

# **THE INFLUENCE OF TOP-SLAG COMPOSITION ON INCLUSION CHARACTERISTICS IN BEARING-STEEL PRODUCTION.**

M.-K. Göransson\*, U. Leray\*\* and M. Andersson\*\*\*

\*Ovako Steel AB, SE-813 82 Hofors, Sweden.

\*\* Formerly Master Thesis Student from The Royal Institute of Technology (Stockholm) at Ovako Steel AB. Presently at Studsvik Nuclear AB, SE-611 82 Nyköping, Sweden.

\*\*\* Tech. Lic. at Division of Metallurgy, The Royal Institute of Technology, SE-100 44 Stockholm, Sweden.

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## **Abstract**

The influence of top-slag composition on inclusion removal and inclusion characteristics during the ASEA-SKF process has been studied. Trials were conducted using different ratios of CaO to Al<sub>2</sub>O<sub>3</sub> in the top slag in the production of high-carbon chromium bearing steel. Analyses were performed using optical light microscopy (in accordance with the Swedish standard 11 11 16 (chart II)) and a modified optical-emission-spectroscopy (OES) technique developed at Ovako Steel AB. The results indicated that there is a relationship between slag composition and inclusion characteristics in steel.

## 1. INTRODUCTION

Inclusion characteristics are an important issue in producing bearing steel. The size distribution, shape and mechanical properties of inclusions determine the fatigue properties of the final product <sup>[1, 2]</sup>. Ovako Steel AB has put a lot of effort into reducing the total oxygen content in bearing steels, managing to reduce the total oxygen content from 10 ppm to today's level of 5 ppm between 1986 to 1996 <sup>[2]</sup>. However, not only the total oxygen content is of interest; the parameters of inclusion size distribution and composition also influence steel cleanliness and the fatigue properties of the final product. When producing clean steel it is important to reduce the sources of reoxidation and thus the formation of inclusions after deoxidation. Parameters related to top-slag composition can also influence inclusion characteristics in the liquid steel, such as viscosity, interfacial surface tension, the ratio of CaO to Al<sub>2</sub>O<sub>3</sub>, and the amount of MgO together with kinetic conditions during the ladle furnace process.

Several researchers <sup>[3-5]</sup> have studied the removal and separation of non-metallic inclusions from the steel at the refractory/steel and top-slag/steel interfaces (the latter of interest in this work). Conditions favour the separation of solid inclusions with a high contact angle between the inclusion and steel to the top slag. Furthermore, a top slag that easily assimilates and dissolves the inclusions is preferable. If the top slag has a low viscosity, the risk of slag entrapment will probably increase when the molten steel and slag is stirred during ladle treatment. <sup>[6]</sup>

The focus in this paper is on the influence of top-slag composition on the removal of inclusions and inclusion composition. The first part of the paper describes plant trials performed at Ovako Steel AB, in which the top-slag composition in the ladle was changed. Next, the results with respect to top-slag composition, inclusion size distribution and inclusion composition are presented and discussed. Finally, some conclusions are presented.

## 2. PLANT TRIALS

### 2.1. General process description

The production at Ovako Steel AB is scrap based. The scrap is melted in a 100-tonne Oval Bottom-Tapped electric arc furnace. After adjusting the steel to desired phosphorous, carbon, and temperature levels, the steel is tapped into a ladle. The steel is then deslagged before transport to the ASEA-SKF ladle furnace station. At the LF station a synthetic calcium-aluminate top slag is added.

The secondary refining process mainly consists of three steps. First, induction stirring and heating with three electrodes is carried out during alloying, deoxidation and melting of the synthetic top slag. Second, vacuum degassing with combined inductive and gas stirring is applied to promote sulphur and hydrogen refining. Third, a final inductive stirring is once more utilised to promote the separation of inclusions from the steel to the

top slag and refractory lining. During the third treatment step heating can also be used to ensure that the desired teeming temperature is achieved. After the ladle-furnace treatment is complete, the steel is teemed with uphill teeming into 24 ingots weighing 4.2 tonnes each.

