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The Effect of Heat Treatment on the Stability of Centerline Segregation

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The paper deals with the stability of centerline inhomogenity of the continuously cast slabs. The pattern of the centerline segregation was modeled physically by preparing a sandwich structure of steel plates with different levels of carbon and alloying elements. The eligibility of sandwich structured samples for diffusional experiments, i.e. the permeability of the metal-metal boundaries in the samples from diffusional point of view was checked by the comparison of measured and theoretically calculated hardness value for plain carbon steels. Diffusional homogenization experiments were performed and the samples were examined metallographically. Great microstructural difference remains between the core and cover layers after a long time diffusional homogenization if there is a difference also in the manganese content in the thickness direction of the sandwich structured sample. Manganese has a double role in this process: it reduces the possibility of homogenization of carbon and exaggerates the effect of this slight difference in carbon content during austenite decomposition.

Keywords: centerline segregation, continuous casting, effect of manganese, diffusional homogenization

0 INTRODUCTION

This paper deals with the characteristic features, role and moderation of centerline segregation in slabs. The centerline segregation is a disadvantageous failure of slabs which can affect the quality properties of the products. During the hot rolling of the slabs the centerline segregation pattern will become thin and stretch and it can detect also in the middle part of heavy plates and coils. Chiefly in case of heavy plates can cause serious problems. It is a common experience that the centerline segregation developed in slabs or heavy plates can not decrease easily by post heat treatment [1]. After a short and general review of the nature of centerline segregation the paper tries to define the parameters affecting the stability of it.

1 THE NATURE OF CENTERLINE SEGREGATION

The centerline segregation in slabs develops in a complex way; it is connected partly to the macrosegregation and partly to the shrinkage of solidifying melt which is influenced by a lot of technological features. According to our results the shrinkage porosity and deformation of slab in the last stage of solidification play the main role in the formation of centerline segregation. The volume change due to solidification and the deformation of slab influence the liquid movement in the mushy zone as well. Among the casting parameters the supporting roll settings in the mushy area is the most important influencing factor concerning the formation of centerline segregation, but all of the casting parameters can affect more or less this process (chemical composition, superheat, casting rate, secondary cooling system, rigidity of the casting machine, roll bearings, etc.).

As a result of these processes the centerline segregated part of the slab will have a different chemical composition compared to the average composition and/or it will contain shrinkage holes.

After the solidification process during hot rolling the complex shaped interdendritic holes will be closed as a function of strains. The difference in chemical composition will remain even though the slab has spent hours over 1000 °C in the soaking furnace before hot rolling. Hot rolling reduces the level of centerline segregation because plastic deformation can close the

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shrinkage porosities and the thickness of the segregated area became smaller. In general, below 10 mm in thickness of heavy plate, centerline segregation can more or less disappear. Heavy plate with centerline segregation will contain - depending on the solidification and technological parameters - a middle part having chemical composition dissimilar to the average. For example in case of St 52-3 grade steel (DIN 7100-80, EN 10025+A1:1993, nominal composition: C_{max} = 0.2 wt%, Mn_{max} = 1.6 wt%) the segregated area can be characterized by a carbon content of 0.3 to 0.5 wt% and manganese content of 1.8 to 2 wt%. This area can also contains remanence of shrinkage holes (flaws).

The question that arises is whether it is possible to decrease the centerline segregation level by diffusional homogenization if there are no flaws – which can impede the diffusion - in the segregated area. According to the industrial experiences the segregation level (including the carbon content) can hardly be decreased by heat treatment. It is claimed that manganese decreases the activity of carbon and this affects the carbon diffusion, but also the other elements like phosphorus can play an important role [1]. This paper tries to give some more answers to this question by experimental results and by theoretical consideration.

2 EXPERIMENTAL WORK

The aim of the experimental work is to map the effect of manganese on the carbon diffusion in an inhomogeneous carbon and manganese distribution. For this reason we decided to prepare and examine the samples with artificial centerline segregation.

The basic idea of the experimental work is to prepare sandwich structured samples with accumulative roll bonding (ARB) process. Tsuji [2] used this method for producing oriented and also nanostructured samples. The banded structure of hot rolled materials can be also modelled and examined experimentally. Majka et al. [3] have prepared banded structure artificially by using this process and they had several strange metallographical observations especially at the boundaries. Concerning the centerline segregation the main aim was to produce three-layered samples representing the higher carbon and manganese content in the middle part.

