DOI: 10.24425/amm.2018.125145

A.M. HUTNY*, M. WARZECHA*#, P. WIECZOREK**, W. DERDA*

SEGREGATION OF ELEMENTS IN BILLETS MADE OF CARBON STEELS FOR LONG PRODUCTS

The article presents the results of investigations performed on segregation of elements in the billets. The research were performed under standard industrial conditions, during high carbon steel production cycle.

Probes (templates with the thickness of 20 mm) were taken from billets with square cross-section of 160 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 two cross-sections. Element contents were performed at points distanced from each other by approx. 10 mm. The segregation of carbon, sulphur and phosphorus was determined for different billets.

Keywords: steelmaking, continuous casting, billet, segregation, optical emission spectrometry

1. Introduction

Casting is the last stage of the steel production technological line. Currently, the continuous casting (CC) is a commonly used method for producing steels. Implementation of this method allows to improve the quality of billets being casted, increse the steel yield and reduce the energy consumption, when comparing it to the method of pouring steel into ingot moulds [1-2]. At this stage of steel production cycle, due to technological errors or improper process conditions, defects in billets can occurr. Some of the defects can lead to redemption of billets from further processing. Therefore, it is significant to get aquinted with mechanisms of the processes responsible for formation of defects. One of the problems encountered in semi-finished steel products, namely in the continuous casting of ingots, is the non-uniformity of the chemical composition, caused by segregation of elements [3-5]. It depends on the conditions in which the solification process occurrs. By controling the casting conditions, for example - such indicators as, the element content segregation - mostly of carbon, phosphorus or sulphur can be decreased. Nowdays, electromagnetic stirring systems [6-7] are for this purpose commonly applied in metallurgical practice, which allow for controlling the solidification proccess in order to minimize the process during which detects are being formed.

Subject of the work are research tests targeted to determine the degree of segregation of particular element contents in CC billets at individual strands. The billets were casted by using an industrial CC unit with six-strands, designed for producing CC billets with square dimensions of 130 and 160 mm, formed of carbon and low alloy steels.

2. Research methodology

The research material, that was subject to tests was aggregate from regular production cycle. Samples for analyzes were collected from continuous billets comming from particular strands of the CC machine. Samples with the length of 400 mm were cut out from ready-made billets, from which two samples with the thickness of 20 mm were extracted. Quantitative element content analysis was performed directly on templets by using the optical emission spectrometry method pursuant to PN-H-04045. Concentrations were determined along two measurement lines: TCB („top layer – centre layer – bottom layer") and CS (center – lateral plane). Details of this methodology were presented in previous work [8].

Following elements: C, Mn, Si, P and S were subject to the quantitative performed by using the SpectroLab spark optical emission spectrometer. In order to determine macrosegregation at the cross-section of billets, the segregation coefficient k was employed, which is defined as:

$$k = \frac{c}{c_0} \tag{1}$$

where: c – actual element content at a given cross-sectional point, c_0 – mean element content at a sample (s) taken from a tundish.

Sizes of particular crystal zones at the cross-section of the continuous billet were determined based on the image of templates being subject to deep etching test. Details of this test are described in [8].

Table 1 presents average contents of elements occurring during metal bath in a tundish. Templates were collected directly

* CZESTOCHOWA UNIVERSITY OF TECHNOLOGY, DEPARTMENT OF METALS EXTRACTION AND RECIRCULATION, 19 ARMII KRAJOWEJ AV., 42-200 CZESTOCHOWA, POLAND
** CZESTOCHOWA UNIVERSITY OF TECHNOLOGY, INSTITUTE OF MATERIAL ENGINEERING, 19 ARMII KRAJOWEJ AV., 42-200 CZESTOCHOWA, POLAND
# Corresponding author: warzecha@wip.pcz.pl

from the billets, after approximately of 82 % of the casting mass was outlet from the total melt weight.

TABLE 1

Average concentrations of elements in steel being casted in a tundish

C	Mn	Si	P	S
0.561	0.781	0.235	0.012	0.019

Steel was casted at a six-strand CC machine, with a medium casting speed of 1835 mm/min for the strand N°1 (billet 1), 1836 mm/min for the strand N°2 (billet 2), and 1822 mm/min for the strand N°3 (billet 3). Moreover, during the casting process, electromagnetic stirring was used, which was placed in the crystallizer's zone, the work parameters of which were: frequency of 5 Hz and current of 175-179 A.

