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SEGREGATION OF ELEMENTS IN CONTINUOUS CAST CARBON STEEL BILLETS DESIGNATED FOR LONG PRODUCTS

This article presents research results concerning designation of the scope of segregation of elements by analysing the ingot, designated for hot rolling of long products. The research tests were performed under industrial conditions, during continuous casting production cycle of high carbon steels. From cc ingots with square cross-section of 160 mm samples having the length of 400 mm were collected, out of which two samples were cut up, the so-called templates with the thickness of 20 mm. Segregation of elements was determined based on the quantitative analysis of results performed by using spark spectrometry pursuant to PN-H-04045. Changes in concentrations of elements were analysed along the line, which join the opposite sides of the sample in their half length and pass through the geometric centre of the square cross-section. In the further course of the research study, there was also determined the segregation along perpendicular line up to the surface connecting the core of the cross-section with lateral plane. Designations of element contents were performed at points distanced from each other by approx. 10 mm and situated on the lines. There was found segregation of carbon, sulphur and phosphorus.

Keywords: continuous casting, billet, segregation

1. Introduction

Segregation of the alloy steel component depends upon conditions under which the solidification process undergoes. Considering the mechanism and conditions for solidification of the continuous cast ingot (cc ingot) being under casting process, the motion of a liquid phase in each case affect the mould's solidification front. Due to such interaction and casting conditions, following can be done, namely: to increase the share of equiaxed crystals, to eliminate adverse phenomenon of the so-called transcrystallisation, to decrease central porosity and the size of inner holes, to reduce the segregation of elements, especially carbon, sulphur and phosphorus, and to reduce the anisotropy influencing the distribution of non-metallic inclusions. All of these treatments will lead to reduction in the number of cc ingot defects, such as inner and superficial cracks, as well as, porosity.

Electromagnetic stirring systems are commonly applied in metallurgical practice to mitigate adverse effects of continuous casting of melts at temperatures much higher than the liquidus temperature for a given chemical composition of steel [1-2]. The values of segregation coefficient such elements as carbon, sulphur and phosphorus can be used to determine of appropriate electromagnetic mould stirrer (EMS) setting ranges. In order to satisfy this goal, there should be carried out segregation of elements in ingots being casted using specific type of continuous casting device by using proposed research methodology, keeping in mind the accessibility of available tools and techniques [3-6].

Research tests presented in this paper, being targeted to determine the degree of segregation of particular elements in the cc ingot, were performed by using industrial unit of continuous casting devise. This unit equipped with six strands is designed for cc ingot of square cross-section with dimensions of 130÷160 mm, made of carbon and low alloy steels.

2. Research methodology

There were analysed a research material produced during normal production cycle. Samples for analysis were collected from cc ingots, derived from particular strand of continuous casing device. From the prepared ingots, samples with a length of 400 mm were cut out; then two samples, the so-called templates with a thickness of 20 mm were cut out (from the entire cc ingot cross-section) (Fig. 1).
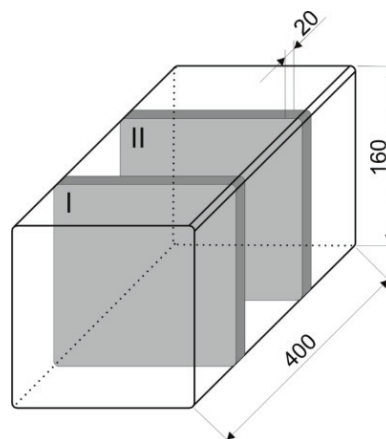

Fig. 1. Sampling point on the cc ingot

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Element content analyses were performed directly on templates by using optical emission spectrometry method pursuant to PN-H-04045. Concentrations were determined along two reference lines: TCB measurement line („top layer – center – bottom layer") and CS, (center – side layer) presented in Figure 2.
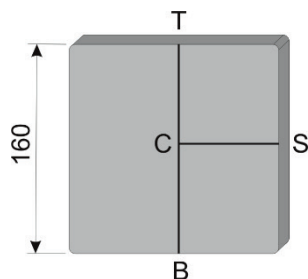

Fig. 2. Reference line position

To eliminate overlapping of the analysed areas, further zones being analysed were distanced by 10 mm from each other. The diameter of active measurement area was 5 mm, while the total impact zone measured 8 mm. Following elements: C, Mn, Si, P, S were subject to quantitative analysis with the use of SpectroLab spark optical emission spectrometer.

In order to determine macrosegregation, the segregation coefficient k was employed, being defined as [6]:

$$k = \frac{c}{c_0} \qquad (1)$$

where: c – actual content of the element at a given point in the cc ingot,
   c_0 – mean content of the element in a ladle sample

Average analysis of steel from ladle sample for a test melt is presented in Table 1.