2.1 Sandwich Sample Preparation by Rolling

For sample preparation two small covering parts (70 x 100 mm) were cut out by CO_2 laser from hot rolled steel plate with 4 mm thickness and a thinner part (1 mm thickness) were also cut out (core material). After inserting the core material between the covering plates the three pieces were welded together by CO_2 laser. The welding has double roles: it gives a rigid mechanical connection between the parts and preserves the inner surfaces of the steel parts from oxidation.

The welded sample "B" (Table 1) was heated up between 1020 to 1050 °C, and after soaking it was rolled in several passes by duo type hot rolling device. For reaching the total 50% strain an intermediate reheating of the samples was necessary.

Table 1. *Characteristics of sandwich samples materials before rolling*

Sample Id.	B	C	D	E
Cover steel C content, wt%, low carbon, low manganese steel	0.05	0.05	0.05	0.05
Cover steel Mn content, wt%, low carbon, low manganese steel	0.3	0.3	0.3	0.3
Core steel C content, wt%, St 52 grade steel	0.05	0.47	1.1	1.1
Core steel Mn content, wt%, St 52 grade steel	0.3	0.6	0.4	0.7
Cover thickness [mm]	4	4	4	4
Core thickness [mm]	1	1	2	2

The metallographical examination of hot rolled sample B revealed the presence of real metallic bonds between the plates and it proved the applicability of ARB method for sample preparation.

The samples described in Table 1 were prepared by the same method. The thickness of the core material was 1 mm in case of "C" series, and 2 mm in "D" and "E" cases. The St52 grade core material in case "D" was carburized up to 1.1 wt% carbon content. In case "E" the core material was grinded out from the middle part of a heavy plate containing centerline segregated area. It was also carburized up to the same carbon content. The hot rolling sample preparation methods were the same in all cases.

These combinations of samples were used both for control the diffusional process in plane carbon steels and diffusion of carbon in steels with non-homogenous manganese distribution. In this paper the experimental and modeling results only of "C" and "E" cases will be discussed.

2.2 Diffusional Homogenization

The small strip shaped (10 mm width) samples necessary for diffusional homogenization experiments were prepared by transversal laser cutting of hot rolled parts containing artificial centerline segregation. These small specimens were covered with mild steel sheets welded down hermetically for defeating the interaction between the sample surface and the furnace atmosphere during the high temperature long time handlings.

The diffusional heat treatments were performed in laboratory furnace at 1000, 1070 and 1150 °C, and 10, 30, 60 and 120 min holding times were chosen. After treatments the specimens were unwrapped. In all cases the surfaces of the samples were absolutely free of oxidation so there was no real interaction between the samples and the atmosphere. Metallographical examinations were performed in transversal cross sections of the specimens, and one part of the samples was quenched from 950 °C into water for hardness testing.

3 VALIDATION OF THE EXPERIMENTAL METHOD

In order to control the eligibility of sandwich structured samples for diffusional experiments (i.e. checking the permeability of the metal-metal boundaries in the samples from diffusional point of view) a detailed analysis was performed for the "C" series samples heat treated at 1000 °C. The main aim of these experiments was to check that the boundary between the core and cover steels does not hinder the diffusion of carbon. The expected carbon distribution inside the specimen was calculated mathematically by using a proper diffusional model. The results calculated by COMSOL 4) software are given in Fig. 1. COMSOL is a commercial FE software package developed for multiphysics modeling and simulation.

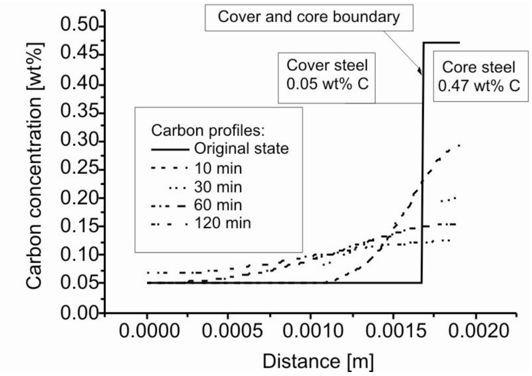


Fig. 1. *Calculated carbon distribution in the half of the sandwich samples "C" (Table 1) after different duration of homogenization at 1000 °C*

For checking the carbon diffusion process taking place in the samples the hardening effect of carbon content was used (carbon content, which remained after the homogenization in the centerline of the specimen). The samples were reheated after the diffusional treatment up to 950 °C and quenched in water. After that the maximum hardness was determined in the core area by microhardness testing.

