Arch. Metall. Mater. **70** (2025), 1, 285-290

DOI: https://doi.org/10.24425/amm.2025.152544

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MACROSEGREGATION OF CARBON IN HEAVY STEEL CASTING

Segregation of elements during solidification of massive steel castings and ingots is caused by their different solubility in the melt and in the newly formed solid phase. The macrosegregation of elements significantly affects the structure in terms of microstructure and macrostructure of the casting as well as on its mechanical and operational properties. This paper deals with the evaluation of macrosegregation of selected elements on a real cross-section of a heavy experimental carbon steel casting. Macrosegregation of elements was determined by spectral analysis at selected locations and compared with the ProCAST software and its results of casting solidification simulation. The macrosegregation was analysed along the height and width of a cross-section of the casting, which measured approximately 1800×600×100 mm. Over 300 points were analysed in this area of the casting. The results present mainly carbon segregation. The carbon segregation is compared to the solidification conditions expressed by the cooling rate and the time between the liquidus and solidus temperatures (mushy zone). The aim of this paper was also to verify the measured results with those calculated using commercial software. In conclusion, the measured macrosegregation of the carbon in the casting is different from the simulated macrosegregation, this fact is not negligible. The difference in measured carbon content is influenced by solidification kinetics and will significantly affect the material properties.

Keywords: Macrosegregation; segregation; solidification; heavy castings; carbon steel

1. Introduction

Large dimensional steel ingots or castings are commonly used in various industries. During solidification of these components, there is a significant segregation of admixture elements in the macro-volume, where we can find a significant difference in admixture concentrations especially between the surface layers and the thermal axis of the casting – ingot. We thus speak of chemical heterogeneity – macrosegregation, which arises as a result of the change in the solubility of impurities in the growing solid phase and melt, and also due to the relative movement between the liquid and solid phases during solidification of the steel. This movement occurs according to [1-3] for example, the thermosolutal convection, flotation and sedimentation of freely moving crystals, mixing, flow during the formation of cavities or gases, deformation of the solid phase, etc. Chemical heterogeneity manifests itself on castings at distances of the scale of centimetres to meters. The segregation of elements with high affinity for oxygen and sulphur into the interdendritic spaces and the thermal axis of the casting also leads to the formation of inclusions, which can form single inclusions or clusters of inclusions depending on the type of deoxidizing element and the oxygen and sulphur content of the melt [4]. Macrosegregation has been investigated frequently in steel ingots and according to many experiments it has been shown that a positive macrosegregation distribution of elements, i.e. an increase in the concentration of elements, is in the upper part of the ingot (ingot head) negative macrosegregation in the bottom part (ingot bottom). In the central part of the massive ingot, i.e. between the surface and the axis of the ingot, there are places containing so-called A-segregates. The ingot centreline is affected, especially in large ingots by the V-segregates [5-8]. Similar is the case with large castings, e.g. press rams, support rings for cement plants, when the content of some elements, especially carbon, increases up to twice as much in the risers [9].

The formation of these typical defects for massive and heavy steel ingots or castings has been the subject of extensive studies for several decades. Efforts to understand and address the issue of macrosegregation led as early as 1970 to the development of the first model of macrosegregation developed by Flemings [10,11].

Other models, which were being developed, were based mainly on binary or ternary systems. Other influences such as

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flow velocity, permeability in the mushy zone during solidification, pressure and gravitational acceleration were gradually considered. Nevertheless, these models still did not consider the temperature gradient and conservation of mass equations that went into practice in the 1980s [1,12]. In the 1990s, other researchers began to study grain sedimentation, melt convection, and later also the effect of morphology and movement of equiaxed grains. The impact on macrosegregation was calculated using a two-stage model [6,13]. After the year 2000, three-phase models containing liquid, equiaxial and columnar phases emerge [5,14]. In 2010, the model was expanded to a four to five-phase model that handles not only shrinkage, cavity formation, deformation, but also interdendritic melt [15]. According to this model, in 2017 Wu at al. [16] analyzed the formation of macrosegregation at the transition from a columnar to a straight-axis structure during solidification.

