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FOAMING OF EAF STAINLESS STEEL SLAGS WITH Cr_2O_3 USING STEELCAL™

1. INTRODUCTION

Industry tests have shown that Steelcal™, a specially modified grade of calcium nitrate, can be an efficient agent for creating foaming slags in electric arc furnaces (EAFs) for melting stainless steels [1]. The reason why steel producers are interested in having foaming slag is the economical benefits that can be achieved by increased productivity and/or reduced energy consumption, reduced electrode consumption, reduced maintenance costs and possible increased recovery of chromium from the slag. Many factors influence foaming, such as gas development in the slag, the slag foamability, injection technique etc., and each of these factors are dependent on several other parameters. When melting stainless steels, foaming is poor, e.g. the Cr_2O_3 content of the slag has a strong influence on the foamability of the slag. In order to try to determine the significance of various parameters, testing of the foaming capability of Steelcal has been conducted at the metallurgical laboratory of the AGH University of Science and Technology in Krakow, Poland.

The purpose of the tests was 1) to recreate the good slag foaming observed in industry tests, and 2) to obtain knowledge of the influence of the most important parameters on the slag foaming.

2. STEELCAL

Steelcal, as a by-product created during fertilizer production, is a hydrated calcium ammonium nitrate with the approximate chemical composition $Ca(NO_3)_2(NH_4NO_3)_{0.2}(H_2O)_2$. Steelcal decomposes in a steel/slag melt at high temperature to CaO and various gases depending of other reactants present. For example, when reacting with carbon the following

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approximate reaction is possible (estimated by the FACTSAGE database for thermodynamic calculations):

$$Ca(NO_3)_2(H_2O)_2 + 5C \Rightarrow CaO + N_2 + 2H_2O + 5CO \quad (1)$$

The reaction (1) will give 8 mol gases per mol of Steelcal.

Industrial tests [1] have shown that, as a rule of thumb, the necessary quantity of Steelcal to achieve foaming relative to the steel weight in an EAF is approximately 1% of the steel weight, or 10% of the slag quantity, assuming that the steel to slag ratio is ca. 10:1. Per ton of steel the gas development in reaction (1) will be:

10 kg Steelcal + 3 kg C + (0.5 kg N_2) => ca. 9 Nm^3 gases, or 56 m^3 at 1600°C.

This estimate shows that Steelcal develops a lot of gas during decomposition, which can create foaming of the slag, provided that the foamability of the slag and the injection technique is right.

Good foaming results have been achieved by injecting Steelcal into the slag, just below the surface of the slag. The angle of injection should be small relatively to the horizontal plane. Injection should make a rotating movement of the molten slag, especially if there is only one injection point.

3. EXPERIMENTAL PROCEDURE

3.1. Experimental equipment

A laboratory EAF installed in the metallurgical laboratory at the AGH UST was used for the Steelcal tests. The EAF has previously been used for slag foaming experiments when melting unalloyed carbon steels [2]. The EAF is a single electrode arc furnace with a conductive hearth. Electrical power is supplied from a 40 kVA transformer. The apparatus consists of a graphite crucible with ceramic linings and conducting bottom. This is placed in a steel frame to ensure electrical contact with a copper plate on the base of the furnace. The graphite electrode is mounted vertically in an electrically driven mechanism, which allows it to be moved up and down automatically or manually.

A sketch of the single electrode unit for arc melting used for Steelcal testing is shown in Figure 1. A sketch of the graphite crucible is shown in Figure 2. Photo of apparatus is shown in Figure 3.

For the Steelcal tests, a hole was drilled in the crucible wall in such a way that it was possible to inject Steelcal (or Steelcal + carbon or others components) through a steel tube by air or nitrogen as a carrying gas at a pressure of 0.10–0.15 MPa. The position and the angle of the injection point caused the Steelcal to enter into the slag phase and stirring the slag.

After injecting Steelcal, the slag level was measured several times by a copper rod. The copper rod was immersed into the slag bath, and after drawing it out, the distance between the top of the crucible and the solidified slag on the copper rod was measured.

A ca 1 kg piece of AISI 304 stainless scrap was introduced into the crucible for the Steelcal tests, and the electrode was moved down. Then the electric power was turned on, and an electric arc ignited. After the steel meltdown (about 3–5 minutes), the slag was added into the crucible and melted.

