A. MAHMUTOVIĆ

ISSN 0543-5846
METABK 52(2) 201-204 (2014)
UDC – UDK 669.18:532.78:621.56/.59:531.76:620.18=111

EFFECTS OF HIGH COOLING RATES ON THE IMPROVEMENT OF CONTINUOUS STEEL CASTING MICROSTRUCTURE

Received – Prispjelo: 2013-03-25
Accepted – Prihvaćeno: 2013-09-25
Preliminary Note – Prethodno priopćenje

This paper has researched into the influence of trace elements in steel, combined with new casting processes, on the microstructure and micro-segregation phenomenon in the case of structural steel. Thermocalc software has been applied for calculation of steel phase.

In the paper, close attention has been paid to monitoring of the influence of the cooling rate in regard to solidification time and to the characteristic elements' segregation coefficient. Higher cooling rates during solidification improve the microstructure and produce positive effects on the metallurgical quality of the steel cast.

Key words: steel solidification, cooling rates, micro-segregation, trace elements

INTRODUCTION

Along with modernisation of classic plants for continuous casting of steel, today there is intensive work on development of new casting procedures producing semi-finished products in quality approaching the form of final products [1,2]. New casting procedures significantly decrease need for plastic deformation of cast and contribute to the energy and time savings, Figure 1 [3].

Also rapid solidification achieved during thin or strip casting could substantially reduce segregation problems and result in a more homogeneous, fine-grained microstructure and produce the desired properties of the material, such as strength, elongation and anisotropy.

On the other hand usage of steel scrap has become important in steel making from the aspect of energy savings and resource conservation. When steel scraps are used, trace elements such as Cu and Sn are retained in the steel because of their being difficult to remove [4]. These trace elements are known to cause surface hot shortness.

Surface cracking is still a serious problem in continuous casting process, especially for micro alloyed steel grades for heavy plate applications [5]. It is supposed that besides mechanical and thermal strains, phase transformation and segregation can provoke cracking sensitivity. Copper is the key element to hot shortness caused by surface defects during hot deformation. In Figure 2, an example of a surface crack which occurred on a steel block surface based on S355 steel during hot deformation [6] is shown. Along the cracks,

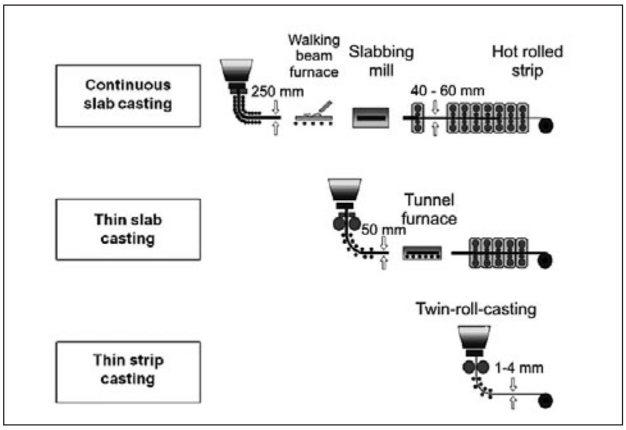

Figure 1 New hot strip production route [3]