## **2.2. Experimental procedure**

The relationship between top-slag composition and inclusion characteristics was studied and the results based on analysis of samples taken during the ASEA-SKF process from 11 heats of high-carbon chromium bearing steel (1 % C, 1.4 % Cr). Synthetic slag formers were added to the studied heats in the amount of 6-8 kg per tonne steel. The synthetic slag formers, used in different proportions, were lime, pure  $\text{Al}_2\text{O}_3$  and a premelted calcium aluminate containing some  $\text{MgO}$ ,  $\text{V}_2\text{O}_5$  and  $\text{SiO}_2$ . The synthetic slag formers were added and melted before vacuum degassing. The inclusion characteristics during vacuum degassing were studied because of the favourable conditions existing for inclusion separation during this process step. During the vacuum degassing the heat was stirred both by inductive stirring and argon bubbling through two porous plugs at the bottom of the ladle. The ladle refractory was magnesia-carbon based.

Steel samples and top slag samples were taken before and after vacuum degassing. Temperatures of the molten steel were measured at each sampling occasion. Slag samples were collected manually with a slag spoon. The temperatures were measured and steel samples were taken using the automatic sampling equipment at the ASEA-SKF ladle furnace. Rapidly solidified steel samples were used for inclusion characterisation<sup>[7]</sup>. The top slag samples were examined using X-ray analysis. The steel samples were analysed for determination of inclusion characteristics using both the modified OES technique<sup>[8-10]</sup> and traditional optical light microscopy in accordance with the Swedish standard 11 11 16. The OES technique is a much more rapid technique for determining inclusion composition compared to the traditional method using SEM-EDX. Determining the composition of 30 inclusions using SEM-EDX can take several hours, but with the new modified OES method, the same task takes only a few minutes. On the other hand, OES analysis does not provide information on inclusion morphology or the presence of sulphide shells. The modified OES technique can only measure oxide inclusions up to a size of 11  $\mu\text{m}$  and the content of Si in inclusions can not be detected with this technique. In this study only the Al, Mg and Ca contents of inclusions were determined; inclusions were not analysed for sulphur content. Inclusion size distributions obtained using the modified OES method are measured in units of inclusion index. The inclusion index is comparable to the number of inclusions per square millimetre determined by optical light microscopy. The inclusion index corresponds to the number of inclusions per fixed number of sparks used in the OES analysis.

### 3. RESULTS

#### 3.1. Top-slag composition

The results from the determination of top-slag compositions are shown in Table 1. Only the four main components (CaO, MgO, Al<sub>2</sub>O<sub>3</sub> and SiO<sub>2</sub>) are listed in Table 1 with oxides like FeO, MnO, Cr<sub>2</sub>O<sub>3</sub> and V<sub>2</sub>O<sub>5</sub> being neglected. The total contents of FeO, MnO, Cr<sub>2</sub>O<sub>3</sub> and V<sub>2</sub>O<sub>5</sub> were rather low and varied between 2.4 to 0.5 % after degassing. The heats were divided into two groups, A and C, with respect to liquidus temperature and thereby the CaO/Al<sub>2</sub>O<sub>3</sub> ratio in the top slag.

Group A, with melting temperatures below 1400 °C, had an average CaO/Al<sub>2</sub>O<sub>3</sub> ratio of 1.04, while group C with melting points above 1600 °C, had an average CaO/Al<sub>2</sub>O<sub>3</sub> ratio of 1.65. The average top-slag compositions of each group are plotted in Figures 1 and 2<sup>[14]</sup>. The amount of MgO varied from 5.1-11.8 % and the amount of SiO<sub>2</sub> from 4.8 - 12.7 % for samples taken after degassing.

#### 3.2 Inclusion Size Distribution and Composition

In Figure 3 the average size distributions of inclusions before and after degassing are plotted for the A and C groups. The size distributions in Figure 3 were determined by means of optical light microscopy in compliance with the Swedish standard 11 11 16. The plot indicates that group A had the largest reduction in the number of inclusions during the vacuum treatment. It also seems as group A has the largest amount of inclusions above 11 µm. The reduction of inclusions smaller than 11 µm seemed to be less effective for heats with a higher CaO/Al<sub>2</sub>O<sub>3</sub> ratio. Fewer large inclusions were found for group C heats.

The samples were also analysed with the modified OES technique. The average inclusion size distribution before and after degassing for groups A and C determined with this technique are plotted in Figure 4. The results showed the same trend for inclusions smaller than 11 µm, as with optical light microscopy. The greatest reduction in the amount of inclusions was seen in the group A heats.