3. Results and discussion. Segregation analysis from CC billets

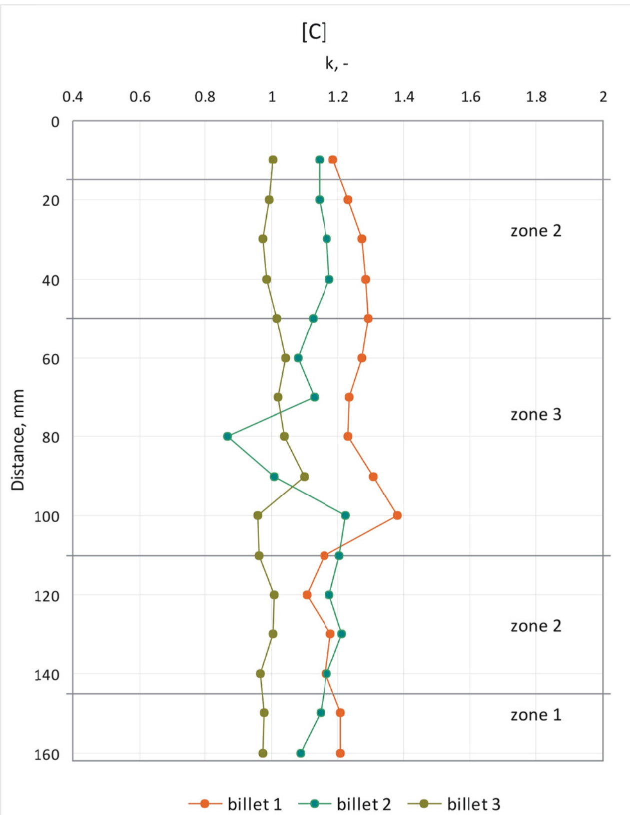
In the presented research work, the distribution of elements in templates collected from three different continuously casted ingots for three tests was investigated. The segregation coefficient was calculated by using the dependence of (1). For particular elements, a change in the values of segregation coefficient in relation to the reference lines were demonstrated in Figs. 1 and 2, and average contents of elements in the analyzed templates were presented in Tables 1-4. Moreover, in presented tables, values of *k* coefficient were given. The figures additionally indicate the range of individual crystal zones, namely: frozen (zone 1), column (zone 2) and equiaxial (zone 3).

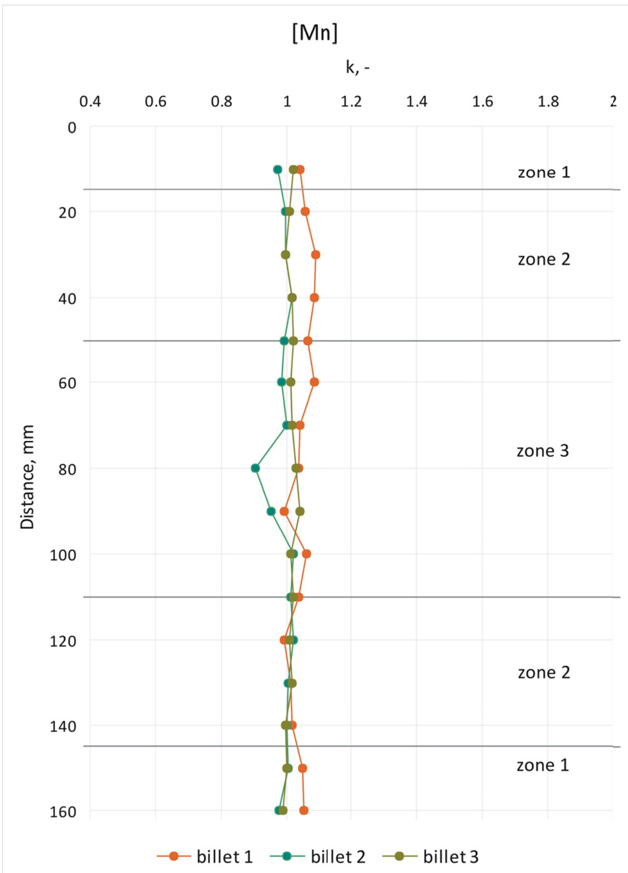
First of all, contents of individual elements along vertical axis were analyzed.

Differences in values of the segregation coefficent for particular strands were determined for carbon. For the most outer strand (N°1), the value of *k* coefficient was approx. 1.2 (a higher content was observed at the billet rather than at the reference sample taken from the tundish); whereas, for the strand N°3 (placed in the closest position to the inlet shroud) it was approx. 1. The largest variations in values of the segregation coefficient were observed for the middle strand (N°2), the mean value of which is in the range of values received for strand No. 1 and 3.

For manganese and silicon – as it should be obvious to be expected – no major variations in concentrations of these elements were observed at the cross-sections of billets; the distribution of concentrations is uniform at the cross-section of the billet, while for Mn, it ranges around the value of 1, and for Si, it receives close to 0.9.

