*Journal of Metals, Materials and Minerals. Vol. 15 No.2 pp.45-51, 2005*

# Centerline Segregation of Continuously Cast Slabs Influence on Microstructure and Fracture Morphology

**Martin Fujda**

*Department of Materials Science, Faculty of Metallurgy, Technical University of Košice, Slovakia*

## Abstract

Metallurgical reasons are sought to explain a centerline segregation consisting of additives and impurities in continuously cast slabs of low carbon steel. The influence of segregation on the microstructure and fracture surface Morphology of specimens cut out from the center of the slab was analyzed. The accumulation of sulphidic inclusions and liquations in the center zone of the slab is a typical sign of the centerline segregation. Carbon segregation was observed together with surface active additives (Sn, Sb, As) into the center of the slab with ferrite-pearlite microstructure and different grains in size and shape.

**Keywords:** continuously cast slab, centerline segregation, sulphide eutectics, microstructure, liquation, fracture surface morphology

## Introduction

During continuous casting crystallization the distribution of additives and impurities in steel is becoming inhomogeneous in the direction across the slab. This macroscopic inhomogenity is caused by microsegregation processes in dendrites during steel crystallization.

The temperature dependence of the solubility of additives and impurities, according to their binary diagrams is different. The distribution coefficients describe the value of microsegregation or dendritic segregation of the individual additives and impurities during crystallization of the steel. The crystallization segregation of elements with low distribution coefficients (k<1) in iron is remarkably high, e.g.: C, S, P (Table1)[(1).] The segregation range of elements in steel is influenced by the crystallized phase type, as well. If it was δ or γ solid phase, then it was characterized by the distribution coefficient $k_\delta$ , or $k_\gamma$ , respectively (Table 2). The values of the individual distribution coefficients $k_\delta$ and $k_\gamma$ show clearly that the solubility of impurities S and P in austenite is lower than in δ-ferrite. This way at γ-phase crystallization the level of their interdendritic segregation is higher than that of the δ-phase crystallization[(2-5).] In the case of peritectic transformation or $\delta \rightarrow \gamma$ transformation the microsegregation during crystallization depends also on the redistribution between δ and γ phases. This redistribution depends on the value of the two phase (δ and γ) equilibrium distribution coefficient $k_{\delta\gamma}$ (Table 2)[(3-5).] For elements having high distribution coefficients $k_{\gamma\delta}>1$ (C, Mn), the concentration of the element in the γ-phase is growing with the $\delta\rightarrow\gamma$ phases transformation. If elements (Si, P, S) have a coefficient $k_{\gamma\delta}<1$, then the formed γ-phase would contains low amounts of these elements and they segregate into the axis of the dendrite[(3-4)]. The amount of impurities (P, S) which is transported into the center of the dendrite is growing with the decrease of the cooling rate in the two phase $\delta + \gamma$ zone due to the longer existence of the δ-phase.

The described processes in the dendrites inevitably could result in the macroscopic centerline segregation of additives and unwanted impurities into the middle zone of the slab at continuous casting. The occurance of centerline segregation in the continuously castings is in close relation to the central hot spot in the center of the casting, solidifying as the last zone[(6).] The centerline segregation, is formed by different small discontinuous zones containing microscopic porosity, accumulation of MnS, or FeMnS sulphides in chains or clusters, and aggregations of other elements[(7).] The centerline segregation in continuously cast slabs cannot be explained obviously by only dynamics of the crystallization. The segregation is influenced strongly also by mechanical factors, e.g. the deformation in the last stages of crystallization (bulging – for unadequate roll pitches etc.)[8]. The centerline segregation can be decreased by the enlargement of the casting center zone with equiaxed dendrites, by the decrease of casting temperature, by the application of electro-magnetic stirring (EMS)[9], by short roll pitches for less bulging, and by low reduction of the slab cross section[10].

The aim of this work is to analyze the reasons of the centerline segregation and the influence on the microstructure and fracture morphology of specimens cut out from the center zone in continuously cast low carbon steel slabs, with graded Cu content.

