are covered.

The next figures (Figs. 7 and 8) again show the course described by segregating elements (element index) over the centre segregation. A slab with strong centre segregation, Fig. 7, is characterized by distinct peaks in the element pattern.

The OES-PDA test also allows the determination of segregation coefficients with the help of an evaluation algorithm, covering the height (segregation peaks) and width of the segregation and establishing a segregation index. A high segregation index means a strong segregation, a low segregation index a weak one.

Moreover, mathematical methods allow deriving insights into overall segregation by assessing the areas below the indicated curves. To compute all concentrations lying above the limiting concentration, \( A_{\text{tot}} \), Eq. (2) is used.

\[
A_{\text{tot}} = \left( \frac{1}{u} \sum_{n=1}^{u} \sum_{m=1}^{K} (K_{\text{hoch}} - K_{\text{Grenze}}) / K_{\text{Grenze}} \right) / 6 \quad \ldots \quad (2)
\]

\( K_{\text{hoch}} \) : Concentration lying above the limiting concentration

\( K_{\text{Grenze}} \) : Limiting concentration (mean value + 3\( \sigma \) standard deviation)

\( u \) : Number of all connected measuring points of the peak showing maximum concentration

2.4. Microprobe—Element Distribution Patterns

With the aid of element distribution patterns, the microprobe (Cameca SX-100) allows the quantitative measuring of both the microsegregation and the centre segregation.\(^9\)–\(^11\)

To determine the macrosegregation, the microprobe scans an area of 40×40 mm with a step size of 95 \( \mu \)m between the measuring points. This furnishes a relatively good image of the area where segregation occurs. The advantage of microanalytical assessment is the fact that the segregation behaviour of the individual elements of a steel grade can be quantified.

Figures 9 and 10 reproduce the outcome of microanalytical tests on slabs having strong and weak centre segregation, respectively. The assessment was based on the element distribution patterns of manganese, phosphorus, chromium and titanium. From the concentration patterns of these elements, quantitative conclusions can be drawn about the segregation behaviour. Segregation coefficients can then be computed with the aid of an evaluation algorithm.

The microprobe check supplies insights into the maximum concentration \( C_{\text{max}} \), the mean concentration \( C_{\text{m}} \) and the minimum concentration \( C_{\text{min}} \) of the various elements in the phases. From these data, the required segregation coefficients for the microsegregation and the centre segregation

\[
\begin{align*}
C_{\text{max}}/C_{\text{min}} \\
C_{\text{max}}/C_{\text{m}} \\
C_{\text{min}}/C_{\text{m}}
\end{align*}
\]

can be computed. For various steel grades, the typical chemical composition and segregation coefficients determined by microprobe check can be gathered from Table 2.

The intensity of the segregation depends on the steel grade. With casting conditions being comparable, rising carbon content and a rising concentration of the various elements bring an increase of the segregation coefficients in the slab.

The element distribution patterns also allow an assessment of the shape, the orientation, and primary dendrite and secondary dendrite arm spacing.
The element distribution pattern of titanium in Fig. 11 is indicative of traces of TiC in the slab centre. For a quantitative assessment of the TiC, an additional test with a reduced step size is required.

The macrosegregation in the slab centre works in two directions: both transversally from one solidification triangle to another, and longitudinally over the entire slab length; cf. Fig. 2 and Table 1. For this reason it is extremely problematic to infer the segregation of a melt from a slab sample of merely 60 mm; and although it is possible to enlarge the sample area for the microprobe to 40×40 mm (step size 95 μm), the basic problem of representativeness remains the same.

Therefore, this method of determining the segregation with a microprobe can only be used in special cases where the noticeable cost and lengthy procedure are acceptable, as for example for creating standards for the OES-PDA assessment.