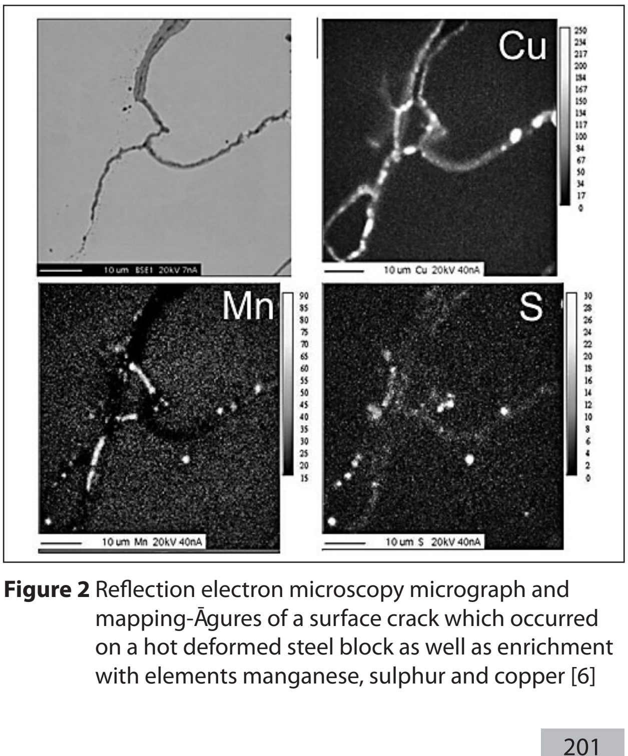

Figure 2 Reflection electron microscopy micrograph and mapping-figures of a surface crack which occurred on a hot deformed steel block as well as enrichment with elements manganese, sulphur and copper [6]

A. Mahmutović, University of Zenica, Faculty of Metallurgy and Materials, Zenica, Bosna and Herzegovina

places enriched with copper could be noticed, as well as with sulphur and manganese.

EXPERIMENTAL WORK

An important criterion for comparison of new casting procedures is thickness of the cast, which defines cooling rate and presents relevant parameter in solidification process as well in microstructure formation. The effect of a different cooling rate on the trace elements segregation in steel within solidification process has been explored in this paper.

The aim has been to compare microstructure and segregation of trace elements through different cooling rates. Two types of specimen based on S355 steel modified with Cu and Sn were used:

- specimen, 40 mm thick and
- specimen, 2 mm thick.

Specimen, 40 mm thick, was casted in the fashion of classical mould casting. Specimen, 2 mm thick, was produced in the fashion of rapid solidification simulation similar to the thin roll casting process, Figure 3. For rapid solidification simulation, half - automatic plunging machine with the copper plate (400 x 50 x 10 mm^3) acting as a mould and enabling „quick solidification process“ was used. The copper plate holder is moved vertically by means of pneumatic cylinder with defined speed. The S355 steel has been molten in a frequent induction furnace with a capacity of 50 kg. By plunging copper plate for 1 second, rapid cooled steel wrapper, 2 mm thick, is obtained as shown in Figure 4.

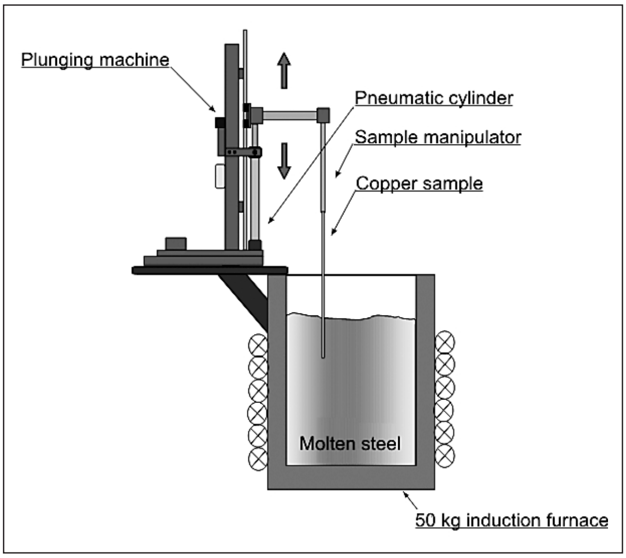

Figure 3 Schema of a half - automatic plunging machine for plunging of copper plate into molten steel

Figure 4 Appearance of rapid cooled steel wrapper on the cooper plate after plunging

Materials

For experimental work for two solidification models, the same low alloyed S355 steel modified with Cu and Sn was used (see the composition in Table 1).

Table 1 **Chemistry of studied steel grade / weight %**

C	Si	Mn	S	Cu	Sn
0,198	0,554	1,546	0,047	0,383	0,031

Characteristic non-metal inclusions in S355 steel are manganese sulphides types without the occurrence of copper: in fact manganese sulphides precipitation starts at around 50 °C below liquidus temperature in mushy zone. Figure 5 shows temperature region where, theoretically based on Thermocalc calculation, it is possible to form sulphides with above mentioned steel that solidifies peritecticly.