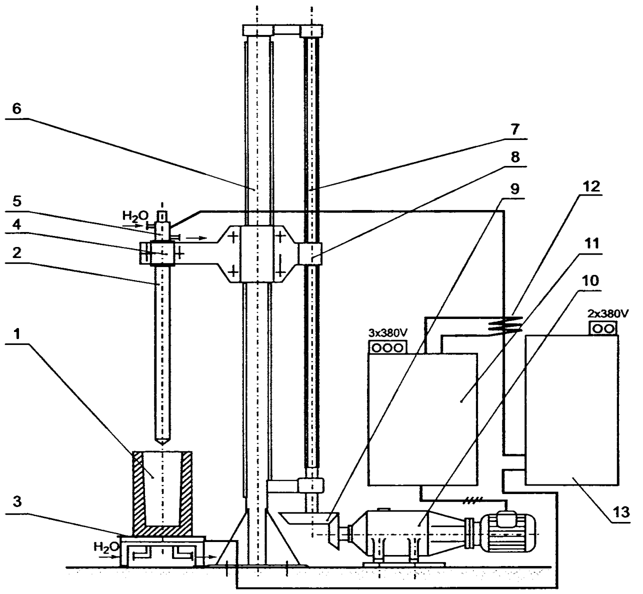

Fig. 1. *A sketch of the single electrode unit for arc melting: 1 – crucible, 2 – graphite electrode (diameter 40, 60, 80 mm), 3 – copper plate, 4 – electrode holder, 5 – current connector, 6 – mast stem, 7 – power screw, 8 – drawing nut, 9 – gear transmission, 10 – electrical engine with speed reducer, 11 – control system, 12 – measurement system, 13 – supply transformer*

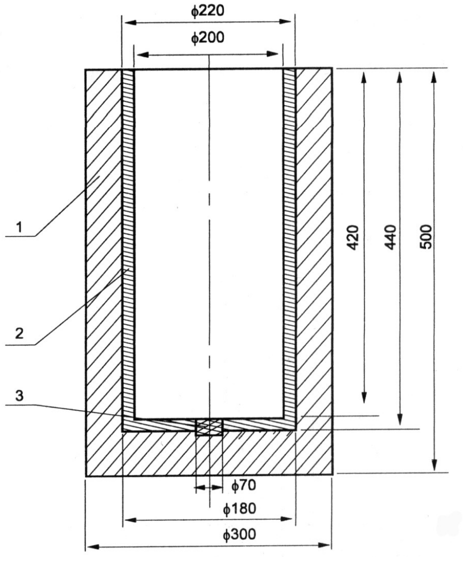

Fig. 2. *A sketch of the graphite crucible: 1 – graphite crucible, 2 – ceramic refractory (normally fire-resisting concrete on Al_2O_3 base), 3 – electricity-conducting material (normally graphite or in some cases molybdenum plate)*

Fig. 3. *Photo of experimental equipment*

3.2. Test program

For each charge approximately 1 kg of AISI 304 stainless steel and 3 kg of slag was melted. The steel-to-slag ratio was thus 1:3, whereas in an industry furnace the ratio is about 10:1. The quantity of the Steelcal injected after melting was therefore related to the slag quantity, i.e. about 10% of the slag or ca 0.3 kg Steelcal, or Steelcal + C when carbon was added. Slag samples were taken after melting, but before Steelcal injection. Slag and steel samples were also taken after the test was finished. All tests were video recorded.

3.3. Slag height measurements

The slag height (thickness) before Steelcal injection, when 3 kg of slag had been melted, was ca. 3 cm, and is denoted as the "0 level". The level of the slag height was measured by a copper rod (ruler) as the distance from the top of the crucible to the slag surface. The 0 level measurement was done immediately after all slag (3 kg) had been melted and before Steelcal injection began. The same slag height increase measurement were done after Steelcal injection.

3.4. Materials for tests:

AISI 304 stainless steel chemical composition:
< 0.08% C, 18–20% Cr, 8–10.5% Ni, < 0.75% Si, < 2% Mn
Carbon steel slag:
35–40% CaO, 15–20% SiO_2, 20–30% FeO, ~5% MnO, 2–5% Al_2O_3, 5–10% MgO
Stainless steel slag:
32% SiO_2, 45% CaO, 6% MgO, 6% Cr_2O_3, 3% MnO, 3% Al_2O_3, 2% TiO_2, 2% FeO, 1% CaF_2, < 1% others.
Steelcal:
$Ca(NO_3)_2(NH_4NO_3)_{0.2}(H_2O)_2$, grain size 2–4 mm
Metallurgical coke:
> 85% C, < 1% S, < 12% ash, 2% vol. el., < 0.8 hydrocarbons, grain size 0.1–0.5 mm > 80%

Injection gas:
Air or nitrogen, pressure 0.10–0.15 MPa.