The aforementioned brief description of approaches to the solution of macrosegregation has been verified by a number of authors [3,5,6,8] for steel ingots. On the other hand, studies dealing with modelling and measuring chemical heterogeneity on solid steel castings are rather scarce [7,9]. The differences in the approach and extent of macrosegregation in steel ingots and castings are mainly caused by the different solidification conditions. As a result of the lower heat dissipation of the foundry sand mould compared to chill mould, the solidification times of solid steel castings are significantly longer. This leads to greater macrosegregation of all elements. The results of macrosegregation measurements on steel castings are thus rare and can serve as valuable data for further research and development. This paper deals in particular with the macrosegregation of carbon and sulphur in a large steel casting with a wall thickness of about 600 mm. The experimental results were verified by numerical simulation in ProCAST [17].

2. Description of experiment

The paper presents the results from the investigation of macrosegregations occurring in the casting rings of rotary cement kilns, which form the inner ring of the rolling bearing for its rotation. The castings have the shape of a hollow cylinder usually with an outer diameter of 5000-8000 mm, a wall thickness of 500-700 mm and a total weight of over 120-240 t. The experimental casting was made of G28Mn6 steel (1.1165). The chemical composition of the steel determined in the ladle before casting is given in TABLE 1 [17].

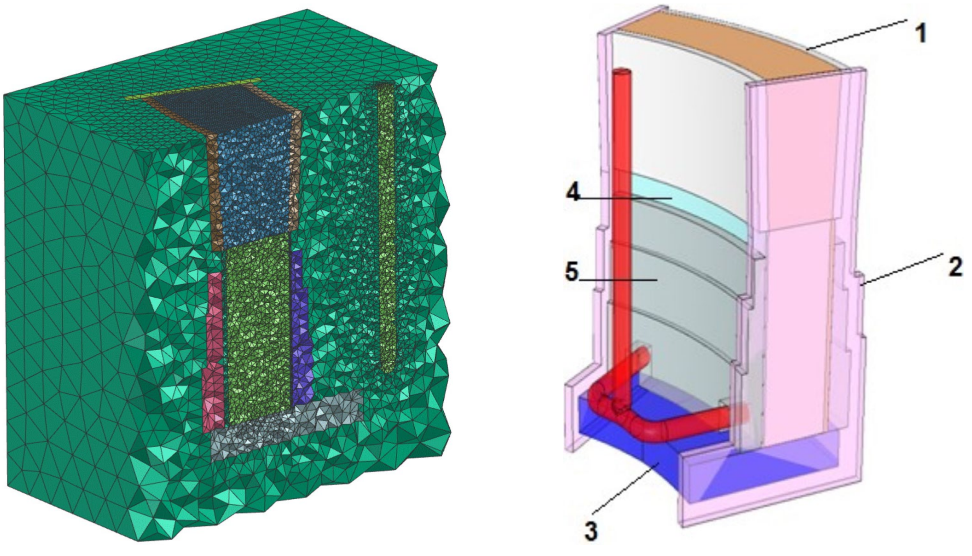
The macrosegregation was observed on an experimental casting, which represented a section of an support ring casting. The size of the section was chosen by solidification simulation so that the temperature field in the centre of the section was comparable to the temperature field of the whole casting.

The weight of the experimental casting was about 18 t. The simulation conditions and geometry of the casting assembly are shown in TABLE 2.

TABLE 1

Prescribed and measured chemical composition of G28Mn6 steel [wt.%]

Element	**C**	**Mn**	**Si**	**P**	**S**	**Cu**	**Ni**	**Cr**	**Mo**	**Al**
Standard G28Mn6	0,25 0,32	1,20 1,80	max. 0,60	max. 0,020	max. 0,020	max. 0,30	max. 0,40	max. 0,30	max. 0,10	—
Composition of the casting	0,278	1,69	0,50	0,008	0,003	0,12	0,01	0,17	0,03	0,033



a) volumetric grid for calculation b) casting assembly and technology used

Fig. 1. Computational grid and selected foundry casting technology. 1 – riser insulation; 2 – insulation of casting wall; 3 – bottom contact chill; 4 – chromite moulding mixture; 5 – non-contact chills

TABLE 2

Casting assembly geometry and casting simulation conditions

Casing volume	1,27 m^3	Weight of casting	10 019 kg
Riser volume	0,94 m^3	Weight of riser	7406 kg
Non-contact cooler volume	0,76 m^3	Bottom cooler volume	0,65 m^3
Non-contact cooler material	steel	Bottom cooler material	steel
chromite mixture volume	0,15 m^3	Moulding mixture volume	22,56 m^3

After casting and removing the casting from the mould, a plate was cut out of the casting in its central section, covering the entire cross-section of the casting and the riser. The plate was 1850 mm high including the riser, 500 mm wide and 250 mm thick.

