

## EVOLUTION OF THE NUMBER AND SIZE OF THE INCLUSIONS DURING STEEL TREATMENT IN A LADLE FURNACE AND IN A VACUUM CAISSON

### ŠTEVILO IN VELIKOST VKLJUČKOV, NASTALIH PRI OBDELAVI JEKLA V PONOVCNI PEČI IN VAKUUMSKI KOMORI

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The production of higher steel grades, such as steel for pipelines, requires monitoring the content of inclusions in the steel. Hence, the steelmakers have to choose suitable technological procedures that ensure the highest purity of the steel. Purpose of this work was to observe the evolution of the inclusions in the steel during its refining in a ladle furnace and in a vacuum caisson. For this purpose the samples of steel were taken at various stages of the processing. In one half of the melts the steel was deoxidised by CaSi-cored wire in a ladle furnace so that it would be possible to observe the influence of the CaSi on the occurrence of inclusions after degassing in the caisson. All the heats were processed in the following technological flow: OBM converter – ladle furnace – vacuum caisson (ISSM) – continuous casting.

Keywords: steel, inclusions, calcium modification

Proizvodnja kakovostnejših jekel, kot so jekla za cevovode, zahteva tudi kontrolo vsebnosti vključkov. Zato se pri izdelavi jekla izberejo ustrezni tehnološki postopki, ki zagotavljajo visoko čistost jekla. Namen tega dela je bil ovrednotenje nastanka vključkov v jeklu med rafinacijo v ponovčni peči in vakuumski komori. V ta namen so bili vzeti vzorci v različnih fazah procesa. Polovica taline je bila dezoksidirana z oplášeno žico CaSi v ponovčni peči z namenom raziskave vpliva CaSi na nastanek vključkov po razplinjenju v komori. Vse taline so bile izdelane po naslednjih tehnoloških postopkih: OBM konverter-ponovčna peč-vakuumska komora (ISSM)-kontinuirno litje.

Ključne besede: jeklo, vključki, modifikacija s Ca

## 1 INTRODUCTION

Inclusions normally deteriorate the mechanical properties of steel. For example, the results reported in<sup>1</sup> proved that spherical inclusions are more suitable than sharp-edged inclusions. The liquefaction of inclusions during steelmaking causes their easier rise from the liquid steel. In steels deoxidised by aluminium, Al<sub>2</sub>O<sub>3</sub> inclusions are formed predominantly. These inclusions are, within the interval of the steelmaking temperatures, solid and sharp-edged. Their liquefaction is obtained by

the injection of CaSi into the steel. This causes an increase in the CaO content with a subsequent drop of the liquidus temperature of the original inclusions, which may more easily rise to the melt surface and be absorbed in the slag.

## 2 EXPERIMENTAL

Three steel grades were chosen for the assessment of the inclusions' development, i.e., the steel marked as A

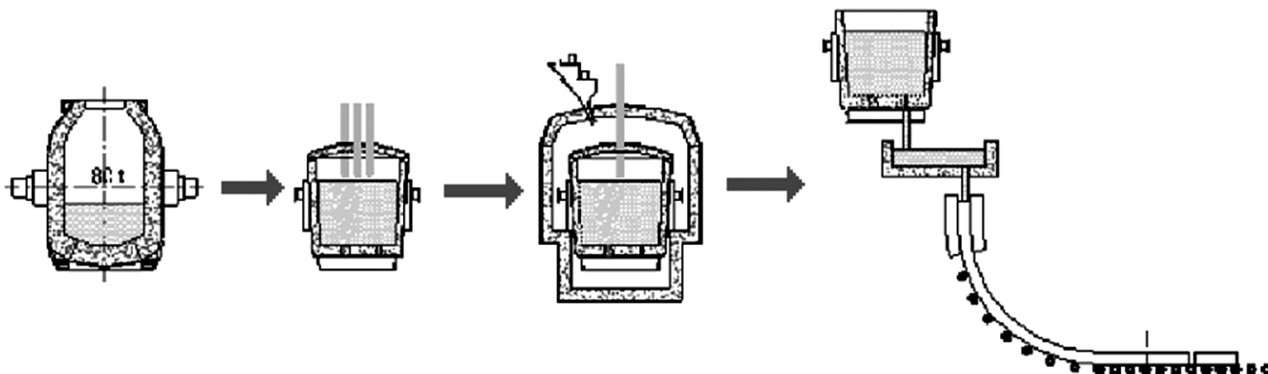


Figure 1: Steelmaking technological flow

Slika 1: Shema tehnološkega postopka izdelave jekla

**Table 1:** Chemical composition of the investigated steels in mass fractions, wt%**Tabela 1:** Kemijska sestava preiskovanega jekla v masnih deležih, wt%

