Effect of superheat on macrostructure and macrosegregation in continuous cast low-alloy steel slabs

T Pikkarainen1,2,a, V Vuorenmaa2, I Rentola2, M Leinonen2 and D Porter1
1Centre for Advanced Steels Research, University of Oulu, P.O. Box 4200, FI-90014, Oulu, Finland
2Ruukki Metals Oy, Rautaruukintie 155, Raahe, Finland
E-mail: a teppo.pikkarainen@ruukki.com

Abstract. The effect of superheat on grain sedimentation and macrosegregation has been investigated using experimental castings of a low-alloyed steel grade. With a high superheat of ~ 40 °C, the central equiaxed parts of the slabs consisted of randomly oriented fine dendrites but with a low superheat of ~ 10 °C, coarse globular structures formed. The mean carbon content measured with optical emission spectroscopy was of the order of 15 % smaller with coarse globular structures than in fine equiaxed dendritic structures. Electron probe microanalysis of other alloying elements indicates that the negative segregation in the slab central zones is caused by sedimentation of globulites. With superheat in the range ~ 20 - 40 °C, the equiaxed zone is bordered by a columnar to equiaxed transition (CET) zone. In this region a positive macrosegregation of carbon and other alloying elements was observed. These phenomena are important when considering the through-thickness properties of the slabs and final products.

1. Introduction

The as-cast structure and its effect on macrosegregation have been studied widely under recent decades. In continuous casting of steel, macrosegregation has been found to be caused by the motion of solute-enriched liquid and solute-lean solid [1]. In ingots, many researchers have found sedimentation of equiaxed grains to be the main cause of negative segregation in the bottom part of the ingot [2-6]. Some researchers have also noted the influence of grain sedimentation on macrosegregation in continuous cast steel slabs [7, 8].

Slab macrostructure is largely related to casting temperature (superheat), strand dimensions, cooling and steel composition. Usually the slabs have a fine equiaxed zone near the surfaces, which is formed during the rapid start of solidification in the mold. Depending on casting parameters, the central area usually solidifies as a combination of columnar dendrites from the chill zone towards slab center and equiaxed dendrites in the central region of the slabs. With a very high superheat, the equiaxed zone can be absent so that the structure is fully columnar dendritic. With a very low superheat, the slabs may solidify with a fully equiaxed dendritic structure. Some researchers [7] have pointed out that the equiaxed zone may consist of randomly orientated dendrites or globulites. When the macrostructure consists of columnar and equiaxed grains, a columnar-to-equiaxed transition (CET) occurs. In slab casting, the CET is often associated with negative segregation, so called white bands, which may occur when using electromagnetic stirring [2]. Positive segregation at the CET has also been reported in the case of continuously cast steel billets [9].

In this study, the effect of casting temperature on slab macrostructure has been studied and the different macrostructures caused by different casting superheat are evaluated. The effect of
sedimentation of globulites on macrosegregation in the slabs is considered in detail and the instances of intermediate superheat, with a positive macrosegregation at the CET are investigated.

2. Experimental procedure

2.1 Materials and sampling

Experimental castings of a low-alloyed steel grade were performed with a different superheat. Composition of the studied steel grade is given in table 1.

| Element | C   | Si  | Mn  | Al  | Cu  | Cr  | Ni  | Mo  | Ti  | B   |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
|         | 0.16| 0.60| 1.10| 0.04| 0.01| 0.60| 0.20| 0.40| 0.02| 0.001|

The dimensions of the casting strand were 270 mm x 1975 mm (thickness x width). Slab samples of 100 mm x 270 mm x 20 mm were cut for studying the as-cast structure from the 1/2 and 1/4 width positions of the strand. Smaller samples of 50 mm x 40 mm x 20 mm were cut from the above mentioned samples for optical emission spectroscopy (OES) and electron probe microanalysis (EPMA) and more detailed characterization of slab macrostructures, see figure 1.

![Figure 1. Sampling of the investigated steels.](image)

2.2 Metallography and chemical analysis

Slab samples of 270 mm x 100 mm x 20 mm were ground and etched with HCl to reveal the primary structure of the slabs. Smaller samples of 50 mm x 40 mm were polished and etched with Oberhoffer’s reagent [10] to reveal the primary structure in detail. An optical emission spectrometer (OBLF QSG 750, OBLF, Witten, Germany) was used for macrosegregation analyses of the slab samples. The sample size was 50 mm x 40 mm (height x width). An analysis matrix of 30 analysis points was used as shown in figure 2.

Microsegregation of Mn, Cr and Si was measured on polished surfaces with an electron probe microanalyzer (JEOL JXA-8200, JEOL Ltd., Tokyo, Japan) using line analyses with a step size of 40 μm, an accelerating voltage of 15 kV and a beam current of 15 nA. Because of their low diffusion coefficients their concentration provides information of the as-cast structure of the slabs.
3. Results

3.1 Slab macrostructure

The macrostructure of the investigated slab samples was divided to three types: columnar dendritic, equiaxed dendritic and globular. The different macrostructures are shown in figure 3.