In the tested billets, the strongest segregation is observed for sulfur and phosphorus. For these elements, larger differences in contents were noted on cross-section for each of the three billets being tested. Particularly large differences were observed for the content of sulfur. However, unambiguous indication of the differences between individual strands is not possible to be carried out.





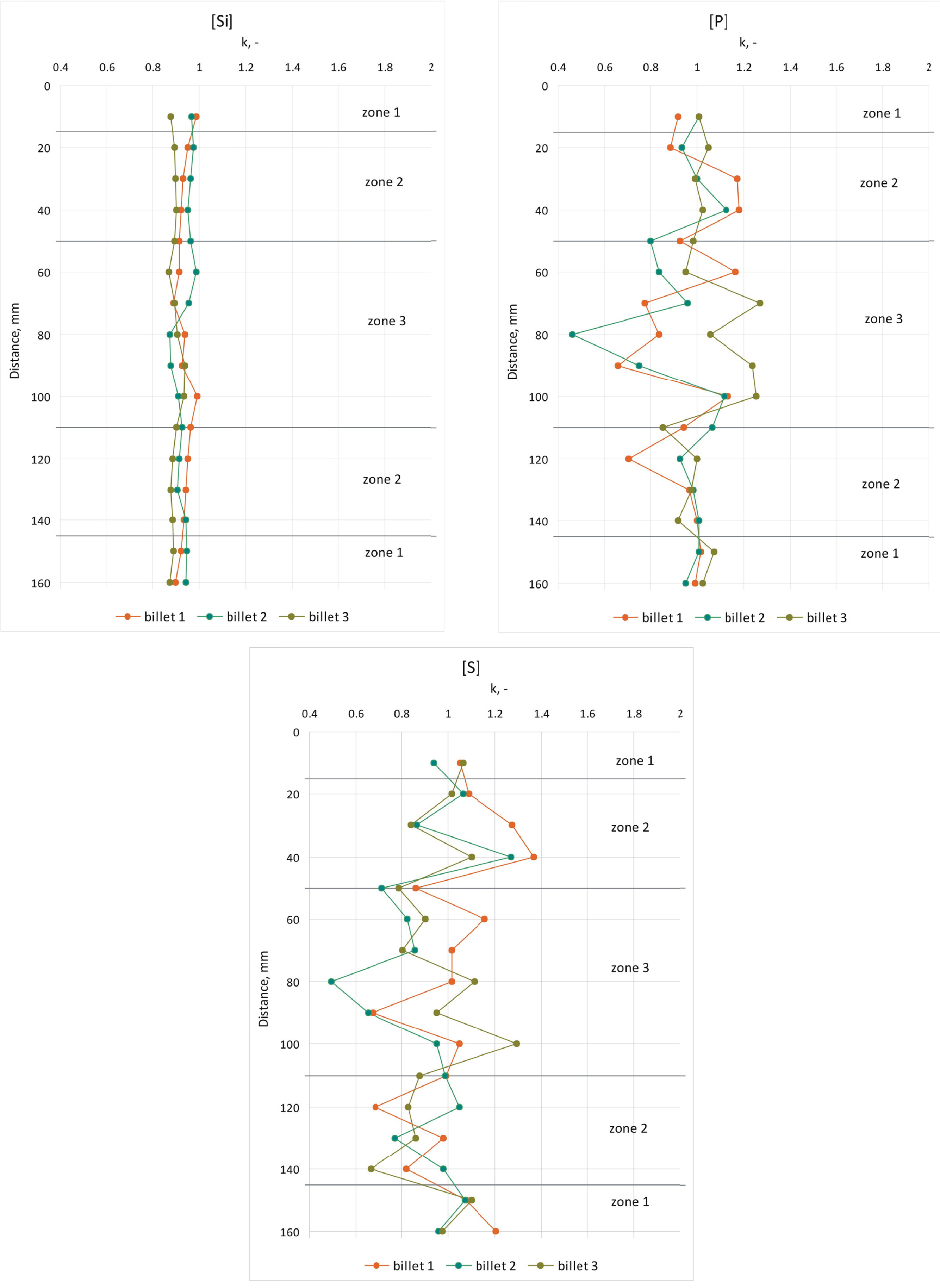


Fig. 1. A change in the element segregation coefficient along the vertical measurement line and crystal zones (zone 1 – frozen crystal zone, zone 2 – columne crystal zone, zone 3 – equiaxial crystal zone)