4. TEST CONDITIONS AND RESULTS

For the first 3 tests, carbon steel slag modified by adding 10%, 15% and 5% Cr_2O_3 respectively, was used. Carbon steel slags are known to be relatively easy to foam by injecting carbon only [2], whereas a high content of Cr_2O_3 is reducing the foamability of slags [3]. It was the purpose of the first 3 tests to examine how the Cr_2O_3 would influence the foamability of a slag that otherwise was supposed to have good foamability.

For the other 19 tests, the industrial stainless steel slag from AvestaPolarit, Avesta, was used. For the last 13 tests, the Avesta slag was modified by adding some FeSi, SiC or CaO, except for tests 12 and 19 where slag-modifying additives were mixed with the Steelcal (see Tab. 1).

Table 1. Description of the foaming material methodology with slag high and Cr_2O_3 content

Test No	Description	Slag high	Increase high	Cr_2O_3 before	Cr_2O_3 after
1	300 g (70% Steelcal +30% C)	11.0	3.67	13.0	17.0
2	300 g (70% Steelcal +30% C)	3.0	1.00	28.0	25.0
3	300 g (70% Steelcal +30% C)	6.0	2.00	11.0	14.0
4	150 g (70% Steelcal +30% C)	5.0	1.67	10.0	16.0
6	200 g (70% Steelcal +30% C)	4.0	1.33	9.6	9.8
5	300 g (70% Steelcal +30% C)	4.5	1.50	10.0	10.0
11	300 g (pure Steelcal) + 100g FeSi	4.0	1.33	8.5	5.3
18	300 g (pure Steelcal) + 100g FeSi[45°]	6.0	2.00	8.3	6.5
12	300 g Steelcal + 100g FeSi mixed	3.5	1.17	9.4	5.9
22	240 g (80% Steelcal + 20% C) +200g FeSi mixed [45°]	7.0	2.33	6.1	4.3
10	200 g pure Steelcal + 50g FeSi	6.0	2.00	8.5	7.9
9	300 g pure Steelcal + 100g FeSi	12.0	4.00	6.7	5.5
13	300 g pure Steelcal + 100g FeSi	5.0	2.67	8.9	5.7
16	300 g pure Steelcal + 100g FeSi mixed	10.0	3.33	7.5	5.7
14	300 g pure Steelcal +300g FeSi	6.0	2.00	7.1	5.5
20	300 g pure Steelcal + 300g FeSi	9.0	3.00	6.9	5.8
19	300 g pure Steelcal + 300g FeSi mixed [45°]	3.0	1.00	9.9	6.8
15	300 g (80%Stelcal+20%C) +100g FeSi	3.0	1.00	8.9	6.3
7	300 g (70% Steelcal +30% C)	3.5	1.17	9.5	9.1
8	300 g (70% Steelcal +30% C) +100g FeSi	9.5	3.17	8.0	4.9
17	300 g pure Steelcal + 100g SiC [45°]	4.0	1.33	5.4	3.2
21	240 g (80%Stelcal+20%C) (charge with CaO)	10.5	3.50	8.0	8.1
22	300 g (80%Stelcal+20%C) + 200g FeSi	7.0	2.33	6.1	4.3

Table 2 shows the most important parameters, the maximum slag height results and the chemical composition of the steel and slag respectively for the tests no. 1–22. The main trends are seen in Figure 4.

Table 2. Main parameters, slag height results, steel and slag analyses (Css = carbon steel slag)