TABLE 1

Chemical analysis of ladle-test cc ingot sample of steel

Element content, wt %				
C	Mn	Si	P	S
0.6	0.83	0.22	0.013	0.033

In order to determine the size of zones of particular crystals at cc ingot's cross-section, macro-etching test was performed on the test case templates. Based on the macroscopic tests, (see Fig. 3) it was determined that the zone of chill "1"crystals reaches approx. 15 mm (from the surface of the ingot) and the zone of columnar crystals "2"is approx. 50 mm. In the central zone of the ingot, equiaxed crystals were observed "3"; core porosity was also discovered (Figure 3).
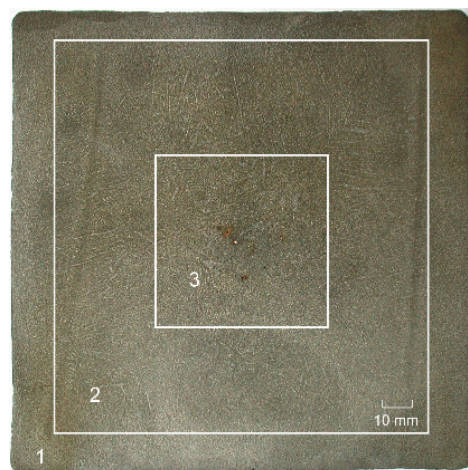

Fig. 3. Crystal zone system in the test case template

3. Results and discussion. Segregation based analysis in continuous cast ingot cross-section

The distribution of elements were analysed for two samples (I, II) collected from the same piece of continuous cast of steel ingot. The segregation coefficient was computed based on the formula (1). For each elements, a change in the value of segregation coefficient along reference lines was presented in Figures 4 and 5. In addition, figures indicate the range of particular crystal zones disclosed in the test sample, as well.

