Centerline inhomogeneity of flat products

M Réger¹, E R Fábián² and L Tóth²
¹Full professor, Óbuda University, Budapest, Hungary
²Associate professor, Óbuda University, Budapest, Hungary

E-mail: reger@uni-obuda.hu

Abstract. Defect free casting requires an excellent accordance between steel properties being cast and the technological parameters, especially from the aspect of inner quality and homogeneity of cast products. Typical serious defects of cast slabs is the centerline segregation (CLS). The centerline segregation in slabs develops in a very complicated way, the main factors influencing the CLS pattern are the macrosegregation and the shrinkage of solidifying melt in the mushy area. The centerline section of the slab can be characterized by different chemical composition compared to the average composition and it can contain shrinkage holes, discontinuities and inclusions. In the hot rolling process the complex shape of interdendritic holes will be modified depending on the strain applied. In chemical composition the difference remains and it can be identified even after the soaking period (over 1050 °C). As an example, the center part of an St52 grade hot rolled heavy plates and strips containing CLS can be characterized by a carbon content of 0,3-0,5 wt% and manganese content of 1,7-1,9 wt%. The segregation level – including the carbon content – can hardly be decreased by post heat treatment or annealing.

1. Introduction

The centerline inhomogeneity frozen in the slab structure can have a detrimental effect on the properties of hot rolled semi or final products, i.e. some remaining forms of this casting defect can be identified even in hot rolled strips. During hot rolling the centerline segregation (CLS) pattern will become thinner and will be stretched, and it can also be identified in the center part of hot rolled heavy plates and strips. Normalizing or homogenization treatment hardly decreases the severity and extent of CLS. Diffusional calculations proved that the thermodynamic activity of carbon can play a governing role in the homogenization process, because the thermodynamic activity is influenced by the uneven distribution of alloying elements. Cross-effect between carbon and alloying elements in the diffusional homogenization process of austenite can be described by calculation of local carbon activity functions taking into account the local influence of individual elements [1, 2].

In case of commercial low carbon steels the chemical elements which are prone to segregate in the centerline area during solidification of continuously cast slabs are carbon, manganese, silicon, phosphorous and sulfur. Although the ratio of segregation of phosphorous and sulfur can reach high values, the total amount of these elements are very low either in the segregated area. As a consequence, they can’t have a strong impact on the activity of carbon in austenite. Furthermore, sulfur liable to form sulfide inclusions in the solidification process, and the chemically bonded part of sulfur don’t play any role in the activity modification of carbon. Manganese and silicon content can be high enough in these steels to modify the carbon activity. Silicon has smaller effect, because on one
hand silicon content in these steels is less than manganese, and, on the other hand silicon has a weaker influence on carbon activity.

Manganese seems to have a double role in stabilizing centerline segregation. It diffuses very slowly, so there is no chance for manganese homogenization under industrial circumstances and this can result in a higher carbon content in the centerline area than the average carbon content, because manganese modifies the activity of carbon locally. On the other hand, during the transformation processes manganese enhances the formation of harder microstructural constituents with lower plasticity like pearlite, bainite and martensite, which, in general, are harmful to the quality of the product.

2. Origin and nature of centerline segregation

CLS of slabs connects to the macrosegregation processes and to the shrinkage effect of metal during solidification [3-6]. In the continuous casting process the segregation develops in the center part of the slab because of solidification and phase transformation processes. Due to the constrained liquid supply the compensation of shrinkage is not exactly accomplished.

After hot rolling or normalizing the centerline segregated mid-thickness area of mild steel heavy plates or strips can contain pearlitic or even bainitic/martensitic banded microstructure (Figure 1). The segregation ratio can exceed 2 or 3 in respect of alloying elements or impurities, typically the manganese, carbon, phosphorus and sulfur are liable for enrichment during the solidification process.

The centerline segregated area frequently contains series of inclusion and sometimes also comprises thin discontinuities (crack like formation, see Figure 2). This latter defect connects to the void (porosity) formation in the final stage of solidification. The small but complex shaped voids are deformed and stretched in rolling direction in the hot rolling step, but sometimes discontinuities can remain because of insufficient welding during hot deformation.