Test No	0	1	2	3	4	5	6	7	8	9	10
Slag type +%Cr_2O_3		Css +10%	Css +15%	Css +5%	Avesta slag	Avesta slag	Avesta slag	Avesta slag	Avesta slag	Avesta slag	Avesta slag
FeSi, kg									0,1	0,1	0,05
Inj. Gas		Air	Air	Air	Air	Air	Air	N_2	N_2	N_2	N_2
Steelcal "S"+%C		S+30C	S+30C	S+30C	S+30C	S+30C	S+30C	S+30C	S+30C	Pure	Pure
Steelcal quant., kg		0,3	0,3	0,3	0,15	0,3	0,2	0,3	0,3	0,3	0,2
Note							C-inj,				2x inj,
Slag height max, cm	0-level = 3cm	11	3	6	5	4,5	4	3,5	9,5	12	6
Steel analysis	"304"										
C	0.07	0.09	0.02	0.02	0.29	0.58	0.75	0.60	1.06	0.79	0.76
Si	0.37	<0.01	<0.01	<0.01	<0.01	0.03	0.05	0.04	0.35	1.46	0.11
Mn	1.66	0.08	0.10	0.10	0.59	0.92	1.10	1.04	1.62	1.77	1.15
P	0.04	0.02	0.16	0.16	0.07	0.04	0.04	0.04	0.05	0.04	0.05
S	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01
Cr	18.40	0.83	2.48	2.60	12.50	17.10	18.30	18.20	20.90	20.50	20.60
Ni	9.93	8.66	11.30	11.20	11.80	11.50	11.30	11.40	10.50	10.30	10.50
Al	0.16	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Cu	0.14	0.13	1.89	1.88	0.16	0.15	0.14	0.15	0.14	0.13	0.17
Mo	0.17	0.11	0.17	0.17	0.19	0.19	0.19	0.19	0.18	0.17	0.18
Ti	0.56	<0.01	<0.01	<0.01	<0.01	<0.01	0.02	0.01	<0.01	<0.01	<0.01
Slag before	Original Avesta	Css +10%	Css +15%	Css +5%	Avesta slag	Avesta slag	Avesta slag	Avesta slag	Avesta slag	Avesta slag	Avesta slag
Fe_2O_3	2.00	28.00	16.00	27.00	3.30	2.30	2.10	2.10	1.50	1.30	1.40
CaO	45.00	34.00	31.00	37.00	40.00	40.00	40.00	40.00	41.00	42.00	41.00
SiO_2	32.00	13.00	12.00	14.00	30.00	32.00	32.00	32.00	33.00	34.00	32.00
Cr_2O_3	6.00	13.00	28.00	11.00	10.00	10.00	9.60	9.50	8.00	6.70	8.50
MgO	6.00	3.00	2.60	3.10	4.70	4.80	5.00	4.90	5.00	5.00	4.80
MnO	3.00	2.90	2.80	3.40	5.40	5.40	5.40	5.40	5.00	4.80	5.50
Al_2O_3	3.00	3.70	6.40	3.10	3.70	3.00	2.80	3.10	3.30	3.70	3.60
TiO_2	2.00	0.40	0.50	0.50	1.80	1.90	1.90	1.90	1.90	2.00	1.90
Basicity	1.41	2.62	2.58	2.64	1.33	1.25	1.25	1.25	1.24	1.24	1.28
Slag after											
Fe_2O_3		17.00	16.00	23.00	2.70	2.00	2.40	1.40	1.00	1.20	1.40
CaO		33.00	32.00	35.00	37.00	40.00	40.00	41.00	42.00	42.00	41.00
SiO_2		12.00	13.00	14.00	28.00	31.00	31.00	31.00	36.00	36.00	33.00
Cr_2O_3		17.00	25.00	14.00	16.00	10.00	9.80	9.10	4.90	5.50	7.90
MgO		3.20	2.20	2.40	4.20	4.60	4.90	4.50	4.70	4.50	4.70
MnO		3.10	2.90	2.90	5.50	5.20	5.30	5.40	4.70	4.50	5.40
Al_2O_3		12.00	6.50	6.20	4.90	4.70	3.80	4.30	4.50	3.60	3.80
TiO_2		0.40	0.50	0.50	1.70	1.90	1.80	2.00	2.00	1.90	1.90
Basicity		2.75	2.46	2.50	1.32	1.29	1.29	1.32	1.17	1.17	1.24