Analysis of carbon content distribution on a cross-section of an cc ingot derived from the sample I, along TCB measurement line indicate its highest content of $k \approx 1.1$ in the chill zone crystals in the top layer of the ingot. Carbon based enrichment of surface zone can come from dissolution of this element being derived from slag-forming powder used in the mould. In the area of columnar crystals, the content is balanced. The highest fluctuations in concentrations of this element are present in the zone of equiaxed crystals, in the core ingot. This can result from longer solidification time in the zone of cc ingot, which favours the diffusion of elements being melted in the direction of ingot's core. In the centre of cross-section a porosity was discovered, which could also affect carbon content distribution. At the bottom of the cc ingot, in the chill zone, its lower content was determined. For manganese, the distribution is more uniform; whereas lower contents were observed in the zone of equiaxed crystals. Similar distribution was for silicon, however, in the top area – in the chill crystal zone – lower content of this element was observed. In the case of phosphorus, by comparing it with the above-mentioned elements, the distribution of its content is uneven. The lowest contents were recorded in the core (equiaxed crystals). In other zones, the phosphorus content is higher comparing with the average ladle sample. Sulphur indicates much higher tendency to segregation, while in the chill zone, its content corresponds to the analysis of ladle sample. Analysis of element distribution along CS measurement line confirms previous observations, despite the fact that they occur with lower intensity. This is also confirmed by designated values of average concentrations of elements for particular lines (Table 2). Average standard deviation for each element is lower for CS measurement line than for TCB measurement, which is embedded in the axis of ingot's cross-section.
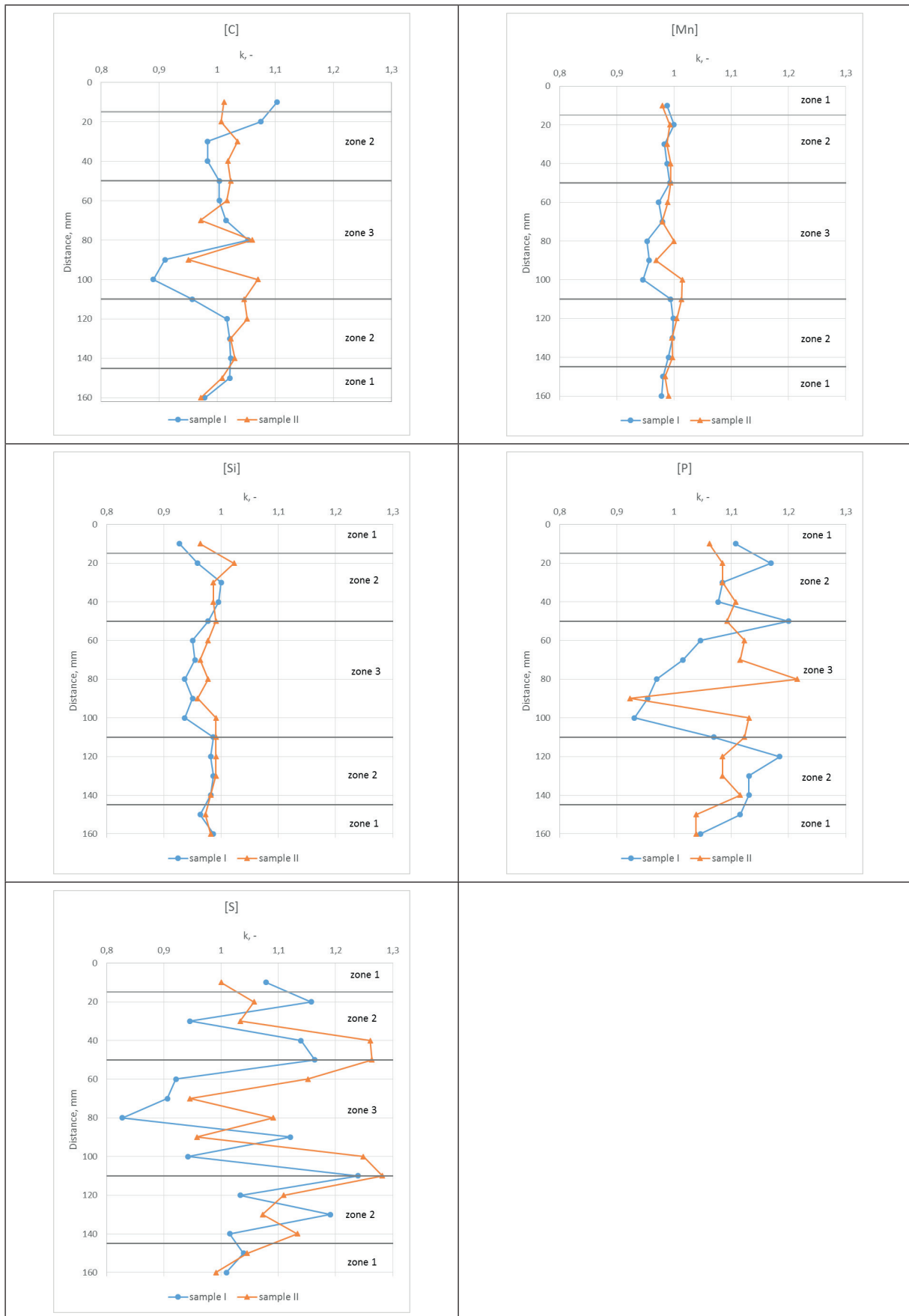
Fig. 4. A change in the value of element segregation coefficient along the TCB line measurements and crystal zones (zone 1 – chill zone, 2 - columnar crystals, 3 - equiaxed crystals)
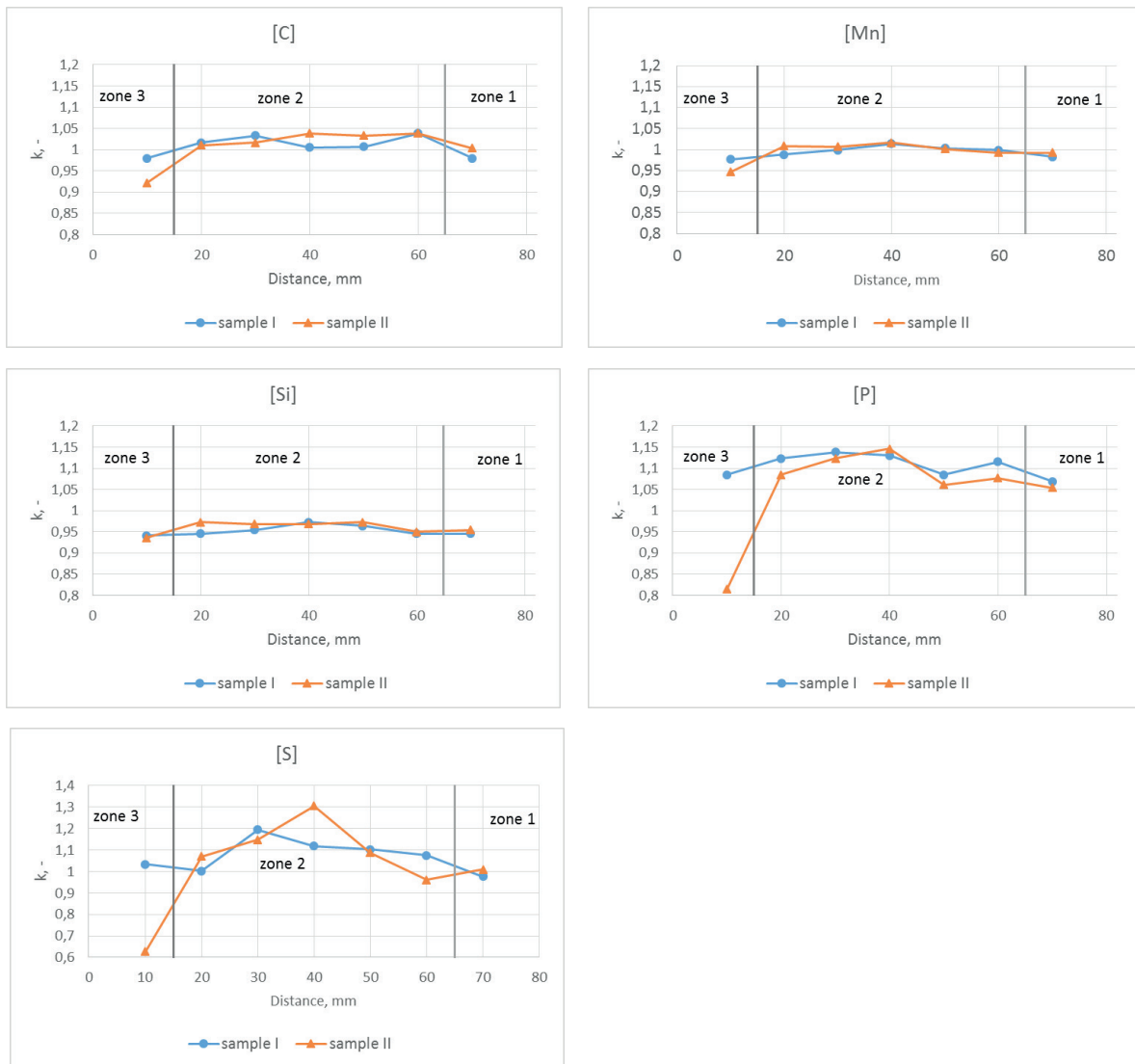
Fig. 5. A change in the value of element segregation coefficient along the CS line measurements