In Figures 5 and 6 are plots of the inclusion composition before and after degassing for group A and C heats. The inclusions are divided into four groups (A, M-A, C-A and C-M-A) depending on their composition. Alumina inclusions, A, are defined as inclusions with at least 95 % Al<sub>2</sub>O<sub>3</sub>. Then there are MgO-bearing Al<sub>2</sub>O<sub>3</sub> inclusions (M-A), CaO-bearing Al<sub>2</sub>O<sub>3</sub> inclusions (C-A), and finally complex Al<sub>2</sub>O<sub>3</sub> inclusions containing both Mg and Ca (C-M-A). The compositions of the inclusions are determined by the modified OES technique.

The average composition, for each of the four types of inclusions defined above, did not change substantially during the vacuum treatment. There was a small increase in %Mg for the M-A inclusions and a small decrease in %Ca for the C-A inclusions during degassing of both A and C heats. The average inclusion compositions did differ for group

A and C heats. However, the relative amount of the different types of inclusions seemed to be dependent on the top-slag composition. In Figure 7, the average distributions of the different types of inclusions are plotted before and after degassing for the group A and C heats. The amount of alumina inclusions increased for group A heats as the relative amount of M-A inclusions decreased. The opposite was noted for group C heats, as the amount of M-A inclusions increased during degassing. The relative amount of C-A inclusions increased during the degassing for both the A and C heats. The relative amounts of complex inclusions of C-M-A type found in the A heats both before and after degassing were somewhat higher compared to the C heats and they also contained more Ca and Mg.

#### 4. DISCUSSION

The  $\text{CaO}/\text{Al}_2\text{O}_3$  ratio in the top slag seems to influence the separation of inclusions as well as the distribution of alumina and M-A inclusions after ladle furnace treatment. In discussing and analysing the results, it is of interest to know how the viscosity of the top slag is influenced by the slag composition. Jönsson et al.<sup>[6]</sup> reported that the viscosity of a  $\text{CaO}-\text{Al}_2\text{O}_3$  slag containing 10 wt% MgO and 10 wt%  $\text{SiO}_2$  decreases with a decreasing  $\text{CaO}/\text{Al}_2\text{O}_3$  ratio as well as an increasing temperature (Figure 8). The results were obtained using the KTH model for multi-component slag viscosity developed by Seetharaman and co-workers<sup>[11]</sup>. A CFD model was used to calculate the mixing between top slag and steel in a 100 t gas-stirred ladle for two slag compositions of different  $\text{CaO}/\text{Al}_2\text{O}_3$  ratios, 2.2 and 1.7. The CFD calculations showed an increase in mixing between top slag and steel for a decrease in the  $\text{CaO}/\text{Al}_2\text{O}_3$  ratio and viscosity.

Heats in group C had liquidus temperatures above 1600 °C and would most probably be partly solidified during the degassing operation. As a slag is not fully liquid, the viscosity of the slag would be increased, due to reinforcement of solidus particles. The results from Jönsson et al.<sup>[6]</sup> further indicate that a higher CaO content in the slag also increases the viscosity. Thus it is reasonable to conclude that the heats of group C had a higher slag viscosity compared to those of group A. A lower viscosity should increase the risk of top-slag entrapment in the steel due to slag/metal mixing. It seems that this occurs before the degassing of the A heats, because the average number of inclusions was generally higher compared to the C heats. However, the degree of inclusion reduction for the A heats are higher compared to the C heats. Most probably the slag used for group C heats was not fully liquid, which resulted in less top slag available for inclusion assimilation.

Okuyama et al.<sup>[12]</sup> reported that the MgO content in  $\text{Al}_2\text{O}_3$  inclusions decreases with a decrease in the  $\text{CaO}/\text{SiO}_2$  and  $\text{CaO}/\text{Al}_2\text{O}_3$  ratios in the top slag. The results of this work do not indicated any differences in Mg content in the M-A inclusions for groups A and C after degassing. Moreover, the Mg content in the M-A inclusions increased during degassing for both A and C heats. However, the relative amount of M-A inclusions increased for group C compared to group A during the degassing operation. At the same time, the relative amount of pure alumina inclusions decreased for group C, while it

increased for group A. The top-slag compositions of the group C heats were closer to MgO saturation compared to those of the group A heats. According to Ohta and Suito<sup>[13]</sup> the iso-solubility of MgO increases with an increased content of  $\text{Al}_2\text{O}_3$  and  $\text{SiO}_2$  in the  $\text{CaO-MgO-Al}_2\text{O}_3\text{-SiO}_2$  slag system. It is possible that group A heats assimilated more M-A inclusions than C heats since they were less near MgO saturation.