Table 2 continued

Test No	11	12	13	14	15	16	17	18	19	20	21	22
Slag type +%Cr_2O_3	Avesta slag	Avesta slag	Avesta slag	Avesta slag	Avesta slag	Avesta slag	Avesta slag	Avesta slag	Avesta slag	Avesta slag	Avesta slag	Avesta slag
FeSi, kg	0.1		0.1	0.3	0.1	0.1	* 0.1 SiC!	0.1		0.3	* 0.3CaO!	0.2
Inj. Gas	Air	Air	N2	N2	N2	N2	N2	Air	N2	N2	N2	Air
Steelcal "S"+%C	Pure	0.3 kg "S" + 0.1 kg FeSi	Pure	Pure	S+20C	Pure	Pure	Pure	0.3 kg "S" + 0.1 kg FeSi	Pure	S+20C	S+20C
Steelcal quant.. kg	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.24	0.24
Note		Mixed "S" + FeSi				Inj. angle 45 deg.	0.1kg SiC		Mixed "S" + FeSi			
Slag height max. cm	4	3.5	5	6	3	10	4	6	3	9	10.5	7
Steel analysis												
C	0.64	0.52	0.56	0.65	0.57	0.55	2.73	0.81	0.61	0.59	0.07	1.03
Si	1.8	0.7	3.2	8.37	6.3	3.9	3.3	3.1	0.85	9.1	0.37	5.6
Mn	2.3	1.6	2.6	2.75	2.7	2	5.1	2.4	1.7	2	1.66	2.2
P	0.04	0.035	0.048	0.035	0.036	0.03	0.034	0.033	0.04	0.035	0.04	0.03
S	0.007	0.007	0.008		0.006	0.005	0.01	0.006	0.009	0.009	0.02	0.008
Cr	20.6	20.1	20.9	19.23	20.2	19.1	27.5	19.9	19.5	17.6	18.40	17.6
Ni	10.3	10.6	10	9.47	10	9.9	8.7	10	10.4	9.3	9.93	9.8
Al	0.01	0.01	0.01	<0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.16	0.01
Cu	0.13	0.13	0.12	0.1	0.12	0.13	0.1	0.13	0.14	0.12	0.14	0.12
Mo	0.17	0.17	0.17	0.16	0.17	0.16	0.13	0.16	0.17	0.15	0.17	0.15
Ti	0.01	0.02	0.02	0.17	0.03	0.01	0.4	0.03	0.02	0.07	0.56	0.05
Slag before	Avesta slag	Avesta slag	Avesta slag	Avesta slag	Avesta slag	Avesta slag	Avesta slag	Avesta slag	Avesta slag	Avesta slag	Avesta slag	Avesta slag
Fe_2O_3	2.1	2.2	2.9	1.4	1.8	1.3	0.9	1.5	2.1	1.1	2.6	1.1
CaO	39.4	39.9	36.8	40.8	40.7	41.1	41.2	40.4	40	41.8	53.3	42.1
SiO_2	34.1	32.4	36.4	35.3	33	33.9	37.5	34.1	31.8	37.5	24.4	35.1
Cr_2O_3	8.5	9.4	8.9	7.1	8.9	7.5	5.4	8.3	9.9	6.9	8	6.1
MgO	4.9	4.9	4.4	5	4.8	4.9	5.1	5	5.3	5	3.6	5.1
MnO	4.9	5.5	5.1	4.4	5.3	5	4.5	5	5.6	4.4	4	4.2
Al_2O_3	3.4	3	3	3.4	2.8	3.5	3.1	2.9	2.7	3.2	2.1	3.6
TiO_2	1.8	1.9	1.7	1.9	1.9	2	1.8	1.9	1.9	1.9	1.4	1.9
Basicity	1.16	1.23	1.01	1.16	1.23	1.21	1.10	1.18	1.26	1.11	2.18	1.20
Slag after												
Fe_2O_3	0.9	1	1.4	1.2	1.5	1.3	0.7	1.4	1.3	1	3.3	1.3
CaO	41.9	41.2	41.8	43.1	41.5	41.7	44.6	42.6	41.6	42.9	52.4	43.5
SiO_2	35	35.3	35.3	35.6	35.2	35.6	36.7	34.4	35	35.3	25.4	36.3
Cr_2O_3	5.3	5.9	5.7	5.5	6.3	5.7	3.2	6.5	6.8	5.8	8.1	4.3
MgO	4.6	4.5	4.6	4.4	4.7	4.7	4.7	4.5	4.2	4.6	2.7	4.6
MnO	4.3	5	4.4	3.7	4.5	4.5	3.7	4.8	5	4	3.8	3.6
Al_2O_3	5.3	4.7	4.4	3.8	3.8	3.9	4.4	3.1	3.4	3.7	2.4	3.6
TiO_2	1.9	1.9	1.9	2.1	2	2	1.7	2.1	2	2.1	1.4	2.1
Basicity	1.20	1.17	1.18	1.21	1.18	1.17	1.22	1.24	1.19	1.22	2.06	1.20