TABLE 2

Average element content along measuring lines and their standard deviations for the sample I

Mean content [wt. %]	C	Mn	Si	P	S
Line TCB	0.601	0.814	0.213	0.014	0.0345
Std deviation [%]	5.42	1.69	2.31	7.45	11.23
k max	1.103	1.000	1.000	1.200	1.239
k min	0.890	0.946	0.927	0.931	0.827
Line CS	0,605	0,826	0,210	0,0144	0,0354
Std deviation [%]	2.33	1.31	1.20	2.48	7.02
k max	1.038	1.014	0.973	1.069	1.194
k min	0.980	0.977	0.941	1.138	0.976

In the sample II, the porosity located in the center of the ingot was significantly greater than in the sample I. Observations of the content of chemical composition along measurement lines are coincident with those obtained for sample I. When measuring the content of sulphur and phosphorus at a distance of 20 mm from the axis at the CS measurement line, lower contents were observed comparing to sample I. For the purpose of confirming the results, the measurements were carried out again, however, the result was similar to the previous one. By comparing changes in concentrations of the the analysed elements in samples I and II, slight diversity can be observed between them. A characteristic feature of element content distribution in both samples is an increase of segregation coefficient „k" for carbon, phosphorus and sulphur in the central part of the ingot's cross-section, in the zone of equiaxed crystals. This consistency is confirmed in specialist literature.

TABLE 3

Average element content along measuring lines and their standard deviations for the sample II

Mean content) [wt. %]	C	Mn	Si	P	S
Line TCB	0.611	0.824	0.216	0.142	0.0364
Std deviation [%]	3.19	1.2	1.54	5.61	10.08
k max	1.070	1.014	1.023	1.215	1.282
k min	0.950	0.969	0.959	0.923	0.945
Line CS	0.6052	0.826	0.0212	0.0136	0.0337
Std deviation [%]	3.93	2.2	1.44	5.6	22,36
k max	1.038	1.012	0.973	1.146	1.306
k min	0.922	0.945	0.936	0.815	0.627

4. Summary and conclusions

Carbon, sulphur and phosphorus segregation along the TCB measurements line were identified. The computed values of carbon segregation coefficient were contained in the range of $0.890 \leq kC \leq 1.103$, sulphur $0.627 \leq kS \leq 1.306$, phosphorus $0.815 \leq kP \leq 1.215$. The observed concentrations of silicon and manganese in the test cross-sections did not indicate significant differences. Porosity in the central zone of the continuous cast ingot and higher segregation coefficients C, S and P in this zone that were identified during tests clearly indicate that it is required to decrease the level of steel overheating during continuous casting of the test species. Such treatment should lead to elimination of central porosity. The lowest measured standard deviation was approx. 10%. The value of standard deviation for points located on the CS line measurements was approx. 3%. The identified values of element segregation are imperceptible, so it can be assumed that the quality of continuous cast ingots from the group of carbon steel before forming treatment satisfy requirements stated for this species.

Nomenclature

k   segregation coefficient
c   actual content of the element at a given point in the ingot,
c_0 mean content of the element in a ladle sample

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