Taking into consideration that Thermocalc calculation is related to equilibrium state and that it is also related to global chemical steel composition, it does not take local enrichment that will appear in inter dendrite region into consideration. The effective cooling rate mainly depends on mould cooling and the micro-segregation behaviour of solute elements in the mushy zone depends on back diffusion ability and local equilibrium at interfaces [7].

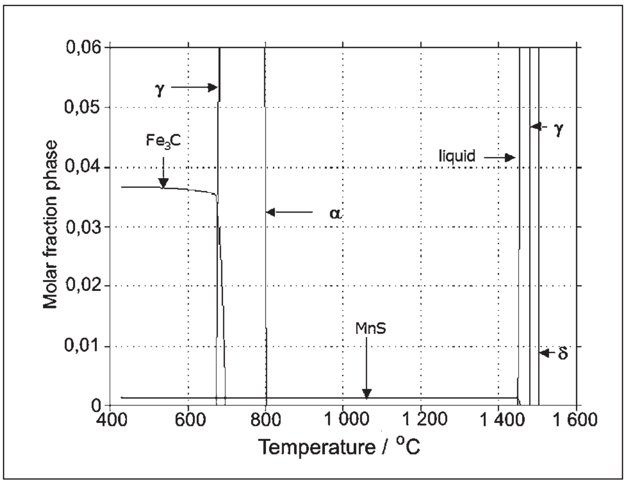

Figure 5 Thermocalc calculations of characteristic equilibrium phases for modiÃed S355 steel depending on temperature

Table 2 **Calculated coefficients of element distributions on the surface at the room temperature c_{min} / c_0 for surface of steel cast block and rapid cooled wrapper**

Calculated coefficients of element distributions	on the surface of steel cast block	on the surface of rapid cooled wrapper
$(c_{min} / c_0)_S$	0,023	0,023
$(c_{min} / c_0)_{Mn}$	0,88	0,93
$(c_{min} / c_0)_{Cu}$	0,71	0,74
$(c_{min} / c_0)_{Sn}$	0,59	0,63

EXPERIMENTAL RESULTS AND DISCUSSIONS

To define solidification conditions and the solidification rate as well as the time of solidifi cation, the measuring of secondary dendrites values are made at the surface of the specimens [8]. The average value of secondary dendrites at the surface of the rapid cooled steel wrapper is 12 µm, and with steel cast block it is 60 µm. From those values, calculated solidification rate of rapid cooled steel wrapper is 490 K/s, and measured local cooling time between T_{Liq} and T_{Sol} is 0,2 s [6,8,9]. With cast block the solidification rate is 5 K/s and local cooling time between T_{Liq} and T_{Sol} is 12 s.

Changes and distributions of elements with microsonde were observed at those tests. Mapping-measuring of sulphides was also made. The example of the concentration distribution results for elements sulphur, manganese, copper and tin at the surface of rapid cooled steel wrapper obtained with line scanning is shown in Figure 6.

Figure 6 shows an increase of Cu concentration at the places of increased concentration of Mn and S which could mean that those are manganese sulphides enriched with copper. By means of additional mapping-measuring of sulphides it has been established that those are pure manganese sulphides with atomic share Mn : S 1 : 1 while copper is dissolved.

Coefficients of elements distributions on the surface, i.e. concentration gradients between secondary dendrites for two mentioned solidifi cated types have been considered. Line – scan measuring is made at the surface of 300 µm and at each of those tests, 100 individual measures were done at each of the tested elements S, Mn, Cu and Sn.

Metal average concentration of each element is defined as $c_{0.}$ Minimal concentration at the room temperature c_{min} is defined as concentration where 3 % of all the values are below this value. At the bases of those data, coefficient of element distributions at the room temperature c_{min} / c_0 for surface of steel cast block and rapid cooled wrapper has been found to have the values as designated in Table 2.