It seems that the composition of the synthetic top slag added in the ladle furnace process influences the inclusion size distribution and the amount of different inclusions existing after treatment is finished. It is thereby of great importance to be able to control top-slag composition and to fully understand the physical and thermodynamic mechanisms of inclusion assimilation and the effects of the top-slag composition. In the future inclusion engineering and the modelling of inclusion characteristics will be essential to meet the increasing demands on steel cleanliness.

## **5. CONCLUSIONS**

The following conclusions were drawn from the study:

- A lower  $\text{CaO/Al}_2\text{O}_3$  ratio in the top slag resulted in a larger number of inclusions before vacuum degassing.
- The degree of reduction in the number of inclusions during vacuum degassing seemed to increase when the top slag had a lower  $\text{CaO/Al}_2\text{O}_3$  ratio.
- An increased  $\text{CaO/Al}_2\text{O}_3$  ratio in the top slag decreased the relative amount of pure alumina inclusions in the molten steel and increased the relative amount of M-A inclusions during degassing.

## **ACKNOWLEDGEMENTS**

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**Tables 1. Heats categorised by slag composition and melting point after degassing**

	Heat	Slag composition after degassing			
		%CaO	%Al <sub>2</sub> O <sub>3</sub>	%MgO	%SiO <sub>2</sub>
<b>A</b>	<b>a</b>	41.2	36.0	11.8	11.0
	<b>b</b>	44.0	42.1	7.7	6.2
	<b>c</b>	46.0	44.1	5.1	4.8
	<b>d</b>	41.7	43.3	7.7	7.3
	<b>Average</b>	43.2	41.4	8.1	7.3
<b>C</b>	<b>k</b>	50.8	30.2	9.4	9.6
	<b>l</b>	50.5	28.2	8.6	12.7
	<b>m</b>	55.4	32.2	7.6	4.8
	<b>n</b>	54.0	31.2	8.8	6.0
	<b>o</b>	51.6	33.2	9.0	6.2
	<b>p</b>	49.8	31.7	8.8	9.7
	<b>q</b>	49.7	32.9	9.9	7.5
	<b>Average</b>	51.7	31.4	8.9	8.0



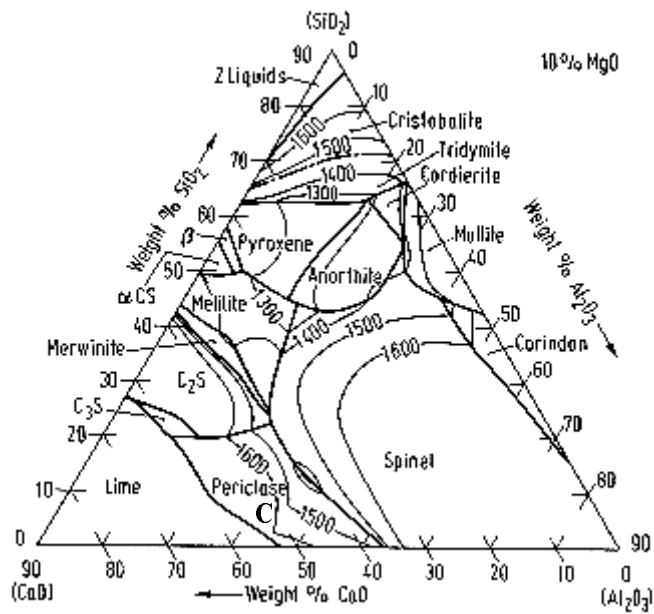


Figure 1. Phase diagram of CaO-Al<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub> slag system with 10 % MgO<sup>[14]</sup>