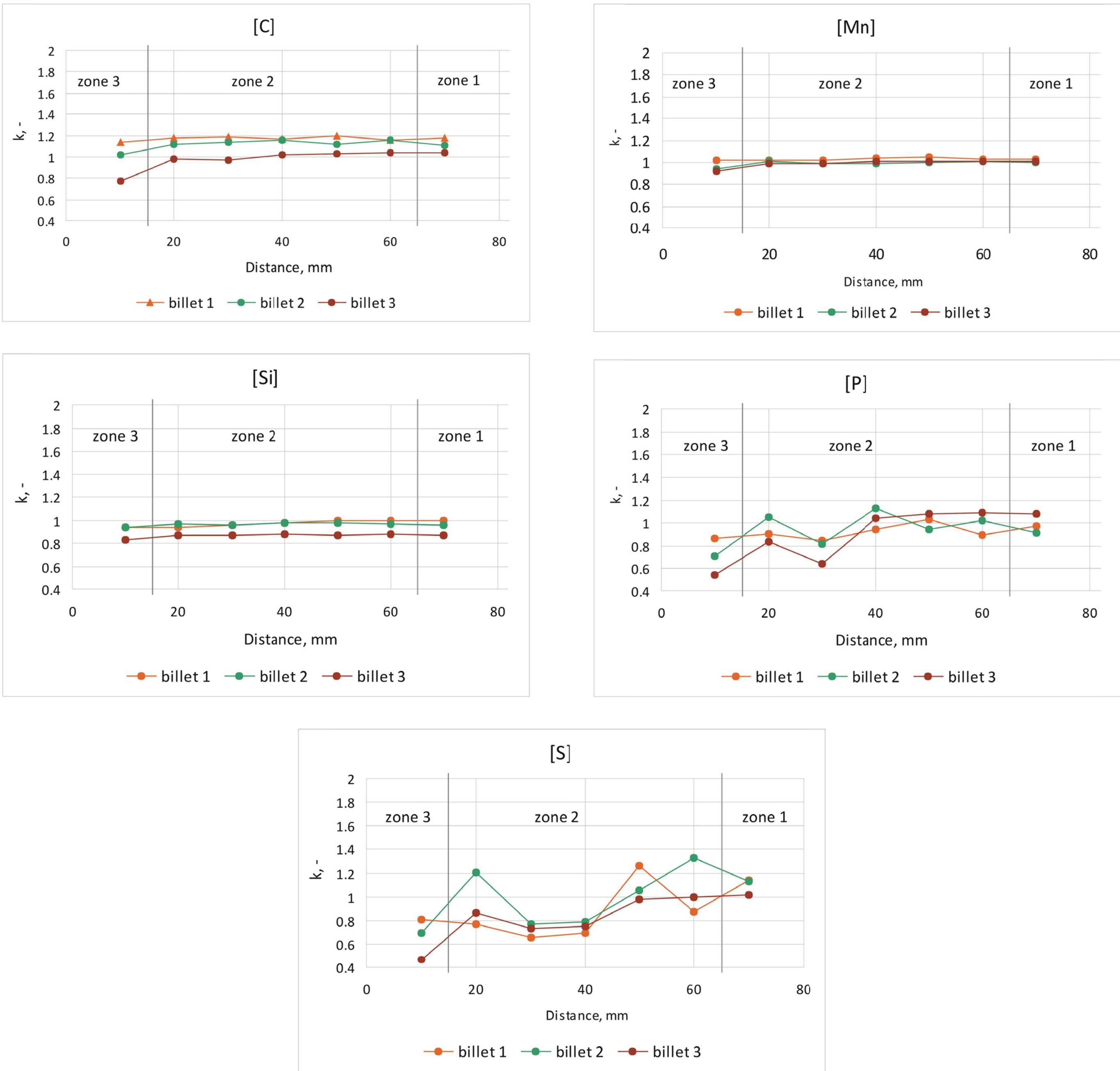


Fig. 2. A change in the value of the element segregation coefficient along the horizontal measurement line

Figure 2 presents distribution of elements along horizontal reference line. For carbon, insignificant differences in segregation of this element were observed for billets collected in particular strands. Certain trends can be noticed, namely a deficiency of the element in the strand situeted closest to the shroud (inlet), and its exceeded value in the most outer (external) strand. For Mn and Si the variations are negligible.

When analysing the distribution of phosphorus and sulphur concentrations, significant variations in the content were noticed. However, the differences for particular strands are impossible to be demonstrated in an unambiguous manner.

Tables 2-4 represent average contents of elements in billets at particular pipes and the minimum and maximum values of the segregation coefficient.