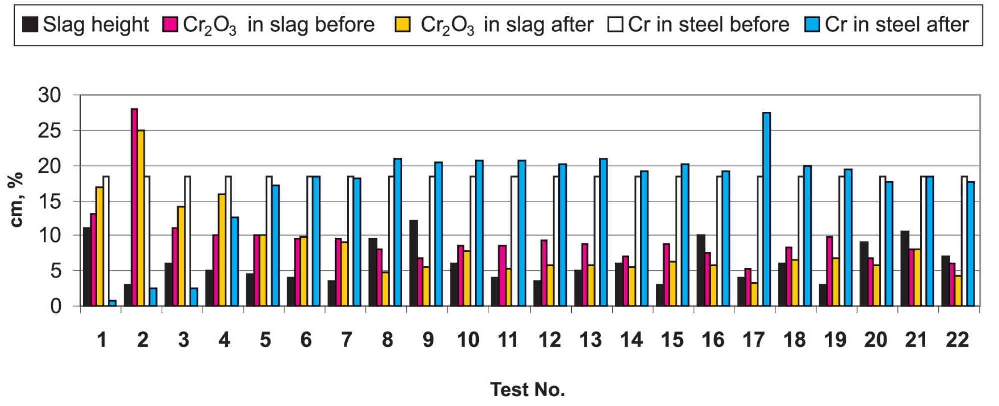

Fig. 4. *Achieved slag height in cm, % Cr_2O_3 in slag and % Cr in steel before and after Steelcal injection for the tests 1–22*

5. EVALUATION OF THE RESULTS

The best result (max slag height 12 cm, 4× original height) was obtained in test 9 when pure Steelcal was injected by nitrogen after modification of the Avesta slag by addition of some FeSi (3%). In this test the Cr_2O_3 content in the slag decreased from 6.7% to 5.5%, and the Cr content in the steel increased from 18.4% to 20.5%. The Cr recovery is caused by the FeSi addition, which also improved the foamability of the slag. The foaming, however, must be solely attributed to Steelcal as the only gas-developing agent.

Good foaming was also achieved in test 1 when carbon steel slag (Css) modified by adding 10% Cr_2O_3 was used, but most Cr in the steel seems to have been oxidised and entered into the slag. The oxidation of the chromium content in the metal bath may have taken place during the first phase of melting the steel, when there is very little slag in the crucible to protect the steel from air, and also by the reduction of FeO to Fe by oxidation of Cr. Foaming was, at least partly, due to the „well known" reaction between C and FeO giving CO. Thus „Fe_2O_3" is reduced from 28% to 17% in test 1.

In test 2, when 15% Cr_2O_3 was added, the concentration of Cr_2O_3 was probably too high for the slag to foaming. Kerr and Fruehan [3] found it very difficult to create the foam in slags with more than 15% Cr_2O_3. The moderate foaming in test 3 when only 5% Cr_2O_3 was added to the carbon steel slag was probably due to an increase in Cr_2O_3 content more than 11% Cr_2O_3 after melting. For all tests 1–3 with the modified carbon steel slag, the Cr_2O_3 content after melting was close or high as the limit of ca. 15% Cr_2O_3 for good foamability.

In the tests 4–7, different quantity of stainless steel slag from Avesta was used, and Steelcal(70%) + carbon (30%) was injected by air. Very little foaming was achieved. The viscosity of the slag seemed to be so low that the slag did not form stable foam, but the gas just passed through the slag as bubbles. In test 4, only half of the intended quantity of Steelcal + 30C was injected due to problems with the equipment (low injection pressure). The loss of chromium from the steel to the slag was considerable, indicating that Steelcal and air may have oxidized the steel, and that the carbon had not been an effective Cr recovery agent, not even in test 6, when additional pure C was injected after reduced quantity of Steelcal + 30C blowing was finished. Pure C did not create any more foaming either. In test 7, nitrogen replaced air as injection gas without any significant effect on Cr in steel and slag compared to test 6.

In the test 8 and 9, some (3.5%) FeSi was added to the slag, and very good foaming was achieved. In test 9, pure Steelcal was injected (no C), and 4 times increase in the slag level took place. In test 10, the quantity of FeSi and pure Steelcal was reduced, and foaming was also less intense.

The intention of tests 11–22 was to change several parameters in order to check the influence of these parameters and to optimize them.

In the tests 11–15, the Steelcal did not seem to enter the melt well, but instead floated on top of the melt before it decomposed. In this way gas from decomposition of Steelcal did not flow through the slag and couldn't contribute to foaming. The reason why this happened was most probably due to wear of the crucible, which made the volume larger and the beginning melt height lower. In combination with a relatively low angle of injection, the lower beginning melt height made it difficult for the Steelcal to enter the melt. This emphasizes that the injection technique is an important parameter. The results from the tests 11–15 are due to this not used in analyses of the parameters that influence foaming the most.

Due to the improper injection in the tests 11–15, the injection angle was changed from ca. 30^o to ca. 45^o in the remaining tests 16–22.

In test 16 it was attempted to repeat the good foaming in test 9 (12 cm), and this was accomplished satisfactorily since a slag height of 10 cm was achieved.