![Figure 1](image1.png)

**Figure 1.** Microstructure of centerline segregated area revealed in a 50 mm thick hot rolled heavy plate. The center part contains bainitic, martensitic structure having a hardness of 520 HV0,1. In the off-center area the microstructure consists of ferrite with pearlitic bands. In the upper part of bainitic-martensitic area having light blue color some crack-like longitudinal discontinuities containing inclusions can be identified. Original magnification 100x, etched in Nital.
Figure 2. Crack-like discontinuity with inclusions in the center area, which is the trace of a shrinkage hole developed in the last stage of solidification, and was deformed during hot rolling. Original magnification 1000x, etched in Nital.

Experience proved that the unfavorable properties of plates and strips due to centerline segregation can hardly be improved by heat treatment (normalizing, homogenization). In general, the level of macrosegregation cannot be reduced significantly and the microstructural characteristics remain more or less unchanged [7, 8].

These experiences suggest that homogenization in a diffusive manner is somehow impeded when heavy plates or strips are re-austenized. Sulfur is immobile because it forms inclusion. In case of manganese, silicon and phosphorus the slow diffusive homogenization rate is caused by the very small value of diffusional coefficients of these elements in austenite. Carbon diffuses very rapidly in austenite, but even after heat treatment the original carbon-related characteristics can be identified in the microstructure.

The mechanism of the redistribution of carbon in the center area of hot rolled product after austenizing can show similarities with the so-called banded microstructure formation, which is the characteristic microstructure of hot rolled, or hot rolled and normalized plates and strips. In case of band formation the uneven distribution of manganese plays the governing role by enhancing pearlite formation in the manganese enriched bands. The uneven manganese distribution is caused by the microsegregation process taking place in solidification, and the structure of manganese enriched bands parallel to hot rolling direction is formed during the hot rolling deformation steps.

After normalizing, the presence of increased carbon content in the manganese enriched center part of the strip can also be explained by the role of manganese in austenite decomposition process. However, some other effects which can play a role in the formation of microstructure also have to be taken into account. First, there are several “natural” obstacles in the centerline segregated area, which counterwork the carbon equalization in the heating and soaking period of heat treatment (net of inclusions, crack-like discontinuities). The position of these obstacles are perpendicular to the diffusion direction necessary for carbon homogenization, so they can stop the diffusion of carbon in some parts of the centerline. Secondly, there are cross effects of diffusion processes of individual enriched elements, and the equilibrium carbon content can be affected e.g. by the local manganese content.
In the following paragraphs the effect of uneven manganese (and silicon) content distribution on the diffusional processes of carbon will be discussed.

3. Theoretical background

Manganese distribution affects carbon diffusion in austenite by changing the thermodynamic activity of carbon locally. The driving force for carbon diffusion depends on the carbon activity differences in the sample. In Fe-C-X systems the activity of carbon depends primarily on the carbon content, on the temperature, and on the quality and quantity of alloying elements.

There are some data in the literature for the thermodynamic activity of carbon in austenitic region and these models give similar results in case of pure iron-carbon systems. For detailed analysis of the carbon activity results three models (developed by Wyss, Huan and Hillert [9-11]) were chosen. Figure 3. summarizes the results for two different temperatures as a function of carbon content without taking into account the alloying effect. Only slight differences can be seen between them.

The correlation between the predicted results of the three models become much worse if the presence of 2 wt% manganese is supposed. Figure 4. shows the results of the models for 1150 °C. Almost a double difference can be found between the results of Hiller’s and of Wiss’ models, and this indicates the reliability of the models.

The diffusion process is governed by the differences of carbon thermodynamic activities in austenite. If the activity level is the same for the whole sample, there will be no more reason for carbon atoms to proceed to diffuse. In a pure iron-carbon system after a long enough period of soaking time this results in a uniform carbon content distribution because the activity level of carbon is also uniform. Otherwise, if the homogeneous carbon activity level is disturbed for some reason (e.g. alloying elements are present), the long term carbon activity equalization will result in a non-homogeneous carbon content distribution. In this case, e.g. after a long term homogenization, there will be some remaining carbon content difference in the sample. Homogenous carbon content distribution can only be achieved in case of a homogeneous carbon thermodynamic activity field.

![Graph](image_url)

**Figure 3.** Activity of carbon in Fe – C biner austenite as a function of carbon content for two different temperatures. The calculation models gave similar results.
In order to estimate the effect of uneven manganese distribution on the carbon diffusion in austenite, heat treatment processes were modelled with real carbon and manganese distributions. The carbon activity calculation was performed by using Huan’s method.