For subsequent analysis of the chemical composition and structure of the casting at selected locations, the plate cut from the casting was further divided according to the plan into 19 layers, which were further divided into 3 parts. The location of the chemical composition analysis points is shown in Fig. 2.

The concentration of elements was measured by spectral analysis at selected locations, as shown in Fig. 3, and the concentrations of carbon and sulphur were supplemented with combustion analysis. Spectral analysis was performed using the Tasman Q4 spark optical emission spectrometer, while combustion analysis was carried out on the G4 Icarus analyser. The heterogeneity of the chemical composition of the casting was subsequently compared to a numerical simulation in the ProCAST software program (ver. 2011).

According to the simulation results, the solidification time of the casting was approximately 12 hours, with the temperature throughout the cross-section of the casting falling below the liquidus temperature after approximately 2 hours. For up to 10 hours, the casting remained in the under-riser area, characterized by a two-phase area of molten metal and solid phase, known as the Mushy zone. The solidification times for both the casting and the riser are indicated in Fig. 4.

Fig. 2. Evaluated segment cut from the casting

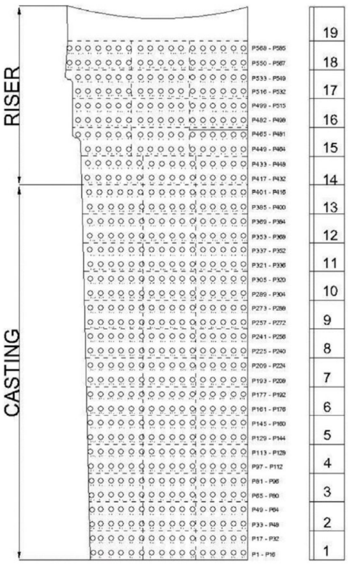


Fig. 3. Locations of the chemical analysis of the casting segment

From the simulation snapshot, it can be inferred that the solidification of the riser completes after approximately 29 hours, and the riser remains in the two-phase region for over 18 hours. Temperature field measurements were not conducted on the specific evaluated casting or the mould. The results of numerical simulations were utilized for the solidification analysis.

Validation and verification of thermos-physical parameters in the simulations were performed based on temperature field measurements in castings and moulds for several different-sized support ring castings. Fig. 5 shows the temperature gradient progression ahead of the solidification front during the solidification of the casting.