![Figure 3. Slab macrostructures in the studied steels. a) columnar dendritic, b) equiaxed dendritic and c) globular. Etched with picral acid, solute enriched areas appear white.](image)

All macrostructures of the studied slabs had a fine equiaxed chill zone near the surfaces. With a high superheat (~40 °C above liquidus) the rest of the solidification structure consisted of columnar dendrites (figure 3a) and an equiaxed dendritic zone (figure 3b) in the central parts of the slabs. With an extremely low superheat (~10 °C above liquidus), the columnar structure was replaced by an equiaxed dendritic structure, and the central areas consisted of a globular structure (figure 3c). The fraction of different solidification structures is given in table 2.

| Table 2. Fractions of solidification structures.          | Sample A | Sample B | Sample C |
|----------------------------------------------------------|----------|----------|----------|
| Superheat (°C)                                           | 44       | 22       | 7        |
| Chill zone (%)                                           | 7        | 7        | 7        |
| Columnar dendritic (%)                                   | 75       | 70       | 0        |
| Equiaxed dendritic (%)                                   | 18       | 4        | 44       |
| Globular (%)                                              | 0        | 19       | 49       |
A dramatic difference in macrostructures is seen between samples A and C, shown in figure 4. The central area of the slab sample cast with high superheat (44 °C) consists of a columnar dendritic zone and an equiaxed dendritic zone (figure 4a). The sample cast with a low superheat consists of a totally globular structure in the central area (figure 4b).

With an intermediate superheat (22 °C) the slabs consisted of a combination of columnar zones and a globular and equiaxed dendritic zone in the center part of the slabs. In some instances an abrupt CET was observed and a positive macrosegregation was seen at the location of the CET. In figure 5, the appearance of the slab structure cast with an intermediate superheat is shown. As can be seen from the image of the sample etched with HCl (figure 5a) there is a positive macrosegregation at the centerline of the sample but also at the location of the CET.

**Figure 4.** Macrostructures of central areas of slab samples a) A (superheat 44 °C) and b) C (superheat 7 °C). Etched with Oberhoffer’s reagent, solute enriched areas appear dark (the bright spots are remnants of the OES analyses).

**Figure 5.** Macrostructure of central area of a slab sample with an intermediate superheat (22 °C). a) etched with HCl, b) section parallel to the casting direction, etched with Oberhoffer’s reagent, and c) section perpendicular to the casting direction, etched with Oberhoffer’s reagent.

### 3.2 OES analyses
OES analyses were made to measure composition changes in the slab samples in a macroscopical scale. Results are presented as segregation coefficients, i.e. local concentration in the measured area relative to the nominal bulk concentration in the steel (C/Cnom). Each measurement is an average over a spot size of approximately 6 mm. The mean, maximum and minimum values of segregation coefficients of C, Si, Mn, Cr, Ni and Mo are given in table 3 for samples A and C. A segregation coefficient for the carbon equivalent CEV is also given.
Table 3. Segregation coefficients from OES analyses of samples A and C.

| Sample | Segregation coefficients C/Cnom |
|--------|--------------------------------|
|        | C    | Si    | Mn    | Cr    | Ni    | Mo    | CEV   |
| Sample A | Maximum | 1.50  | 1.09  | 1.07  | 1.05  | 1.12  | 1.14  | 1.19  |
|         | Average | 1.03  | 1.02  | 1.00  | 1.01  | 1.05  | 1.02  | 1.01  |
|         | Minimum | 0.89  | 0.96  | 0.95  | 0.97  | 1.02  | 0.98  | 0.95  |
| Sample C | Maximum | 0.93  | 1.03  | 1.00  | 1.02  | 0.97  | 1.05  | 0.96  |
|         | Average | 0.81  | 0.98  | 0.94  | 0.99  | 0.92  | 0.98  | 0.91  |
|         | Minimum | 0.72  | 0.95  | 0.91  | 0.96  | 0.89  | 0.93  | 0.87  |

It can be seen that carbon is the element with the highest and lowest segregation coefficient of the elements considered. In sample A, the maximum carbon segregation coefficient 1.5 was measured at the centerline segregation. The average values C/Cnom of carbon in samples A and C are 1.03 and 0.81, respectively. Considering other elements, the difference between samples A and C is small. Thus, the average values of C/Cnom for carbon equivalent CEV in samples A and C are 1.01 and 0.91, respectively. In a dataset of 120 OES measurements C/Cnom for carbon was 15 % smaller in samples cast with a low superheat (\(~10 \, ^\circC\)) than in samples cast with a high superheat (\(~40 \, ^\circC\)). The OES analysis curves are shown in figure 6a. An example of macrosegregation at the location of the CET is given in figure 6b.