3. Numerical Calculation of Microsegregation

The importance of microsegregation for the formation of a banded structure in the rolled product was outlined in a recent publication.10) Microsegregation is a phenomenon, which can hardly be influenced by changing casting parameters within the relatively small operating window of a slab.
casting machine. The cooling conditions during solidification and further cooling and the steel composition determine to what extent the enrichment is still existing after the end of the casting process. Nevertheless, the prediction of microsegregation in the cast slab is an important basis for the quantification of the influence of the rolling parameters on the formation of banded structures during further processing.

Thus, a model for the prediction of microsegregations in dependence on the steel composition and plant parameters was designed. This was preceded by extensive metallographic research to determine structural parameters such as the secondary dendrite arm spacing, $\lambda_2$, a measure for the diffusion path. Figure 12 shows measured $\lambda_2$-values versus distance from the strand surface for a high-strength structural steel (St52, compare Table 2). Every mean value and standard deviation represents more than 100 measurements by digital image analysis on Bèchet-Beaujard-etched slab specimen.

$\lambda_2$ is proportional to the local solidification time, which is, together with the thermal history during further cooling, calculated from a solidification model of the slab caster. The solid line in Fig. 12 stands for the calculated $\lambda_2$-spacings of the high-strength structural steel across half the slab section, based on the following empirical formula,

$$\lambda_2 = 14.775 \times t_f^{0.475}$$

where $t_f$ denotes the local solidification time in s, $\lambda_2$ in $\mu$m.

In the same way, relationships were defined for all other analysed steel grades. The cooling of the slab in the solid phase and the diffusion path together with the diffusivity of the segregated elements decides about the further reduction of the enrichment.

The connection between local solidification time and secondary dendrite arm spacing builds a main feature for numerical microsegregation calculations in the way, that the secondary arm spacing is accounted as characteristic solidification domain. To simplify the problem of diffusion and moving phase boundaries, the boundary positions are made stationary by means of coordinate transformation methods. 14 The transformation of the diffusion equation results in a convective-diffusion type partial equation, which is solved with the central difference scheme. 15 In the case of a peritectic reaction, each physical solid domain respective austenite and ferrite, is mapped in a transformed stationary computational domain. For the liquid phase a fast diffusion behaviour is adopted, which results in a uniform concentration profile. The required phase boundary conditions for the transitions between ferrite/austenite and the melt, or between ferrite and austenite, are indicated in the model by way of dynamic mass balances. 14,16 As a general assumption the liquid-solid phase boundary grows with a parabolic rate in time. To represent a phase diagram for multi-component systems, a simplification via linear phase boundary relations was performed. 17 As far as the possibility of precipitations from the melting phase is concerned, these may occur in the form of manganese sulphides 18 and titanium-niobium-carbonitrides. 19 Below solidus temperature the enrichment of elements is lowered through diffusion in the solid. This process is calculated for the local cooling conditions until no further remarkable concentration changes appear. The calculation scheme will be outlined in detail in an upcoming publication. 20 The necessary physical properties, like distribution and diffusion coefficients, were extracted from the software packages Thermo-Calc and DICTRA.

In order to compare the calculated and measured enrichment (compare Sec. 2.4) of different segregating elements in different steel grades, the calculated absolute concentrations were reduced to a segregation index, the ratio between the maximum and minimum concentration, as described above. The curve in Fig. 12 describes, as an example, the remaining interdendritic enrichment of Mn between the strand surface and the centre at room temperature. The measured segregation coefficient of 1.69 in Table 2 (75 mm below surface) agrees well with the calculated value, conforming with results for Cr or Si. The remaining concentration distribution of elements with a high diffusivity, like carbon, is rather influenced by secondary and tertiary phase transformations, than by microsegregation. Phosphorus is a further element difficult to calculate with the present model, as the maximum concentrations are often found in a spot-like form along primary grain boundaries.

Based on the calculations, it is possible to predict enrichments on the microscopic level under consideration of the steel composition and process parameters. This might be an important tool for assessing the process parameters during the further processing of the cast material.