The diffusion coefficients of segregated elements (e.g. manganese) are much smaller than of carbon (the difference is 4 order of magnitude). This means that practically only carbon will diffuse during the handlings, i.e. the chemical composition of the core will be changed only regarding carbon. The quenched hardness of the core depends on its carbon content. The expected microstructure and hardness of core steel depending on the carbon content were calculated by ADC (Austenite Decomposition) software. The ADC software was developed at Helsinki University of Technology, Finland partly on the theoretical base of IDS (Interdendritic Solidification) software) calculation method. ADC predicts the expected hardness and microstructure of the sample depending on chemical composition, austenitic grain size and cooling rate.

Fig. 2 shows both the calculated and measured hardness concerning the centerline of core. Taking into account the carbon content as a variable in the chemical composition the quenched hardness was calculated by applying cooling rate of 50°C/sec in the critical transformation temperature region. This value represents the cooling conditions in the middle of the specimen during quenching. Fig. 2 shows a good correlation between the measured (HV10) and calculated hardness. This good correlation proves that the metal-metal boundaries inside the sample do not hinder the carbon diffusion.

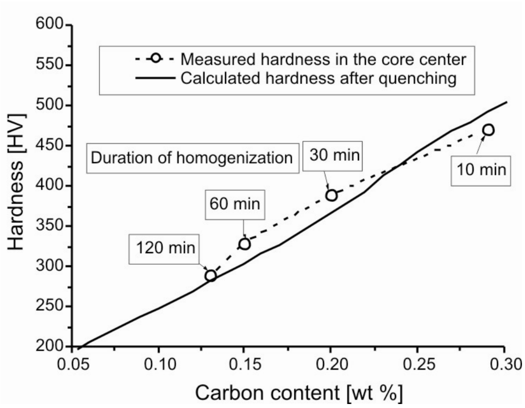
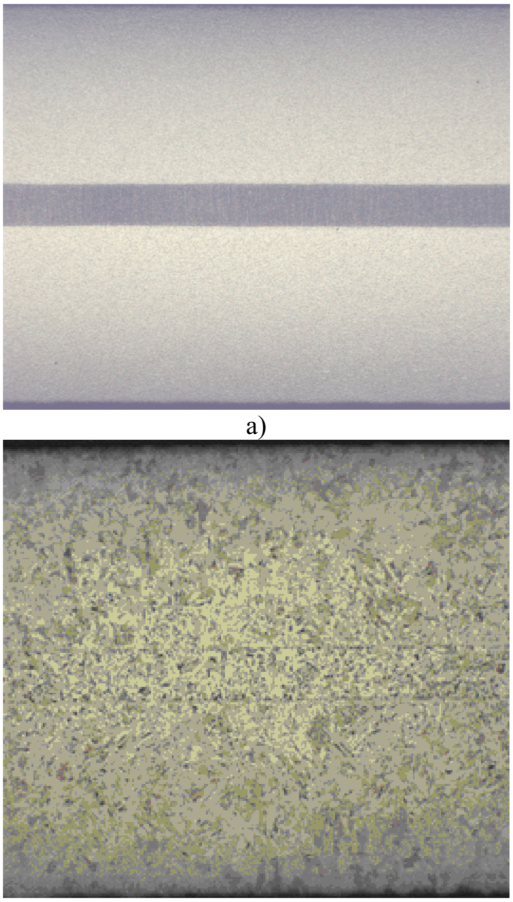


Fig. 2. *Calculated a measured hardness of samples "C" (Table 1) homogenized at 1000°C, cooled down slowly to room temperature, and quenched from 950 °C into water*

The metallographic examination of "C” series samples approves the calculation results. Fig. 3a shows the initial structure of the sample, the darken strip inside is the artificial macrosegregated area. Fig. 3b displays the microstructural change as a result of diffusional treatment.

4 RESULTS OF SAMPLE "E"

On the basis of metallographical examinations it is obvious that after the homogenization treatments the microstructural differences between the core and cover steels are much greater in case if "D" and "E" series (Fig. 4) than in case if "C" samples. It is caused by the different carbon content and core thickness, but the increased manganese content also plays a role. The manganese decreases the carbon content of the eutectoid and stabilizes the austenite enhancing the pearlite formation.


a)

b)

Fig. 3. *a) Structure of sample "C" after hot rolling and b) the microstructure after homogenization at 1150°C for 120 min, (M=10, etched in Nital)*

The aim of these experiments is to reveal the effect of manganese concentration step present in the sample on the diffusion of carbon.