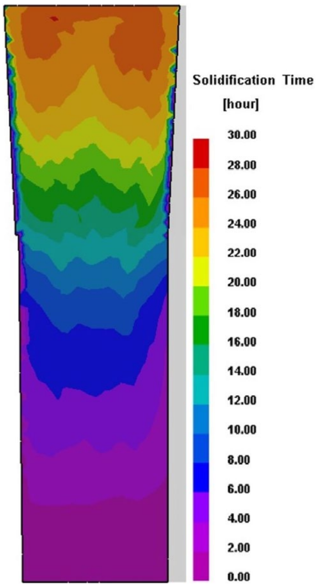


Fig. 4. Solidification time of the support ring casting

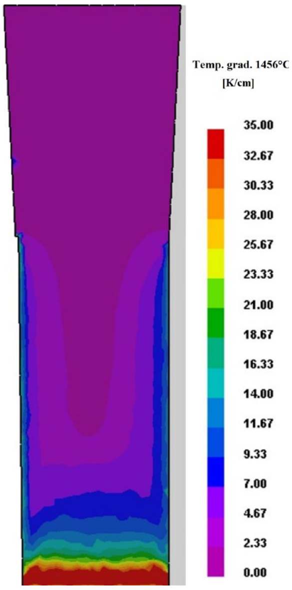


Fig. 5. Temperature gradient progression in the support ring casting

From Fig. 5, it is evident that in the lower section of the casting, which is intensely cooled by a steel cooler, rapid solidification occurs, and the temperature gradient in the melt ahead of the solidification front is very high. Its value exceeds approximately 35 K.m^{-1}. The high value of the temperature gradient aids in the elimination of microporosity and shrinkage defects in the casting and also influences the extent of macrosegregation. With increasing distance from the bottom chill of the casting, the value of the temperature gradient in the axis decreases to below 1 K.m^{-1}. In the case of solidification of steel castings, the critical value of the temperature gradient is 0.5 K.m^{-1} in terms of the occurrence of porosity according to [18].

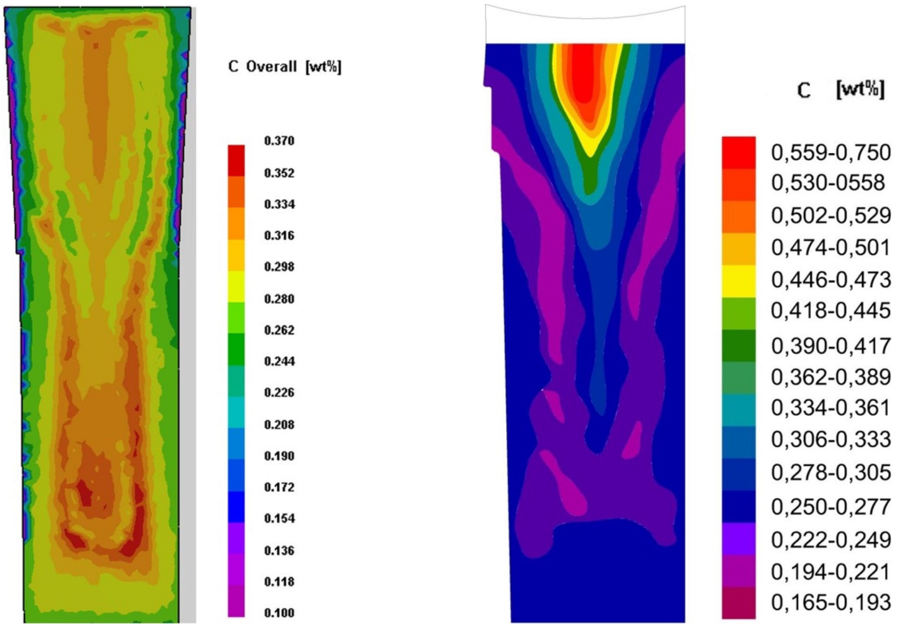
3. Results

The results of numerical simulation of carbon macrosegregation during solidification and cooling of the support ring casting are shown in Fig. 6a. From these carbon macrosegregation simulation results, it can be concluded that the carbon content in the casting can vary from 0.15 to 0.37 wt.%. In the higher parts of the casting and especially in the riser, one would expect a carbon content lower than the composition of the melt from which the casting was cast (C_0). It is a negative macrosegregation in the locations of the skin of a casting. The composition in most of the casting volume corresponds approximately to the composition of carbon C_0. Only at locations with a colour scale from yellow to red is there a significant positive segregation of carbon. This is an increase in carbon concentration of max about 0.1%, i.e. about 20% higher than the corresponding C_0 carbon composition. The increased carbon concentration was simulated particularly at locations where the transition from columnar to straight-axial grains occurs in the casting structure. As expected, a higher carbon concentration was also simulated in the thermal axis of the casting. Fig. 6b shows the distribution of the carbon concentration determined by measurements on the casting cut-out according to the map in Fig. 3. The numerical results of the chemical analyses from the selected points were converted into a colour scale in AutoCAD 2012. Each chemical composition analysis point was assigned a colour map according to the colour scale. Fig. 6b thus gives a sufficient overview of the macroscopic distribution of the element of interest over the casting cross-section.