SiC was added to the slag in test 17 in order to see how this would influence the foamability of the Avesta slag, but the result was disappointing. The SiC burned vigorously in the crucible on the surface of the slag, and the slag height after Steelcal injection was only 4 cm. The Cr recovery was however very good as Cr in the steel increased from 18.4% to 27.5%, and the Cr_2O_3 content in the slag decreased from 5.4% to 3.2%. SiC seems to be a very efficient chemical for Cr recovery and also for adding heat in the form of chemical energy to the melt. This is difficult to explain (there is low Cr_2O_3 and high basicity – good foamability parameters). Maybe other parameters, such as the temperature of the melt/slag, had more extensive influence. Higher temperature will reduce the viscosity and hence the foamability and burning of SiC increased the temperature.

Air as injection gas was tried again in test 18 with the other parameters the same as in the successful tests 9 and 16, and the slag height rose from 3 cm to 6 cm. The Cr recovery was good, - Cr in steel increased from 18.4% to 19.9%.

In test 19, FeSi was mixed with Steelcal and injected into the unmodified Avesta slag. This gave no foaming. However, the Cr_2O_3 content was reduced from 9.9 to 6.9%. Possibly gasification of the Steelcal came too late to exploit the lower Cr_2O_3 levels. The foamability of the slag must probably be improved before Steelcal is injected.

Increasing FeSi addition to the slag was attempted in test 20 when 0.3 kg FeSi was added (10%). Foaming was again good (9 cm). The Cr percentage of the steel decreased from 18.4 to 17.6%, although the Cr_2O_3 content of the slag was reduced. However, the mass of metal was increased by Si (9.1% of Si). Thus, in spite of the decrease of Cr percentage content in the steel, the mass of Cr in the steel increased, and this is in line with the Cr_2O_3 reduction in the slag.

In industry tests, successful foaming had been achieved with a high basicity slag (basicity CaO/SiO_2 >2) [1]. A high basicity will give higher viscosity, which should be beneficial for the foamability. CaO was therefore added to the Avesta slag in test 21, giving a basicity of 2.18 before Steelcal injection, whereas for the other tests using the Avesta slag the basicity had been below 1.4. In test 21, a Steelcal + 20% C mixture was used, in an attempt to try neutralize the oxidizing effect of Steelcal. Foaming was good also in test 21, i.e. 10.5 cm slag height. As expected, the slag analysis did not change significantly, since no efficient reducing agent, such as FeSi, had been added. This result may indicate that at high basicities, Cr_2O_3 solid phase is not formed in the Avesta slag at concentrations around 8%. Then it does not seem to be necessary to add FeSi for reduction. However, only one experiment of this kind has been conducted, and it would be extremely interesting to study this case further.

In test 22 FeSi of 0.2kg was added to the slag and Steelcal + 20% C was injected by air. Foaming was moderate (7 cm). Again the % of Cr in the steel was reduced, as in test 20, but the total metal quantity was increased since the Si content increased (to 5.6% Si) as in test 20.

For an in-depth evaluation of the influence of various parameters, some tests are disregarded:

- tests 1÷3; since modified C-steel slag was used,
- tests 11÷15; since Steelcal did not enter the slag properly,
- test 17; since SiC was added to the slag and SiC burned above the melt.

For the other tests (4–10, 16, 18–20, 22) the influence of the Cr_2O_3 content of the slag on the foamability can be seen in Figure 5. The trend lines in figure 5 clearly indicate that a high content of Cr_2O_3 in the slag makes it difficult to foam it. This result is in line with other researchers, e.g. Kerr and Fruehan [3].