**Table 1.** Equilibrium distribution coefficient of elements in the iron.

| element | C | Mn | Si | Al | S | P | H | N | O | Cu | As | Sn | Sb |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $k_0$ | 0.13 | 0.68 | 0.64 | 0.87 | 0.055 | 0.13 | 0.3 | 0.28 | 0.13 | 0.81 | 0.20 | 0.27 | 0.13 |

**Table 2.** Equilibrium distribution coefficients of elements in the γ-phase, δ-phase and in the γ-δ interface.

| element | C | Mn | Si | Al | S | P | Cu |
|---|---|---|---|---|---|---|---|
| $k_{\gamma\delta}$ | 1.79 | 1.03 | 0.68 | - | 0.70 | 0.57 | - |
| $k_\delta$ | 0.19 | 0.77 | 0.77 | 0.92 | 0.05 | 0.23 | - |
| $k_\gamma$ | 0.333 | 0.785 | 0.52 | - | 0.035 | 0.13 | 0.96 |

## Materials and Experimental Methods

The centerline segregation of additives and impurities was studied on cut outs from slabs cast on a vertical curve type continuous casting machine. Three casts of low carbon steel with graded Cu content were analyzed. The casting temperatures were for steel A: 1519°C, for steel B: 1534°C and for steel C: 1544°C. The liquidus temperatures according to the casting were for steel A: 1517°C, for B: 1522°C and for C: 1517°C. All slabs were in the secondary zone cooled with two media cooling (water + air cooling). The mean casting rate (pulling rate) was for steel A: 0.89 m/min, for B: 0.77 m/min and for C: 0.98 m/min. Cut outs from the slab centerline were divided into specimens for chemical analysis metallography and Charpy impact tests in bending. The mean chemical composition of cut outs is in Table 3.

**Table 3.** Mean element contents (wt. %) of from analyzed slabs.

| slab | C | Mn | Si | P | S | Al | $N_2$ | Cu | Sn | Sb | As |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ***A*** | 0.166 | 0.34 | 0.23 | 0.010 | 0.018 | 0.025 | 0.006 | **0.560** | 0.007 | 0.002 | 0.006 |
| ***B*** | 0.166 | 0.33 | 0.20 | 0.013 | 0.020 | 0.014 | 0.007 | **0.310** | 0.009 | 0.003 | 0.016 |
| ***C*** | 0.170 | 0.46 | 0.10 | 0.007 | 0.010 | 0.067 | 0.009 | **0.046** | <0.001 | 0.002 | 0.006 |

The concentration profile of additives and impurities was determined by the classic chemical analysis. The Cu and surface active elements (Sn, Sb, As) contents were determined by absorption spectroscopy. Surfaces for optical microscopy were ground, polished and etched by the usual methods used to analyze the microstructure of the tested slabs. The Charpy impact tests in bending were done at 20°C, on test pieces with dimensions 5 x 10 x 55 mm with a machined V notch, 2 mm deep. The test pieces were from the center zone and oriented in the longitudinal direction. The fractured surfaces were analyzed by a scanning electron microscope to determine the fracture morphology and the statistics. Particles in the microstructure and on fracture surfaces were identified using EDX ray analysis.

## Results and Discusion

### Additive and impurity concentration profiles of the slab

Analysis of the additive and impurity concentration profile of the slab showed, at a nearly similar mean concentration in the three steels (Table 3) a gradual growth of carbon concentration to the center of the slab up to 0.17% (for B) and 0.15% (for C). However, for slab A, the carbon content was the maximum (0.19%) in the transcrystalline zone and to the center it was decreased to 0.07 %.

Graphic illustrations in Figure1 show the profile of sulphur concentration in the analyzed slabs. The mean S content in the cross section was higher in slabs A, and B and lower in slab C (Table 3). For slabs A and C it is possible to identify a tendency of S content to grow into the center of the slab. For the slab B, the marked growth of S content in the center was obviously reaching 0.37 %. For slabs B and C, the content of P was growing in the direction to the center, however, markedly only for slab B up to 0.016 %. For slab A, a slight decrease of P content was observed, only.

For slab A, the Cu content was growing markedly in the direction to the center from 0.2 % up to 0.85 %. An increase of Cu content was seen in slab B, too, though it was in a moderate level (the increase was only 0.05 %). The Cu content in slab C, did not change significantly For surface active elements Sn, Sb, As in slabs A and C, a slight increase was seen in the center of the slab. On the other side, for slab B, a marked increase was seen for Sb to 0.04 % and As to 0.02 %.

The centerline segregation of C and impurities S, P and surface active elements Sb, Sn, As is the result of dendritic segregation (low distribution coefficients, Table 1) and as the result of macro segregation in the direction to the center of the slab. The significant Cu segregation into the center of the slab A with the high mean Cu content, as it is supposed, was caused by the low overheating in the ladle and high casting rate of the slab.