4. Implications for Industrial Operation

Soft reduction is used for continuous casting steel of grades with high requirements regarding macrosegregation. Whether the parameters for soft reduction have been correctly adjusted can be checked with the aid of the OES-PDA test.

4.1. Description of the Continuous Casting Machine with Soft Reduction

One way of keeping macrosegregations and segregation peaks in the slab centre low is the use of soft reduction. 4,5,11,12

In voestalpine’s Linz works, the casting plant CC5 was revamped for soft reduction in 2001. The key operational data of the CC5 are summarized in Fig. 13. Conversion of the CC5 line was done step by step, i.e. segment by segment. Each segment is equipped, beside the four hydraulic positioning cylinders, with four compensating cylinders for approaching the set position. Each compensating cylinder

Fig. 12. Measured and calculated $\lambda_2$-spacings over half the slab thickness and segregation coefficient for Mn.
has an integrated path encoder for position monitoring. If the actual value differs from the set value more than a certain value, the cylinders will restore the set value.

The strand design of the CC5 is such that after the bending zone 16 adjustable SMART segments (Smart—single minute adjustment and replacement time) are provided. The casting gap can be adjusted within a range of between 3.9 m and 35 m beneath the mould level. In this way the thickness reduction can be adapted to the end solidification point even under non-stationary conditions, such as when changing the tundish.

Depending on the steel grade, the quality control system imposes an operating regime with soft reduction. The temperature model DYNACS (Dynamic cooling system) computes the position of the end solidification on-line. Based on these data the ASTC model (ASTC—automatic strand taper control) then calculates the set values for the segment positions, which are transferred via Level 1 to the Segment Controller. With a standard casting thickness of 215 mm, the casting thickness is typically reduced by 4 mm from the middle of the end solidification point to the 100 % solid fraction, with reduction rates of 0.8–1 mm/m.

4.2. Practical Application of the Results of the OES-PDA Test

One example of the in-house application of the results gained from the OES-PDA assessment of the centre segregation is shown in Fig. 14. For the purposes of our research, the respective steel grade was cast with a static soft reduction regime (4 mm thickness reduction at the beginning of horizontal zone) in order to be able to vary the casting speed between 1 and 1.2 m/min. As Fig. 14 shows, the lowest segregation index ($A_{tot}=0.3$) for this steel grade can be achieved at a casting speed of 1.15 m/min and a given set of soft reduction parameters. For the first slab from heat 735084-01, slab witch was casted without soft reduction, a high segregation index was determined ($A_{tot}=25.0$). At slab 735084-03 soft influence on centre segregation is visible and segregation index decrease ($A_{tot}=6.8$).

When the soft reduction is set constant, different casting speeds will cause a change in end solidification point and hence in centre segregation. Therefore, these tests were performed for the most divers steel grades at different casting speeds, and the centre segregation determined. This helped to evaluate the end solidification point calculated with the ASTC models and to adjust the model accordingly.

As a consequence, the optimum soft reduction regime can be chosen for each steel grade depending on the casting speed and the steel grade itself. The main advantage is that soft reduction can be dynamically adjusted during the continuous casting process to any changes in the casting speed.

5. Concluding Remarks

This contribution shows that there are several possibilites to perform an assessment of the macrosegregation (centre segregation). Assessment by microprobe (Fig. 15) is highly accurate but time-intensive (i.e. slow) and costly. By contrast, the OES-PDA test is accurate, fast and cheap. This has induced voestalpine at Linz to adopt in future the OES-PDA test.

Although in assessing the porosity a volume is tested, the OES-PDA test was given preference. The decisive argument was the good correlation between the porosity index established by US-test and the macrosegregation index (OES-PDA test); see Fig. 16. Optical assessment and the
porosity test were eliminated due to the long testing time and the high cost.

The successful control of the casting process with the OES-PDA test results is confirmed by the excellent outcome of the mechanical tests performed on the workpiece samples.

REFERENCES

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