In Fig. 6 we can then clearly compare the carbon distribution on the cast section determined by numerical simulation and the measured concentrations on the cast section according to Fig. 3. Comparing the results, it is clear that the distribution of carbon in the casting differs in terms of concentrations as well as locations with positive segregation ($C > C_0$) or negative segregation ($C < C_0$) in the casting.

According to the simulation results, the cooling effect of the bottom chill only occurs up to a distance of about 120 mm from the bottom edge of the casting. In this range of distances, carbon segregation is only minimal according to the simulations. As shown by the results of measurements on the casting (Fig. 6b), the effect of the chill on suppressing macrosegregation is much more significant under realistic conditions. At the distance of up to 350 mm from the chill, no significant macrosegregation of carbon was detected in the casting.

Negative macrosegregation was observed on the real casting where macrosegregation was also excluded for other elements (P, S, N, Mn) that formed complex compounds. Structural heterogeneities were also evident at these locations. These were mainly the locations of the transition of columnar grains to straight-axial grains. In these areas, the carbon content ranged from 0.194 to 0.249%. This area corresponds to the bright region in Fig. 6a, where a higher density of dendrites was measured. These are generally poorer in all elements, and the solidified melt in the interdendritic regions is enriched in carbon. This is valid for predicting the macrosegregation of carbon in the thermal axis, especially in the upper part of the riser where the melt solidifies last. The conical shape of macrosegregation corresponds to the directional solidification of steel in the casting. In the vicinity of the central shrinkage cavity in the actual casting, a carbon concentration of up to 0.75% was measured, which is more than double compared to the simulation results. The deviations of carbon concentration between the actual and calculated state ranged from 0 to 0.4 wt.%. The largest deviations between the simulated and measured carbon content were found at the last solidification point, i.e. in the casting riser.



a) Carbon macrosegregation calculated

b) Carbon macrosegregation measured

Fig. 6. Comparison of carbon macrosegregation in the experimental casting segment

The influence of solidification conditions on carbon segregation along the axis of the casting is depicted in Fig. 7. The image shows the relationship between the magnitude of the temperature gradient in the melt ahead of the solidification front at selected locations in the casting and the riser, and carbon concentration from the bottom edge of the casting to the riser. The calculated temperature gradients shown in Fig. 5 and the carbon concentrations determined by measurements at specific locations in the casting (Fig. 6b) were used to construct the diagram. The graph suggests the assumption mentioned in the paper [18], where it can be expected that with decreasing solidification rate and the associated decrease in temperature gradient, there will be a greater tendency for macrosegregation of all impurities in the melt. From the perspective of both chemical and structural homogeneity of steel castings as well as ingots, it is desirable to increase solidification rates and, through directional solidification and intensification of heat removal at selected locations in the casting, also increase temperature gradient values above approximately 1 to 1.5 K.m^{-1}.

The macrosegregation of all important elements was determined by measuring the chemical composition in selected locations of the casting. In this paper, only the extent of carbon macrosegregation is described, which was expressed in individual zones and layers of the casting according to the map in Fig. 8 using the so-called heterogeneity index (1).

$$I_h = \frac{C_{\max} - C_{\min}}{C_0} \tag{1}$$

$C_{\max}$ – maximum carbon content at a given location of the casting [wt.%],

$C_{\min}$ – minimum carbon content at a given location of the casting [wt.%],

C_0 – carbon content of the melt sample [wt.%].

The graph in Fig. 7 shows that only slight negative segregation is evident in the surface layers of the casting from the outer and inner wall to a depth of about 50 mm. The points on a given vertical distance from the surface show differences in heterogeneity along the height of the casting ranging from 375 to 1275 mm. At a distance of 100 mm from the outer surface and 100 mm from the inner surface, the largest negative carbon segregation is found, expressed by a heterogeneity index ranging from 0.65 to 0.95. The segregation index increases with approach to the thermal axis of the casting from both the outer and inner surfaces of the casting, moving into the positive segregation region.