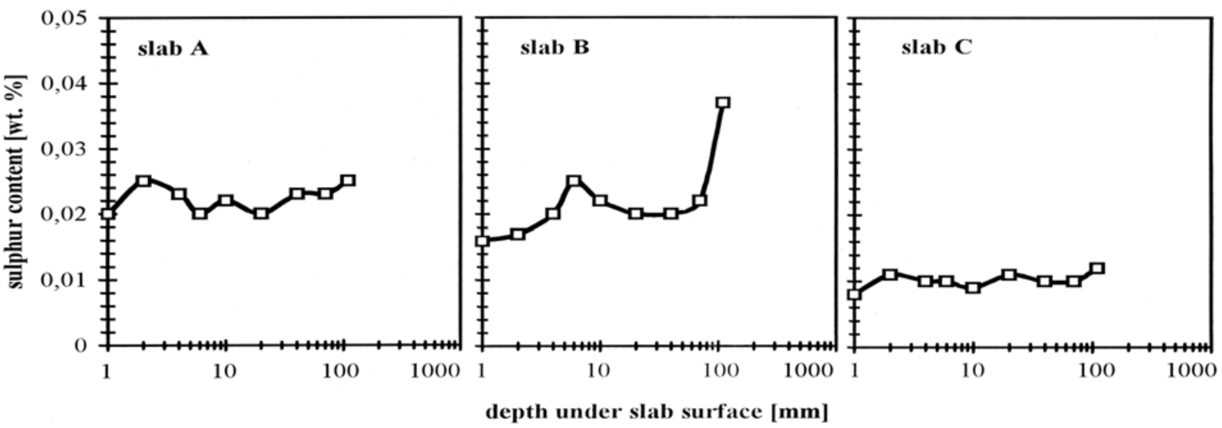


**Figure 1.** Concentration profiles of sulphur from slab surface to the center of slab thickness.

### Microstructure analysis in the center of the slab

In the centers of slabs it is possible to identify clustering of inclusions and that they are precipitated mainly in primary grain boundaries dispersed in forms of bands or chains (Figure 2). Inclusions were observed but less frequently in the form of eutectic type dispersed particle clusters inside the grains, as shown in Figure 3. The number of inclusions in the center line of slab B is the largest. On the other hand, it is the smallest in slab C. It is corresponds to the mean S content in the slabs and to the obtained concentration profiles (Table 3 and Figure 1). In fact, in all cases, the inclusions were complex sulphides FeMnS, as it has been confirmed by the EDX analysis. The spectrum of inclusion EDX analysis (Figure 4) in the centerline zone of the slab shows the presence of S, Mn and with a high probability of Fe in the particles.