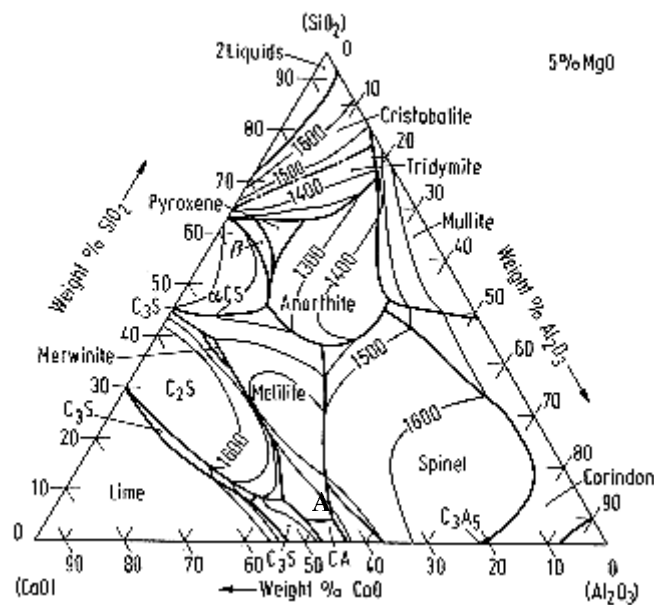


Figure 2. Phase diagram of CaO-Al<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub> slag system with 5 % MgO<sup>[14]</sup>

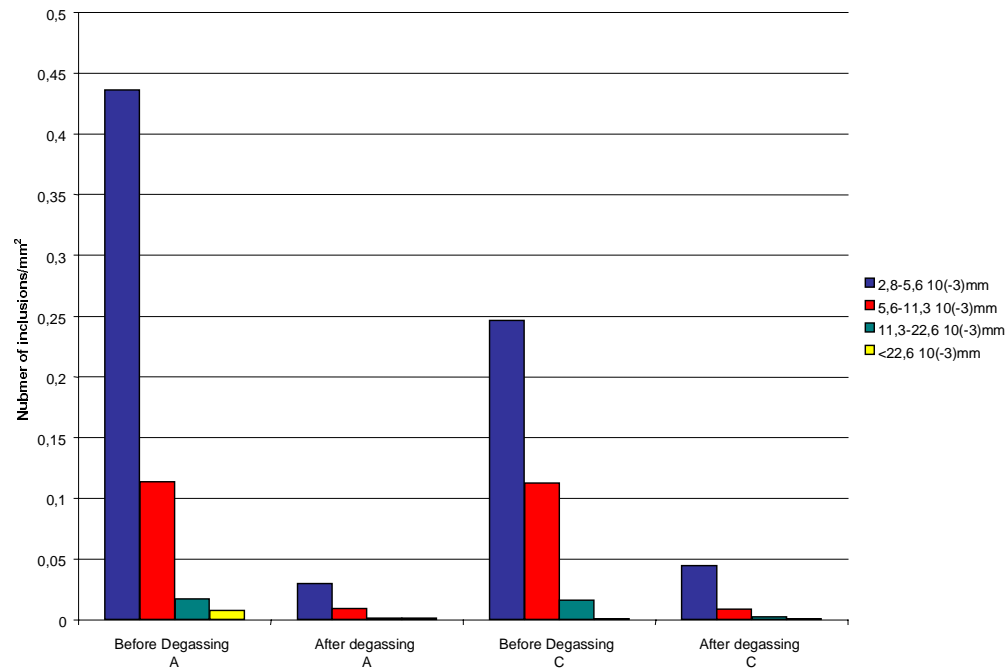


Figure 3. Average values of inclusion size distribution before and after degassing depending on top-slag composition determined by optical light microscopy and SS 11 11 16