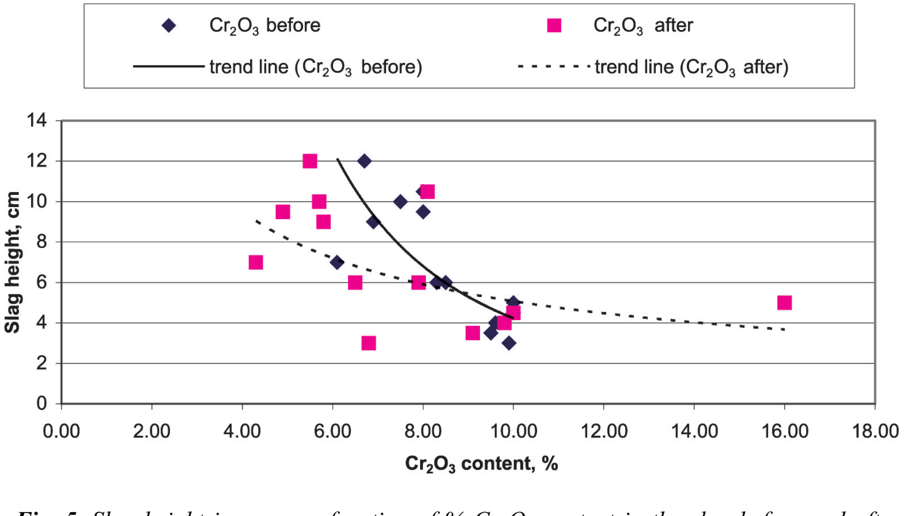

Fig. 5. *Slag height in cm as a function of % Cr_2O_3 content in the slag before and after Steelcal injection with trend lines*

Si addition to the slag as FeSi clearly reduces the Cr_2O_3 in the slag to Cr in the steel, increases the SiO_2 content and may improve the foamability by giving a higher viscosity.

For all the tests with Avesta slag, most of the carbon seem to have dissolved in the steel and thus did not contribute to foaming, but the C level in the steel also rose in the tests when no C was added. This C may have come from the crucible or from C in the FeSi and plays little role in producing foaming (except in tests1 and 3 with high values of Fe_2O_3 in the slag). It mainly dissolves in the steel (as indicated in test 17 when SiC was added and C in steel increased to 2.73%). Or it simply burns with air (this may have been the case in test 2 and 3).

In these tests only a narrow range of parameters, slag compositions and basicity have been studied. In earlier industry tests, however, Steelcal was able to foam slags with a wide range of chemical compositions and basicity ranging from 1.1 to 2.6. Also, a high basicity seemed to be beneficial [1].

6. CONCLUSIONS

Testing Steelcal as a stainless steel slag foaming additive in a laboratory furnace has been successful. The main objectives of the testing have to a large extent been achieved. Recreating the good slag foaming observed in industry tests has been possible. Knowledge of the influence of the most important parameters on the slag foaming has been acquired.

The laboratory experiments support the result in the literature that foaming is poor at high Cr_2O_3 contents-possibly corresponding to the presence of a solid Cr_2O_3 phase in the slag. For more than around 10% Cr_2O_3 significant foaming is not accomplished in the laboratory experiments when only adding Steelcal + 20–30 % carbon. To get good foaming at the high Cr_2O_3 levels a strong reductant such as FeSi must be added to the slag prior to the injection of Steelcal or Steelcal + carbon. These results are in good agreement with thermodynamic calculations and the literature information, which indicates that carbon does not reduce the Cr_2O_3 to Cr dissolved in the steel.

In the laboratory, the best results have been achieved with injection of pure Steelcal by nitrogen after Cr_2O_3 has been reduced and the slag viscosity has been modified by FeSi addition, but also mixing Steelcal with carbon has given good foaming. However, the results have not demonstrated that it is an advantage to add carbon to Steelcal when FeSi has been added previously to the injection of Steelcal.

Air may be used as an injection gas. FeSi addition seems to be the easiest to use and most efficient additive for Cr recovery, and this should be ready to apply in industry._The results indicate that it is important that the injected Steelcal penetrates the slag. Thus an angle between the injection lance and the horizontal of 45 degrees was better than 30 degrees in the laboratory, but this angle is depending on the dimensions of the crucible or furnace. With one exception good foaming was attained with a Basicity = $\%CaO/\%SiO_2$ in the range 1.1 to 1.4. Some interesting properties of SiC as an additive have been demonstrated, but how SiC should be applied has not been found yet.

The tests have confirmed some already known facts on what parameters influence foaming of stainless steel slags, such as the Cr_2O_3 content and viscosity, and also given some new information on how Steelcal works and can be utilized. There are, however, still some factors that should be pursued.

The effect of the various reducing agents that may be added to the slag (C, FeSi, SiC) is not fully understood, and should be a scope for further research.

Slag composition variation and modification should also be examined by using slag from various steelmakers.

The slag viscosity and other properties should be modified by adding various quantities of SiO_2 or CaO.

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In the laboratory, the best results have been achieved with injection of pure Steelcal by nitrogen after the slag viscosity has been modified by FeSi addition, but also mixing Steelcal with carbon has given good foaming. Air may be used as an injection gas. FeSi addition seems to be the easiest to use and most efficient additive for Cr recovery, and this should be ready to apply in industry. The interesting properties of SiC as an additive have been demonstrated, but how SiC should be applied has not been found yet.

Continued tests are recommended on the subject of combining Steelcal with various types and quantities of reducing agents and slag additions in slags of various compositions.

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