TABLE 2

Average contents of elements along measurment lines and their standard deviations measured for strand N^{o}1

Average incl. wt. %	C	Mn	Si	P	S
Vertical line	0.672	0.817	0.222	0.012	0.022
Std. deviat.	0.031	0.018	0.006	0.001	0.005
***k* min**	0.604	0.788	0.216	0.010	0.014
***k* max**	0.715	0.842	0.236	0.014	0.035
Horizontal line	0.642	0.812	0.218	0.013	0.013
Std. deviat.	0.052	0.027	0.007	0.003	0.003
***k* min**	0.583	0.793	0.204	0.010	0.010
k max	0.757	0.877	0.227	0.019	0.019

TABLE 3

Average contents of elements along measurment lines and their standard deviations measured for strand N°2

Average incl. wt. %	C	Mn	Si	P	S
Vertical line	0.618	0.795	0.229	0.011	0.017
Std. deviat.	0.017	0.011	0.003	0.001	0.003
***k* min**	0.578	0.769	0.225	0.009	0.009
***k* max**	0.660	0.813	0.234	0.013	0.023
Horizontal line	0.663	0.819	0.224	0.013	0.022
Std. deviat.	0.032	0.016	0.004	0.001	0.005
***k* min**	0.594	0.787	0.219	0.011	0.015
***k* max**	0.691	0.839	0.233	0.014	0.030

TABLE 4

Average contents of elements along measurment lines and their standard deviations measured for strand N°3

Average incl. wt. %	C	Mn	Si	P	S
Vertical line	0.545	0.782	0.216	0.012	0.017
Std. deviat.	0.009	0.007	0.004	0.001	0.003
***k* min.**	0.530	0.764	0.207	0.010	0.014
***k* max**	0.556	0.791	0.221	0.014	0.022
Horizontal line	0.547	0.784	0.211	0.011	0.015
Std. deviat.	0.018	0.009	0.004	0.001	0.003
***k* min**	0.521	0.771	0.205	0.009	0.010
k max	0.567	0.798	0.216	0.012	0.019

4. Summary and statements

The objective of the research presented in this work was segregation analysis on selected elements in billets collected from a steel continuous casting machine. The differences in segregation coefficients are consistent with generalny documented facts where C, P, and S in particular, segregate much more in both levels of sample analysis (vertical and horizontal). However, as shown in the results, it is clear that the EMS in the mould has a significant positive effect on the suppression of the segregation phenomenon. Turning to the centre of the billets, this effect, again in line with previously published results of many other authors, decreases the degree of suppression of segregation of critical elements. Yet it remains largely above its equilibrium values. To significantly reduce segregation at the centre of the billets, it is necessary to apply the EMS or the soft reduction method in the area closer to the end of the two-phase region (mushy zone) and possibly to modify Rother parameters of the casting process influencing the course of solidification of the steel.

The justification of the different character of segregation in terms of the casting stand position relative to the shroud cannot be substantiated on the basis of the methods used. Moreover, the differences are not such significant. Due to the complex nature of segregation processes in such a heavily heterogeneous system (steel), it is not possible to expect an exact match between the resulting chemical compositions on the samples. In addition, if no more cross-sections of each casting strand have been evaluated. The influence of changing casting conditions is not substantiated. Arguments with different casting speeds, such as the difference in casting speeds in max value of 15 mm/min difference, are also not relevant.

Acknowledgements

Acknowledgements to the National Centre for Research and Development for financial support (project No PBS2/ A5/32/2013).
This scientific work has been partly financed from the resources of Ministry of Science and Higher Education as statutory researches.

REFERENCES

[1] S., Yogeshwar, Metal. and Mater. Trans. B, **47**, 2096-2106 (2016).
[2] T.R.Vijayaram, International Journal of Manufacturing & Industrial Engineering **1**, 17-36 (2014).
[3] J. Dongbin, W. Weiling, L. Sen, J. Cheng, Z. Miaoyong, Metal. and Mater. Trans. B, **48**, 3120-3131 (2017).
[4] A. Ghosh, Sādhanā **26**, 5-24 (2001).
[5] M. Changwen, S. Houfa, H. Tianyou, Tsinghua Science and Technology **9**, 550-554 (2004).
[6] J. Dongbin, Z. Miaoyong, Metal. and Mater. Trans. B, **48**, 2096 – 2106 (2017).
[7] J. Cibulka, D. Bocek, T. Huczala, J. Cupek, Journal of of Achievements in Materials and Manufacturing Engineering **55**, 638-643 (2012).
[8] A.M. Hutny, M. Warzecha, W. Derda, P. Wieczorek, Archives of Metallurgy and Materials **61**, 2037-2042, (2016).