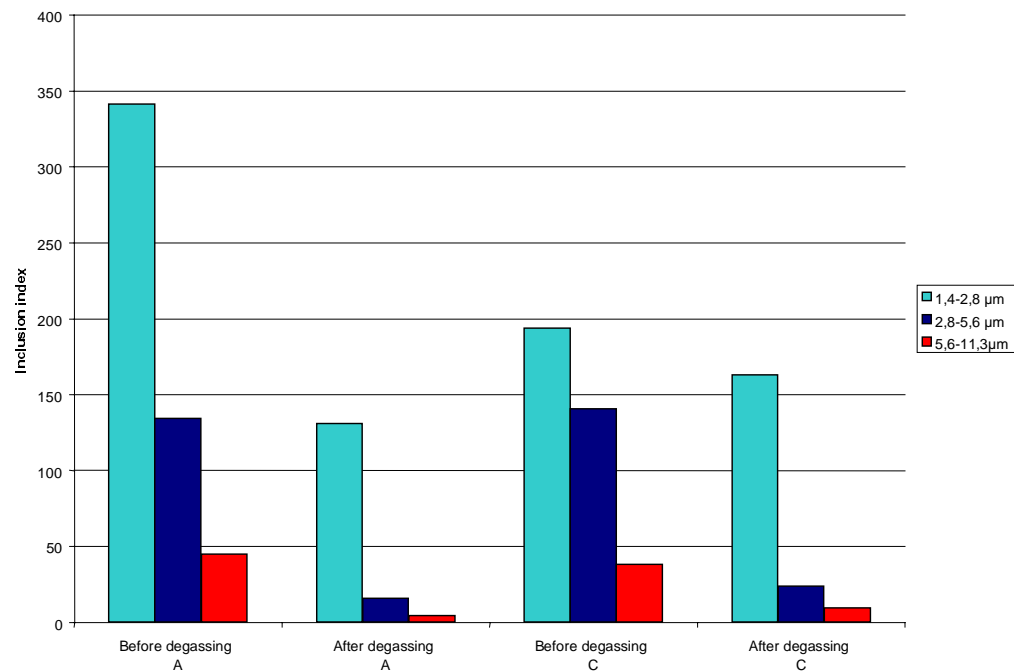


Figure 4. Average values of inclusion size distribution before and after degassing depending on top-slag composition determined with the modified OES technique

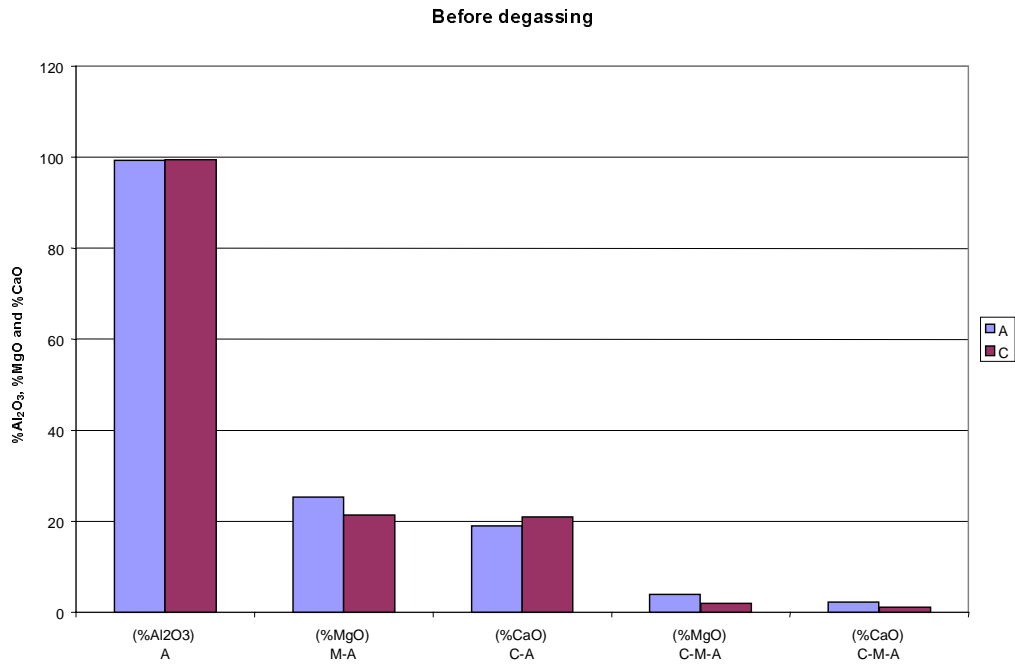


Figure 5. Average composition of the different types of inclusions found before degassing