In this paper one of the results of sample "E" series (1150 °C, 120 min) will be discussed. This series represents the effect of the real centerline segregated area.

This specimen was also quenched and hardness tested after the homogenization treatment. Fig. 5 shows the calculated, expected hardness distribution in the half thickness of the specimen.

Under these kind of conditions 0.4 wt% C content is expected in the centerline. The carbon content - quenched hardness connection is also calculated by IDS, for the chemical composition of the core with 0.4 wt% carbon the expected hardness is 625 HV (cooling rate 50°C/sec). The maximal hardness measured in the centerline is 610 HV. The good agreement between the calculated and measured values seems to prove that there is no essential effect of manganese step on the carbon diffusion process.

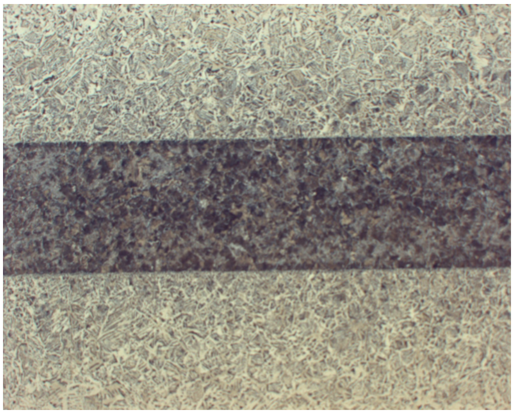


Fig. 4. *Structure of sandwich sample "E" treated at 1150°C for 120 min (M=10)*

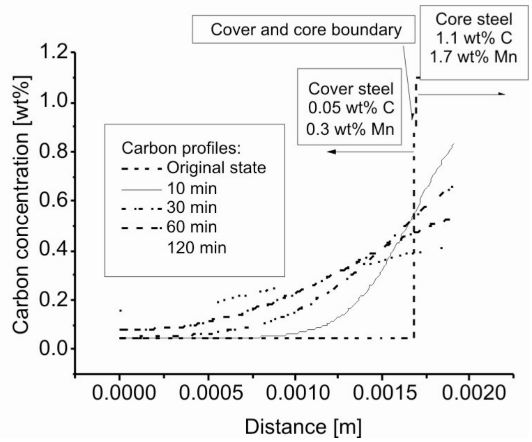


Fig. 5. *Calculated carbon distribution in the half of the sandwich samples "D" after different duration of homogenization at 1150 °C*

At the same time the results of metallographical examinations are not so unambiguous. In Fig. 6 the edge of sample "E" soaked at 1150°C for 120 min can be seen. The diffusional calculations predict a 0.18 wt% carbon (Fig. 5) in this region, meaning that about 20% of pearlite in the structure is expected. In the reality the pearlite ratio is below 10%.

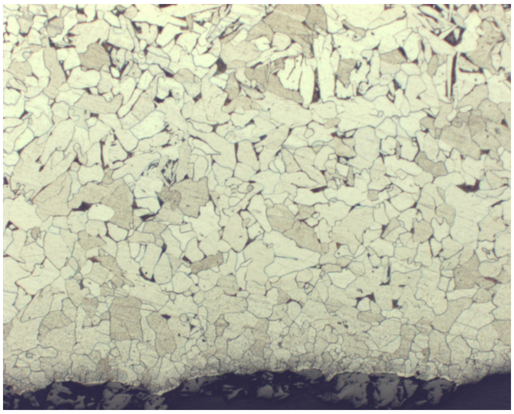


Fig. 6. *Microstructure around the edge of sample "E" shown in Fig. 5 (M=250, etched in Nital)*

5 DISCUSSION

Calculations performed by Thermo-Calc software [6] and [7] and by other thermodynamic models [8] to [11] concerning the interaction between manganese and carbon in iron prove that the manganese decrease the activity of carbon in the fully austenitic range. These models give almost the same values in case of pure iron-carbon systems. Fig. 7 compares the carbon activity results of three models [9] to [11] for two different temperatures as a function of carbon content. There are only slight differences between them. The correlation is much worse if the presence of 2 wt% manganese is supposed. Fig. 8 summarizes the results of the three models for 1150°C. Almost a double difference can be found between the results of Hiller's and of Wiss' models, which indicates the uncertainty of the models under these circumstances.

The activity of carbon depends on the carbon and manganese concentration. In the model of Hillert [9] the coefficient of carbon is positive and of the manganese is negative, but this latter is smaller in absolute value. It means that in a real case of segregation, the manganese decreases the activity of carbon on one side, but on the other side the carbon itself compensates this difference, even over-compensates it. So in the beginning of the homogenization process (after hot rolling) in the austenitic region the difference between the activities of cover and core steels is lowered by the presence of high amount of manganese in the core, but the difference in carbon content over-compensates it.