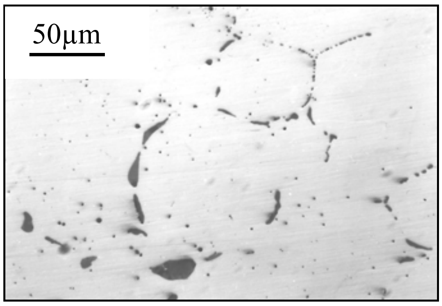


**Figure 2.** Inclusions of chain type in the centerline zone of slab C

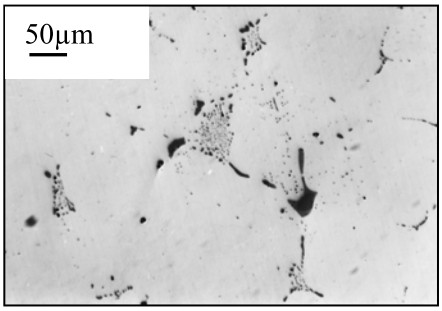


**Figure 3.** Inclusions of eutectic type in the centerline zone of slab B

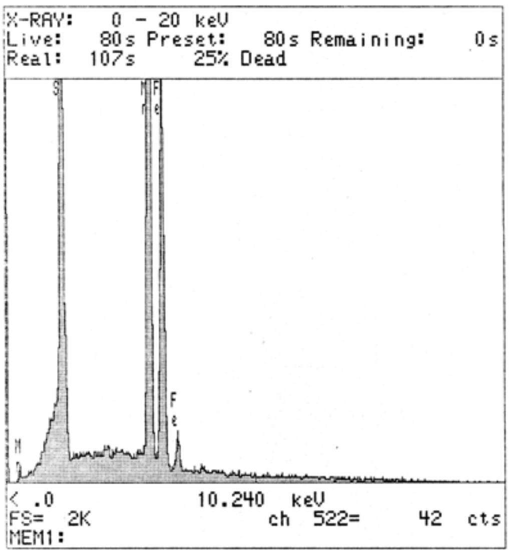


**Figure 4.** Spectrum of inclusion EDX analysis in the centerline zone of slab B

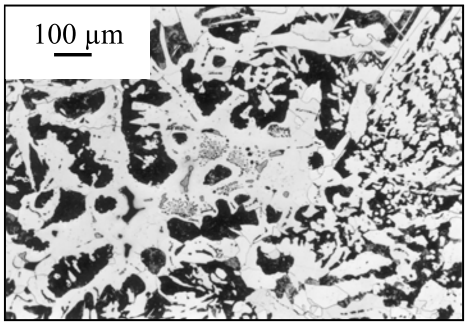


**Figure 5.** Ferrite - pearlite microstructure in the centerline zone of slab B

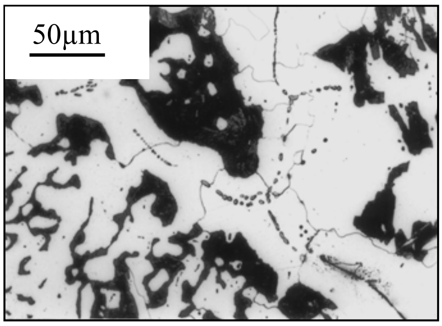


**Figure 6.** Detail of microstructure and inclusion in the centerline zone of slab B

The microstructure in the center zones is uneven with grains different in shape and size (Figure 5, and 6). In between the individual ferrite grains, bands, chains and eutectic clusters of inclusions were extracted inside or on the ferrite grain boundaries. The pearlite content in this area is higher if compared to the skin of the slab as documented in Tablde 4. Also listed are the maximum values of pearlite fractions, Table 4, observed through the cross section of specimens cut from the center zone of the slabs, where the uneven pearlite redistribution was detected. The maximum values of pearlite portion were in the center of the slabs, in the zone of centerline segregation. Pearlite content percentages are the lowest for slab A, then higher for slab B, and the highest for slab C. It is supposed that it is in a good correlation to the mean carbon content (Table 3) in the analyzed specimens and the conditions the slabs were treated during continuous casting.

According to Reference[7] in the last moments of crystallization in a steel rich in impurities in the center zone of the slab (centerline segregation of S, P and other elements) at the clash of crystallization fronts monotectic and eutectic sulphides are formed. They are deposited into ferrite probably by the phosphorus segregation in these areas, in concurrence to the carbon segregation[11]. Increased pearlite portion in the center area of the slab is the result of centerline carbon segregation.

**Table 4.** Values of pearlite portion percentage in the slab zones.

| slab | mean values of pearlite portion in the slab zones (surface: 0 – 5 mm; under-surface: 9 – 14 mm; centerline: ~ 110 mm) | | | maximum value of pearlite portion in the centerline zone |
|---|---|---|---|---|
| | surface zone | under-surface zone | centerline zone | |
| **A** | 8 % | 6 % | 11 % | 14 % |
| **B** | 11 % | 13 % | 17 % | 24 % |
| **C** | 15 % | 16 % | 21 % | 29 % |

## The fracture surface morphology

The impact test toughness values KCV of the analyzed cut outs from the center zone of slabs are low, (for slab A: 10.1 $J.cm^{-2}$; for B: 13.3 $J.cm^{-2}$; and for C: 17.5 $J.cm^{-2}$). They are corresponding to the embrittling effect of the high portion of pearlite, the high content of dispersed sulphidic inclusion particles FeMnS and liquations in the center of the slab. Embrittlement can be also caused by S, P, Sn, Sb, As, or Cu segregation into the grain boundaries. There is a high concentration of these elements in the center zone.

The low values of impact toughness KCV are in correlation to the large portion of brittle transcrystalline cleavage facets and to the low portion of signs of transcrystalline ductile fracture in fracture surfaces. There were also smooth intercrystalline cleavage facets, first in specimens from slab B. The smooth intercrystalline cleavage facets are prevailingly in the centerline segregation area, around liquations and sulphides as documented in Figure 7. The intercrystalline fracture is caused by the segregation of impurities (S, P, Sn, Sb, As and probably Cu) in austenite grain boundaries in the centerline.