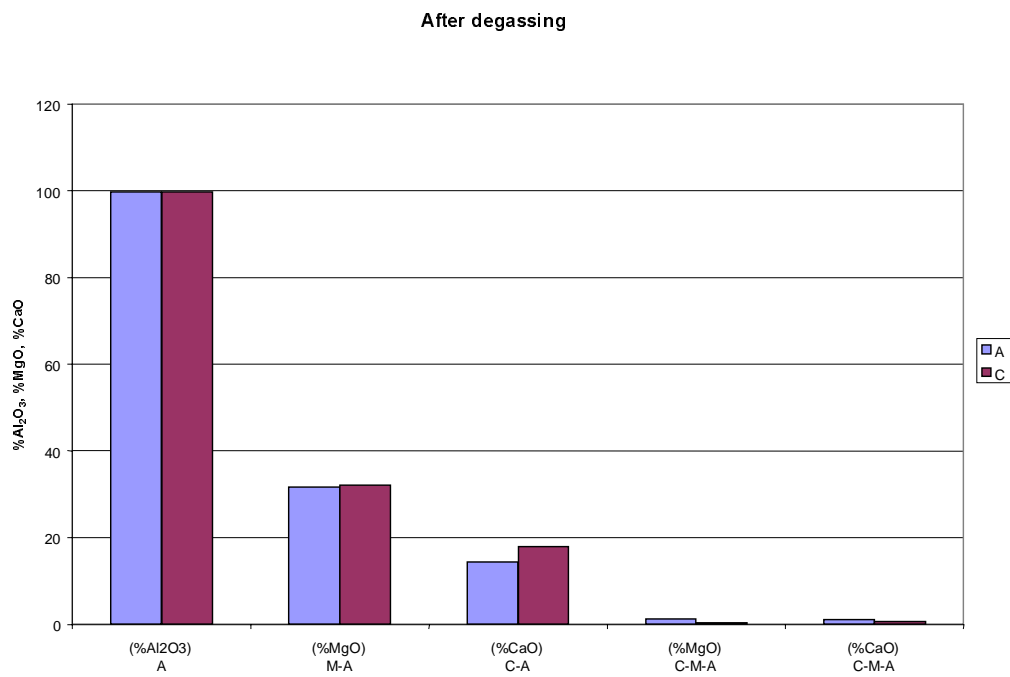


Figure 6. Average composition of the different types of inclusions found after degassing

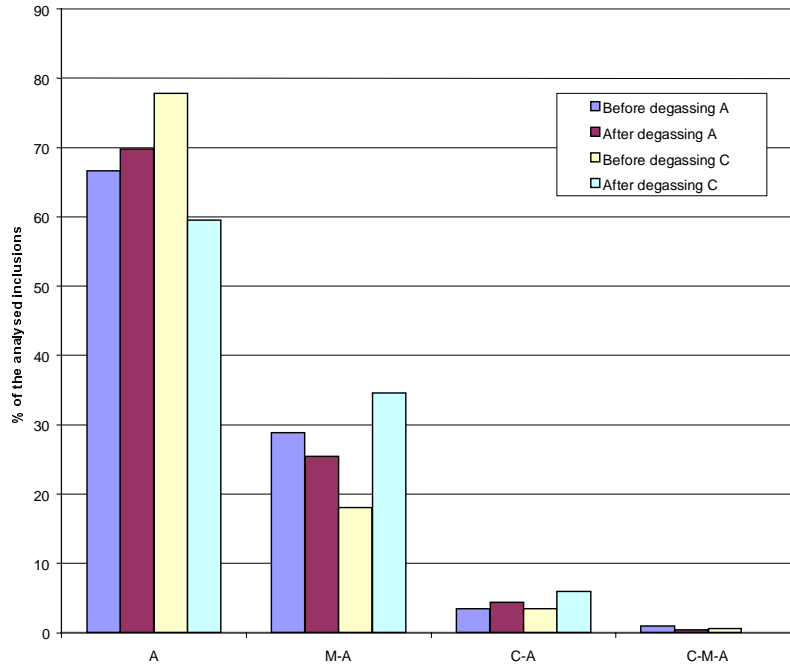


Figure 7. Average percentile distribution of different types of inclusions found before and after degassing for different top-slag compositions.

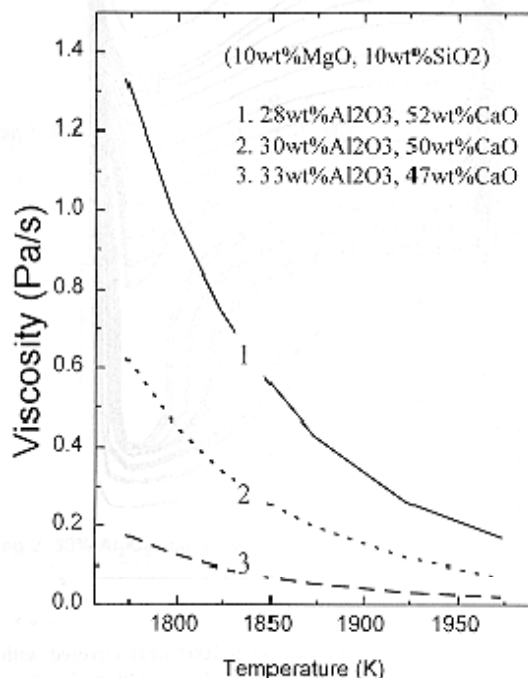


Figure 8. The effect of the replacement of CaO by Al<sub>2</sub>O<sub>3</sub> on viscosity. <sup>[6]</sup>