So the driving force, the difference in activities is greater in case "D" or "E" than in case "C".

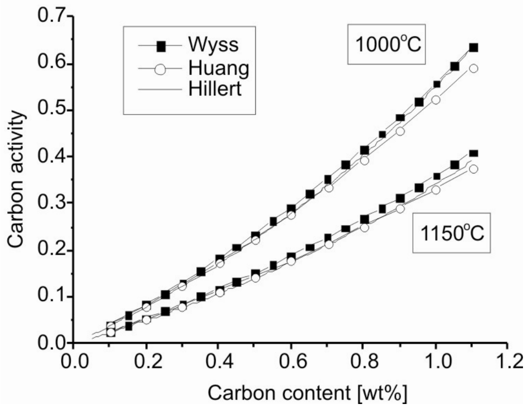


Fig. 7. *Activity of carbon in austenite as a function of carbon content*

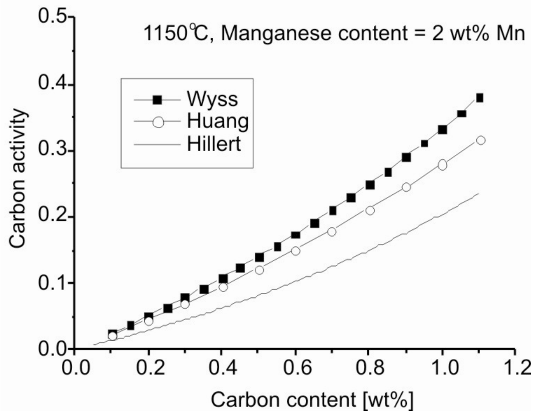


Fig. 8. *Effect of manganese on the activity of carbon in austenite*

Let us see what happens during the homogenization in case of “E” series. The carbon content is decreasing in the manganese rich core and increasing in the cover steel with lower manganese content. We can follow the change of the activities in Fig. 9 which were calculated by using of Huang’s model for 1150°C.

From Fig. 9 two conclusions can be drawn. On one hand, the driving force of diffusion (the difference between the activities of core and cover steels) decreases as the difference of carbon contents decreases in the core and cover. On the other hand, when the core carbon content is low enough, the activities approach each other and finally they become equal. In this case there is no more driving force of the diffusion. For example, if the carbon content approaches 0.26 wt% in the core (Fig. 9) and the cover steel carbon content is close to 0.18 wt%, at the boundary of manganese step the activities will be identical in both sides.

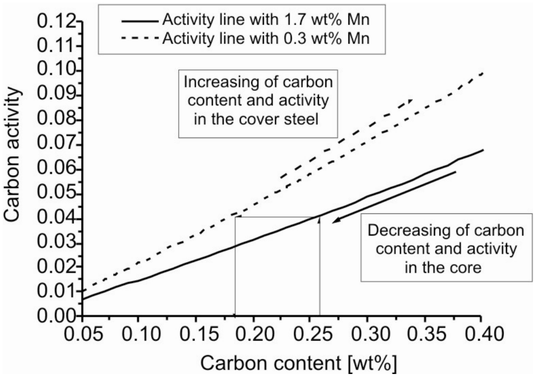


Fig. 9. *Change of activities in the core and cover steel at 1150°C during the diffusional homogenization*

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6 SUMMARY

As a summary on the basis of experimental work and theoretical considerations the followings can be laid down. In case of centerline segregation having a great difference in manganese content between the segregated and non-segregated areas at the beginning of the homogenization process the manganese step can enhance the diffusion. As the carbon content difference decreases between the two areas the driving force decreases because of the decreasing difference in activities. Depending on the initial concentrations, plate and segregated area thickness and the process parameters (e.g.

temperature), the homogenization process can stop because of the lack of driving force. This stop can result in a remaining carbon content difference around 0.05 to 0.1 wt% between the core and cover areas. This means that in these cases the carbon content difference can not be eliminated and the process rate is very low, which corresponds to the experiences.

The effect of a relatively small difference in carbon content is exaggerated by the manganese difference because in the presence of higher amount of manganese over 0.2 wt% carbon pearlite or even non-equilibrium (bainite, martensite) microstructural constituents can be formed in the middle part of normalized heavy plates.

7 ACKNOWLEDGMENTS

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