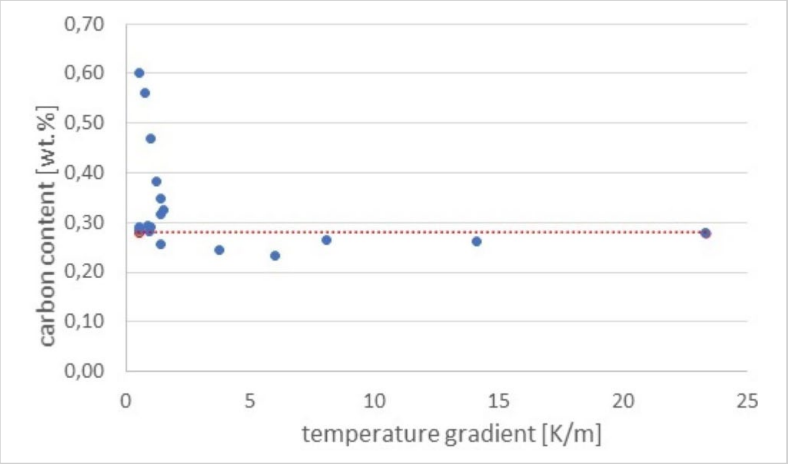


Fig.7. The influence of solidification conditions on carbon segregation

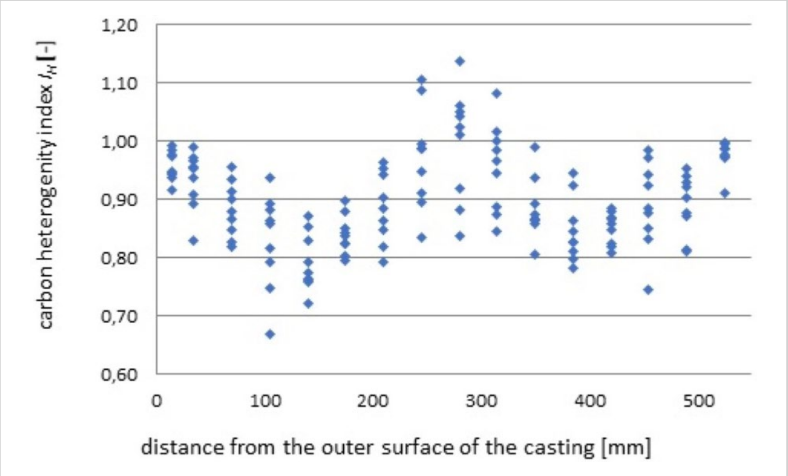


Fig. 8. Progress of the heterogenity index for the layers of the casting at a height of 375-1275 mm

4. Conclusion

This paper describes the evaluation of carbon macrosegregation in a test casting that represents the solidification of heavy solid steel castings used as bearing rings in rotary cement kilns. The method of filling the casting and the kinetics of solidification of the casting is completely different than in the case of steel ingots. The moulding compounds used for mould making have significantly lower heat dissipation than ingot moulds, resulting in significantly lower solidification rates. This often results in a range of macro The study of macrosegregation in steel castings is the subject of relatively few professional and scientific papers. For example, as shown in the article [18], macrosegregations in steel castings have a significant influence on the material structure and the associated change in mechanical properties. For the castings studied, the extent of macrosegregation was influenced by the use of a large volume of chills, both in direct contact with the melt and those located below the moulding compound layer. This made it possible to significantly reduce the solidification time of the castings from the original time of about 18 hours to about 12 hours and thus to increase the values of the temperature gradient in the melt during solidification. As can be seen from the results of numerical simulations and measurements on a real casting, the macrosegregation of carbon is particularly significant at the locations of dendrite density refinement and at the interface between the columnar grains and the planar structure and the thermal axis of the casting, i.e. at the locations of exclusion of A segregation and V segregation. Common trends between the carbon macrosegregation calculated using numerical simulations and the macrosegregation measured on the casting are evident in the casting. However, they differ in terms of the maximum carbon concentration measured in the pour. The difference is more than 0.4 %. Differences in simulated and actual carbon concentration may also be due to the formation of microporosity, which may have affected the accuracy of spectral analysis in such affected areas. For this reason, the upper part of the riser was not evaluated structurally nor metallographically.

Acknowledgment

This work was supported by the specific research project of BUT FME Brno, no FSI-S-22-8015:Výzkum v oblasti tavení a metalurgického zpracování vysokoteplotních slitin.

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