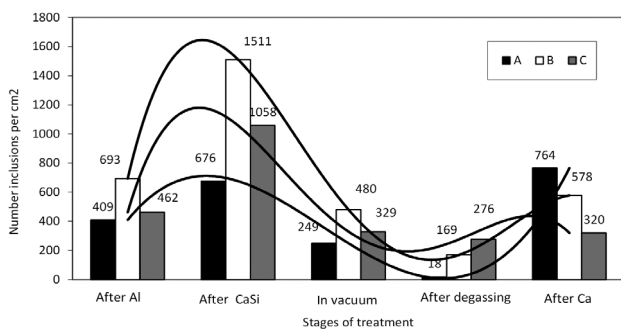
A – structural steel											
	C	Mn	Si	P	S	Cr	Al	Ti	Nb	V	N
Min.	0.10	0.3	0.20	–	–	–	0.020	–	–	–	–
Optimum	0.12	0.4	0.25	–	–	–	0.035	–	–	–	–
Max.	0.13	0.5	0.30	0.02	0.01	0.3	0.050	0.01	0.01	0.01	0.01
B – steel for ship plates											
Min.	0.150	1.40	0.3	–	–	–	0.020	–	–	–	–
Optimum	0.165	1.45	0.4	–	–	–	0.035	–	–	–	–
Max.	0.180	1.50	0.5	0.02	0.01	0.03	0.050	0.01	0.01	0.01	0.01
C – steel for pipelines											
Min.	0.08	1.35	0.20	–	–	–	0.020	0.018	0.020	0.030	–
Optimum	0.12	1.40	0.30	0.010	0.002	–	0.030	0.025	0.030	0.050	–
Max.	0.10	1.50	0.35	0.015	0.005	0.02	0.050	0.030	0.050	0.080	0.008

(structural steel), B (steel for the fabrication of ship plates), C (steel for pipelines working in an acidic environment). **Table 1** gives the chemical composition of these steels. The steel was processed in the following technological flow: basic oxygen converter OBM – ladle furnace – vacuum caisson (ISSM) – continuous casting (**Figure 1**).

For each steel the samples were taken from two heats. In the first heat  $Al_2O_3$  inclusions were modified in the ladle furnace by CaSi and the inclusions in the second heat were not modified.

The sequence of taking the samples from heats, in which the inclusions were modified by CaSi in the ladle furnace (LF), is as follows:

1. After deoxidation of the steel by aluminium in the LF (marked after Al)
2. After injection of the cored wire with CaSi in the LF (marked after CaSi)
3. After achieving a good vacuum in the ISSM (marked in vacuum)
4. After degassing in M (marked after degassing)
5. After modification of the steel by calcium (cored wire) at the end of the heat in the ISSM (marked after Ca)

**Figure 2:** Number of all the inclusions in the course of the steel treatment by secondary metallurgy methods**Slika 2:** Število vseh vključkov pri postopku sekundarne metalurgije izdelave jekla

Only samples 1, 3, 4 and 5 were taken from the heats, where no modification of the inclusions by CaSi was made in the ladle furnace LF. The samples were sucked into a submersible sampler and rapidly cooled in water to preserve the inclusions present in the liquid steel and to prevent the creation of inclusions during the cooling and solidification of the steel.

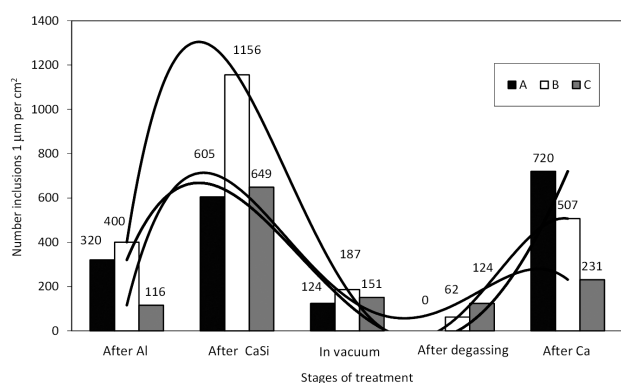
The objective was to assess the development of the number and size of the inclusions at individual stages of the steel treatment in the heats in which a modification by CaSi was made in comparison with the heats without this modification.

### 3 RESULTS AND DISCUSSION

#### 3.1 Evaluation of the inclusions on the basis of their number and size

At first the evolution of the number of inclusions at individual stages of the steel treatment is assessed for the heats in which the inclusions were modified by CaSi in a ladle furnace. It is evident from **Figure 2** that the number of inclusions after modification by the cored wire containing CaSi increased and afterwards their number decreased considerably during degassing – regardless of the steel grade. The increase in the number of inclusions after the injection of the CaSi can be explained by the reduction of the activity of  $Al_2O_3$  in inclusions due to their modification, which is followed by the reaction of metallic aluminium with oxygen. The vacuum treatment improves the kinetic conditions for the rise of the inclusions and the modified inclusions are quickly absorbed by the slag. The share of removed inclusions is proportional to their original number. At the end of the treatment after the degassing of the steel, altogether 95 % (grade A), 76 % (grade B) and 40 % (grade C) of the inclusions were removed, as compared to the initial number after the de-oxidation by aluminium.