It can be seen from figure 6a, that both samples A and C have macrosegregation peaks at the slab centerline, and areas of negative segregation adjacent to centerline. In sample A the centerline segregation is higher and in general the carbon segregation coefficient and CEV values are smaller in sample C. In figure 6b, one sample shows a positive macrosegregation at the CET, and in the other sample, the composition stays nearly constant. The macrosegregation peak at the CET is wider than at centerline in sample A (figure 6a), but the maximum segregation coefficient is smaller at the CET than the centerline.

![Figure 6](a) OES measurements from slab samples. (a) A (superheat 44 °C) and C (superheat 7 °C). (b) Samples with and without CET segregation (superheat ~20 °C). (Analysis numbers are spot numbers in a matrix like those shown in figure 4. Increasing number means increasing distance from the top surface of the slab.)
3.3 Microsegregation analysis

EPMA line analyses of Si, Cr and Mn in different cast structures are given in figure 7. From figure 7, it can be seen that the distance between microsegregations is smaller in the equiaxed dendritic zone (figure 7c) than the globular zone (figure 7d). Segregation intensities are slightly higher in the globular zone (figure 7b). The composition stays more stable in the equiaxed dendritic zone (figure 7a), as in the maxima compared to the minima of the compositions are higher in the globular zones.

![Figure 7](image_url)

Figure 7. Segregation coefficients determined from EPMA line analyses (a), (b) and macrostructures (c, d). (a) and (c) equiaxed, (b) and (d) globular structures.

4. Discussion

The slab samples cast with a very low superheat were seen to be depleted of carbon and other solutes in the central areas. This is consistent with the sedimentation of globulites as suggested by Wunnenberg and Jacobi [7]. To produce a homogeneous concentration profile through the slab thickness, a columnar dendritic, or a combination of columnar dendritic and equiaxed dendritic structures would therefore be desirable. According to [7] there is a certain temperature below which the globular structure starts to dominate the casting structure. The present results suggest that, in the case studied, that temperature is of the order of 20 °C. Therefore, casting should be performed at high temperatures in applications where negative segregation is undesirable. Casting at an intermediate superheat causes the formation of a CET. Sometimes, positive macrosegregation was observed at the CET boundaries. According to Combeau et al. [5] the fraction of solid is larger in the packed globular zone than in the equiaxed dendritic zone. In continuous casting when the globulites sink in the strand in front of the columnar dendrites, the remaining solute-enriched liquid may result in positive CET segregation at the boundaries of columnar and the tightly packed globular zones. With regard to spot-like segregations, some researchers have pointed out the importance of minimizing local segregation width for improved inner slab quality [1, 11, 12]. This work has shown that the width of the segregation spots is larger in globular structures than in randomly orientated dendritic structures. The EPMA
analyses also revealed that intensity of the segregation was higher in the segregation spots in globular zones than in equiaxed zones. Overall, therefore, globular structures in the central parts of the slab are undesirable if uniform element concentration distributions are desired, i.e. narrow low-intensity spot-like segregation and absence of positive CET macrosegregation.

5. Conclusions
This study has shown that continuous casting with very low superheat causes sedimentation of globulites and negative segregation in the slab central areas. In addition to centreline segregation, with intermediate superheats positive macrosegregation may occur at the columnar to equiaxed transition boundaries. Spot-like segregation widths are smaller with equiaxed dendrites than globular structures. The importance of these phenomena will depend on the intended final product and requirements with regard to the homogeneity of the chemical composition.

Acknowledgements
This work has been done within the DEMAPP programme of the Finnish Metals and Engineering Competence Cluster FIMECC Ltd. We gratefully acknowledge the financial support from the Finnish funding agency for innovation Tekes and the companies participating in the programme.

References
[1] Ghosh A 2001 Segregation in cast products Sadhana 26 5
[2] Lesoult G 2005 Mater. Sci. Eng. A 413–414 19
[3] Flemings M 2000 ISIJ Int. 40 833
[4] Pickering E 2013 ISIJ Int. 53 935
[5] Combeau H, Zaloznik M, Hans S and Richy P 2009 Metall. Mater. Trans. B 40B 289
[6] Ludwig A and Wu M 2002 Metall. Mater. Trans. A 33A 3673
[7] Wunnenberg K and Jacobi H 1983 Arch. Eisenhüttenwes. 54 217
[8] Schwerdtfeger K 1992 Metallurgie des stranggießeins (Düsseldorf: Verlag Stahleisen)
[9] Choudhary S and Ghosh A 1994 ISIJ Int. 34 338
[10] Vander Voort G 1984 Metallography: Principles and Practice (New york: McGraw- Hill)
[11] Matsumiya T 2006 ISIJ Int. 46 1800
[12] Shima S, Maruki Y, Nakashima J, Yamamura H and Oka Y 2004 Scanmet II - 2nd International Conference on Process Development in Iron and Steelmaking, Luleä, 2 19