![Figure 4](image.png)

**Figure 4.** Activity of carbon in Fe – C – 2 wt% Mn ternary austenite as a function of carbon content at 1150 °C calculated by different models.

4. Calculation examples
In the following paragraphs two different flat products are discussed from the point of view of behavior of centerline segregation in a re-austenizing process. The extent and severity of the enrichment of carbon and manganese in the center area of the three products are different, so these examples exhibit also the high variability of the appearance of CLS in the final or semi-final flat products. Stationary and time dependent approaches will both be applied. In these calculations only the effect of manganese and silicon uneven distribution is taken into account. Because these elements have a much less rate of diffusion in steel than carbon, the unchanged distribution of manganese and silicon was supposed (even in case of the stationary calculation). The main aim of the calculations was to clear up the role of those highly enriched elements in the CLS, which can affect the diffusion of carbon (especially manganese) on the redistribution process of carbon in the heating and cooling process.

4.1. Example 1: Heavy plate with severe CLS
The most important parameters of the production technology, the composition and CLS are given in Table 1.

The typical appearance of this defect in the heavy plate can be seen in Figure 1. This picture also shows microstructural variability inside the CLS region, which is caused by the compositional inhomogeneity. According the average composition measured in the CLS region given in Table 1. CLS can be characterized by a segregation index of 2.3 for carbon and 1.4 for both manganese and silicon. The CLS region also contains several longitudinal crack-like discontinuities with elongated inclusions, which can also hinder the diffusional processes.

The carbon content unevenness will decrease during the heating in the austenitic region. The driving force is the activity difference of carbon along the cross sectional area, but the activity is
affected by the uneven manganese distribution as well. In general the higher the manganese level, the lower the activity of carbon. This so called “up-hill” diffusion effect results in a non-continuous carbon distribution function (see red curves in Figure 5 and 6). The small step on red curves coincides with the manganese distribution step resulted by CLS formation. The blue lines represent the expected carbon distribution when neglecting the effect of manganese on the thermodynamic activity of carbon.

**Table 1.** Characteristic parameters of the heavy plate and the centerline segregated zone.

| Technology                  | Conventional CC and hot rolling, as rolled |
|-----------------------------|--------------------------------------------|
| Grade                       | S355                                       |
| Slab thickness, mm          | 240 mm                                     |
| Plate thickness, mm         | 50 mm                                      |
| Nominal comp, wt%           | C 0.18, Mn 1.60, Si 0.29                   |
| Thickness of CLS in plate, mm | 0.3                                        |
| CLS comp., average, wt%     | C 0.41, Mn 2.15, Si 0.4                    |

**Figure 5.** Calculated carbon distribution close to the center in thickness direction of the heavy plate. Black line represents the as-rolled carbon distribution at room temperature, the color lines show the expected carbon distribution at 900 °C after half-an-hour treatment.

The effect of enriched elements on the long-term diffusional processes of carbon during austenizing was estimated by stationary calculation. In the homogenous austenitic region, the final carbon distribution also follows the uneven distribution of manganese, which results in a 0.05 wt% increase of carbon content in the CLS region as can be seen in Figure 7 (represented by red line). If the effect of silicon is also taken into account, the difference decreases a little bit, because of the counteractive effect of silicon on the mobility of carbon.
Figure 6. The same as in Figure 5, but the color lines show the expected carbon distribution at 1100 °C after half-an-hour treatment.

Figure 7. Calculated carbon distribution close to the center in thickness direction of the heavy plate at 900 °C for stationary case. Note that in this calculation zero manganese and silicon diffusion rate was supposed! Red line represents the final carbon distribution when the effect of manganese, the blue line when both the manganese and silicon effects are taken into account.

4.2. Example 2: Hot rolled strip with severe CLS and banded structure
This example was taken from a research study dealing with the suppression of banded structure of hot rolled products. It was performed by an EU consortium in the frame of RFCS project [12]. The research activity focused on the formation and possible elimination of the characteristic banded
structure of hot rolled steel products, but – as a special case of bands – the CLS region was also investigated (Figure 1 shows several bands as well). A very detailed analysis of the enriched areas of high manganese DP steels was performed in the frame of this project.

In this case the thickness of CLS area is much thinner (the difference is one order of magnitude), but the severity is higher than in Example 1. The estimated segregation indexes are 3.3 and 1.5-2 for carbon and manganese, respectively. In reality, manganese has a non-uniform distribution inside the CLS region, neither in cross sectional, nor in longitudinal direction, which can be clearly seen in Figure 8.