After final dosing of the calcium into the degassed steel the number of inclusions increased. Due to the low oxygen content (below  $5 \cdot 10^{-4}$  wt%) after degassing, the



**Figure 3:** Number of inclusions up to the size of 1 µm for the course of the steel treatment by secondary metallurgy methods (A, B, C)

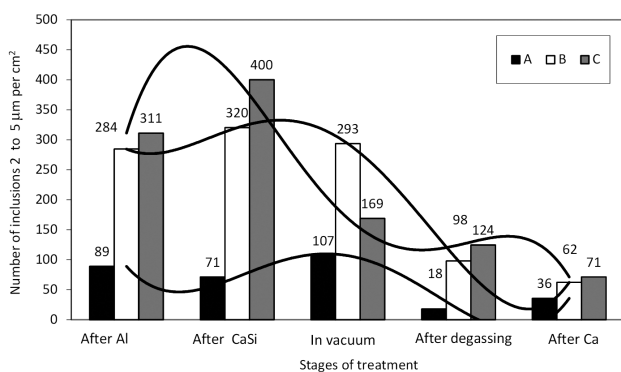
**Slika 3:** Število vključkov do velikosti 1 µm pri postopku sekundarne metalurgije izdelave jekla (A, B, C)

creation of new  $\text{Al}_2\text{O}_3$  inclusions was already very limited.

A similar change in the number of inclusions during individual stages of the steel treatment was found for the smallest inclusions with a size of 1 µm (Figure 3).

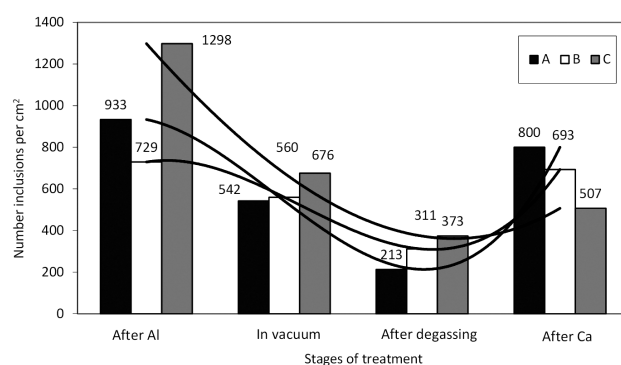
The number of inclusions with a size from 2 µm to 5 µm did not change much after the addition of CaSi, and thus the creation of new inclusions is compensated for by their assimilation by the slag (Figure 4). The drop in the number of larger inclusions during degassing (in vacuum) in comparison to the smallest samples was less distinct. This indicates that larger inclusions, apart from rising from the steel, are being newly formed by the coalescence and coagulation of the smallest inclusions. A further reduction in their number occurs only after full degassing. After the dosing of the calcium cored wire the number of large inclusions does not increase, which suggests the creation of only the smallest inclusions.

A similar evolution in the number of inclusions as in Figure 2 was also observed for the application of technological flow without modification of inclusions by CaSi in the LF (Figure 5). Only the total number of inclusions after degassing is higher in the case of non-modified steel. In the course of degassing the



**Figure 4:** Number of inclusions with sizes from 2 µm to 5 µm in the course of the steel treatment by secondary metallurgy methods

**Slika 4:** Število vključkov velikosti od 2 µm do 5 µm pri postopku sekundarne metalurgije izdelave jekla



**Figure 5:** Number of all the inclusions in the course of steel treatment by secondary metallurgy methods without modification in the ladle furnace

**Slika 5:** Število vseh vključkov pri postopku sekundarne metalurgije izdelave jekla brez modifikacije v ponovni peči

number of non-modified inclusions drops as well. After degassing, altogether 77 % (grade A), 57 % (grade B) and 71 % (grade C) of inclusions were removed, in comparison with the initial number after deoxidation by aluminium. After the final modification by calcium their number increases again, also due to the higher contents of oxygen ( $7 \cdot 10^{-4}$  to  $10 \cdot 10^{-4}$  wt%) in the steel, which was not modified by CaSi during the second stage.

The comparison of two technological flows from the viewpoint of the number of inclusions shows that the removal of inclusions in the course of degassing is better after modification of the steel by CaSi in the LF. Apparently, this is related to the liquefaction of the inclusions. Liquefied inclusions attain a drop shape, which reduces the melt resistance by moving the inclusions towards the surface.

## 4 CONCLUSIONS

The following can be concluded from the results of the assessment of the evolution of the number and size of the inclusions during steel refining in a ladle furnace and in a vacuum caisson (ISSM):

- CaSi modification of the steel de-oxidised by aluminium caused, at first, an increase in the number of inclusions, which was strongly reduced during the vacuum treatment. This evolution of the occurrence of inclusions was observed particularly for the small inclusions with a size up to 1 µm.
- For larger inclusions (2 µm to 5 µm) the decrease of their number during the vacuum treatment was apparently slower due to the joining of small inclusions into larger ones.
- A similar evolution of the number of inclusions was also observed in the technological flow without any modification of the steel by CaSi. Only the overall number of inclusions was higher after the degassing.
- The final dosing of calcium into the degassed steel caused, in all the cases, an increase in the number of

inclusions, but mostly in the group of the smallest inclusions with sizes up to 1  $\mu\text{m}$ .

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### 5. REFERENCES

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