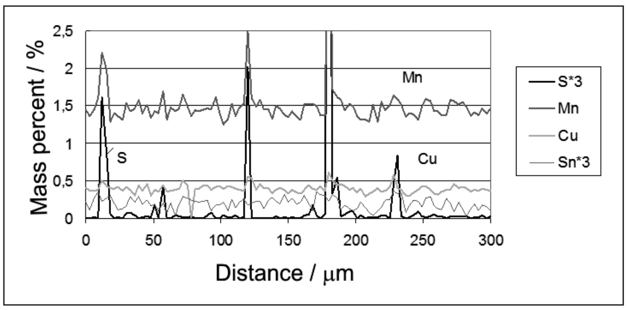

Figure 6 Example of concentration distribution for sulphur, manganese, copper and tin at the rapid cooled steel wrapper's surface obtained with microsonde

Compared with other elements in the **steel,** sulphur has a much higher segregation ratio at the end of the **solidification.**

Calculated coeffi cients of elements distributions at the rapid cooled steel wrapper 's surface are a little bit higher than those at the cast block and therefore its tendency toward segregations of tested elements have been found to be substantially lower.

CONCLUSIONS

The effect of a different cooling rate on the segregation of trace elements in steel during solidifi cation process was investigated. Low-alloyed modified S355 steel with Cu and Sn and its tendency toward segregations and phenomenon of non-metal inclusions were investigated. Thermocalc calculation is related to equilibrium and for modifi ed S355 steel shows the precipitation of manganese sulphides which starts at around 50 °C below liquidus temperature in mushy zone.

Relations of microstructure and of micro-segregation were investigated on the basis of two solidification models of steel cooling parameters. The solidifi cated structure of the cast was described by means of secondary dendrites' values. Infl uence of cooling rate on micro-segregation ratio for average secondary dendrites values of 10 µm and 60 µm has been compared. The cooling rates and times during solidifi cation of both models were calculated according to the secondary dendrites' values.

Line – scan measuring has been made at the surface of both solidification models and individual measures at each of the tested elements S, Mn, Cu and Sn were done. Coefficients of element distributions of S, Mn, Cu and Sn on the surface at the room temperature c_{min}/c_0 for surface of steel cast block and rapid cooled wrapper have been calculated. Higher cooling rate during solidifi cation, i.e. rapid solidification reduces segregation problems and result in a more homogeneous microstructure.

REFERENCES

[1] M. Korchynsky, New steels for new mills, Scandinavian Journal of Metallurgy 82 (1999) 1, 40-45.

[2] M. C. M. Cornelissen, J. A. Kromhout, A. A. Kamperman, M. Kick, F. Mensonides, High productivity and technological developments at Corus DSP thin slab caster, Ironmaking & Steelmaking 33 (2006) 5, 362-366.

[3] M. Daamen, B. Wietbrock, S. Richter, G. Hirt, Strip Casting of a High-Manganese Steel Compared with a Process Chain Consisting of Ingot Casting and Hot Forming, Steel Research 82 (2011) 1, 70-75.

[4] B. A. Webler, E.M. Nick, R. O'Malley, S. Sridhar, Influence of cooling and reheating on the evolution of copper rich liquid in high residual low carbon steels, Ironmaking & Steelmaking, 35 (2008) 6, 473-480.

[5] D. Senk, A Mahmutović, Metallurgical Aspects of Scrap Use in Production of High Quality Steel, Workshop Ultra Steel, NIMS Tsukuba, Japan, 24/25. Jun 2003 NIMS 2003, 224-229.

[6] A. Mahmutović, Einfluß von Begleit-elementen auf die Heißrissanfälligkeit des Stahls S355 bei unterschiedlichen Erstarrungs- und Abkühlungs-bedingungen, Diss, IEHK, RWTH Aachen (2004) 107-121.

[7] W. Weiling, Z. Miaoyong, C. Zhaozhen, L. Sen, J. Cheng, Micro-Segregation Behavior of Solute Elements in the Mushy Zone of Continuous Casting Wide-Thick Slab, Steel Research International 83 (2012), 12, 1152-1162.

[8] H. Jacobi, K. Wünnenberg, Solidification structure and micro-segregation of unidirectionally solidified steel, Steel research 70 (1999), 362-367.

[9] E. Schürmann, T. Stišović, Berechnung der Liquidustemperatur aus der chemische Analyse legierter Stahlschmelzen, Stahl und Eisen, 118 (1998) 11, 97-102.

Note: English language editor: Henrijeta Pašagić, Zenica, Bosnia and Herzegovina