**Table 2.** Characteristic parameters of the hot rolled strip and the centerline segregated zone.

| Technology              | Conventional CC and hot rolling, as rolled |
|-------------------------|--------------------------------------------|
| Grade                   | DP800                                      |
| Slab thickness, mm      | 250 mm                                     |
| Strip thickness, mm     | 3.2 mm                                     |
| Nominal comp, wt%       | C 0.15, Mn 1.9                             |
| Thickness of CLS in plate, mm | 0.03                              |
| CLS comp., average, wt% | C 0.5, Mn 2.8 (max 4)                     |

![EPMA map of manganese in the center area of a DP800 grade as rolled 3.2 mm thick strip (above). Line scan of manganese content distribution (wt%) in cross sectional direction (below) [12].](image)

A set of calculations was performed in order to estimate the effect of manganese non-uniform distribution on the carbon distribution in homogeneous austenite at elevated temperature. Because of the high diffusion rate of carbon and of the very small thickness of CLS in the strip the calculation
results for 900 °C are displayed here. The manganese content in the CLS area was supposed to be 2.8 wt% as the average of measurement according to Table 2.

A very short treatment can result in a drastic decrease in the central carbon content (Figure 9), but as a result of higher enrichment of manganese, the step height caused by manganese content change at the CLS border is higher and approaches the 0.1 wt% value. After half-an-hour treatment at these temperatures the carbon diffusion almost reaches its stationer state (see Figure 10), and the carbon increment in the center is around 0.08 wt%.

Figure 11 shows the results of the calculation performed for stationer conditions. Only the carbon diffusion was taken into account and it was supposed that the manganese can’t diffuse despite the infinite time.

![Figure 9](image_url)

**Figure 9.** Calculated carbon distribution in thickness direction close to the center of the strip. Black line represents the as-rolled carbon distribution at room temperature, the color lines show the expected carbon distribution at 900 °C after one minute treatment.

Figure 11 contains calculation results in which manganese content over the average value given in Table 2 was used inside the CLS area. The EPMA mapping measurements proved that the manganese distribution fluctuates in a relatively wide range inside the CLS area. According to the measurements, the manganese content difference between the steel average composition and the local manganese composition somewhere inside the CLS zone can approach higher and lower values. In this cases the effect of higher manganese content differences were modelled. According to the calculation results given in Figure 11 at this high manganese difference can result in a multiplied effect on the carbon enrichment in the homogenous austenitic phase, and the carbon content difference inside the strip can reach the 0.25 wt% value.

5. **Conclusions**

Centerline segregation in the middle of hot rolled flat products is a defect inherited from the slab solidification process. The only effective way of preventing CLS formation is to modify the solidification conditions in continuous casting in the last stage of solidification. During hot rolling the severity and extent of CLS decrease, but the remaining traces of CLS can hardly be reduced by post heat treatments.
The same as in Figure 9, but the color lines show the expected carbon distribution at 900 °C after half-an-hour treatment.

Figure 10. The same as in Figure 9, but the color lines show the expected carbon distribution at 900 °C after half-an-hour treatment.

Calculated carbon distribution close to the center in thickness direction of the strip at 900 °C for stationary case. Note that in this calculation zero manganese diffusion rate was supposed! Color lines represent the final carbon distribution for different manganese contents in the center area.

Figure 11. Calculated carbon distribution close to the center in thickness direction of the strip at 900 °C for stationary case. Note that in this calculation zero manganese diffusion rate was supposed! Color lines represent the final carbon distribution for different manganese contents in the center area.

The stability of CLS in hot rolled flat products is caused by the enrichment of alloying elements and impurities in the center area of the plates and strips. These alloying elements and impurities have a very low diffusion rate in austenite, i.e. they are keeping their original uneven distribution, which has developed in casting and rolling during the post heat treatments. Manganese has a decisive role,
because it is prone to enrich, has a low diffusion coefficient in austenite, enhances the formation of pearlite and non-equilibrium microstructural constituents in decomposition of austenite. At the same time the manganese content difference can modify the thermodynamic activity of carbon in the austenite depending on local manganese content, resulting in an uneven carbon distribution in the austenitic phase during homogenization.

The crack like discontinuities and series of elongated inclusion perpendicular to the diffusion also decelerate the homogenization process.

6. References
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