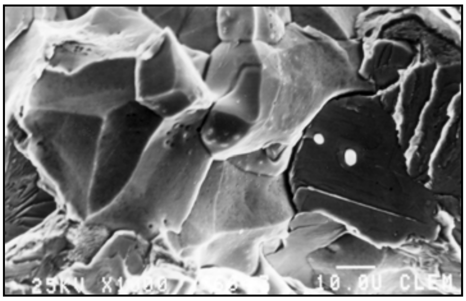


**Figure 7.** Smooth intergranular facets on fracture surface, centerline zone of slab B.

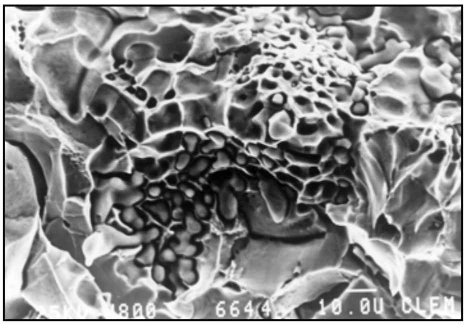


**Figure 8.** Sulphide eutectics on fracture surface, centerline zone of slab B.

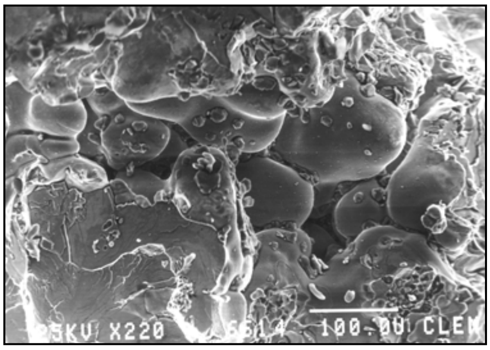


**Figure 9.** Liquations on fracture surface, centerline zone of slab B.

In fracture surfaces from the centerline zone of slabs also inclusion particles were also observed in the form of eutectics and areas of liquations. Eutectics were in the slab zone of impurity centerline segregation (Figure 8.) and according to the EDX analysis they were complex sulphides FeMnS. They were particles, observed in the optical microscopy as documented in Figures 3 and 6. The percentage of the eutectics and liquations in the fracture surface is the highest for the slab B. The liquations are characterized by the naked surface of dendrites, frequently with inclusion particles, Figure 9. Porosity and liquations are from the crystallization shrinkage of the molten steel between dendrites with higher impurity contents in the center areas of the slab[(6-8).]

## Conclusion

In the analyzed steel slabs with a similar mean carbon content (~ 0.17 %), with graded copper content and very low content of unwanted elements, the cut outs from the center areas of the slabs had a high enrichment with impurities S, P, Sn, Sb, As, Cu and C. The additives and impurities segregation into the centerline of the slab for the slab with high Cu content is in agreement to the rules of the dendritic segregation process at steel crystallization, including all the conditions of the crystallization technology.

The microstructure in the center of the slabs was uneven, formed by ferrite and pearlite grains different in size and shape. The pearlite portion in this area was much higher than in the surface areas or under the surface, and it was caused by the carbon segregation into the center of the slab. By sulphur segregation into the center of the slab a band of complex sulphidic FeMnS inclusions is deposited inside and on ferrite grain boundaries, and they look like dispersed particles in the form of chains, bands and eutectics.

The centerline segregation of additives and impurities was manifested also by the fracture surfaces of Charpy impact test pieces cut out from the center zone of the slabs. Besides the majority of transcrystalline cleavage facets, a low content of transcrystalline ductile fracture facets with dimples was observed. There were in fractured surfaces also sulphidic eutectics, liquations and smooth facets of intercrystalline cleavage.

## References

(1) Kuchař, L. 1988. *Metalurgie čistých kovů, část I., Skript.* VŠB, Ostrava : 338.

(2) Matsumiya, T., Kajioka, H., Mizoguchi, S., Ueshima, Y. and Esaka, H. : 1984 *Transactions ISIJ,* 24 : 873 – 882.

(3) Schneider, M. C., and Beckermann, C. 1995. Simulation of Micro-/Macrosegregation During The Solidification of A Low-Alloy Steel. *ISIJ International,* 35 : 665 – 672.

(4) Ueshima, Y., Mizoguchi, S, Matsumiya, T and Kajioka, H. : 1986. *Metallurgical Transactions*. 17B : 845 – 859.

(5) Morita, Z. and Tanaka, T. 1983. *Transactions ISIJ* 23 : 824 – 833.

(6) Sladkoštejev, V.T., Potanin, P.V. and Suladze, I.S. 1974 Nepreryvnaja razlivka stali na radialnych ustanovkach, Moskva, *Metallurgia* : 288.

(7) Sasaki, K., Sugitani, Y. and Ishimura, S. 1980. *Tetsu to Hagané*. 1 : 43 – 52.

(8) Sasaki, K., Sugitani, Y. and Ishimura, S. 1980. *Tetsu to Hagané*. 1 : 53 – 62.

(9) Mizukami, H., Komatsu, M., Kitagawa, T. and Kawakami, K. 1984. *Transactions ISIJ*. 24 : 923 – 930.

(10) Tsubakihara, O., *et. al*. 1985. *Transactions ISIJ,* 25 : 686 – 706.

(11) Mišičko, R. and Longauerová, M. 1997 *Hutnícke listy,* č.1 : 11 – 13.