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Reduction of chromium oxide containing slags using CaC_2 injection

J. BJÖRKVALL*, S. ÅNGSTRÖM*, and L. KALLIN†
**MEFOS–Metallurgical Research Institute AB, Luleå, Sweden*
†Sandvik Materials Technology, Sandviken

In this paper results from industrial trials of CaC_2 injection during stainless steel production in an electric arc furnace at Sandvik Steel is presented. The main purpose of the investigation was to analyse the effect of the injection on slag foaming and final chromium oxide concentration in slag. The results show that both an increase in slag foaming and a decrease of the final chromium oxide could be obtained during the charges with CaC_2 injection. On the basis of the results, the economical requirements are also discussed. Both the technical and economical requirements could be achieved for steels alloyed with Mo. In order to secure the economical requirements for all steel grades of interest, the injection technology must be further developed. It would also be important to utilize the positive effect of the slag foaming on the electric energy consumption. The work has been performed as a part of MEFOS frame research programme with participants from Sandvik Steel, AKZO Nobel and AvestaPolarit.

Keywords: stainless steel, EAF, slag foaming, injection, CaC_2

Introduction

A research project has been performed as a part of MEFOS frame research programme with participants from Sandvik Steel, AKZO Nobel and Avesta Polarit. The main purpose has been to investigate the effect of CaC_2 injection on the overall slag performance during electric stainless steel production. During the melting of stainless steel scrape in the electric arc furnace, EAF, it is not possible to avoid some oxidation of chrome metal into the slag. It has been reported that roughly 97% of chromium losses during scrape based stainless steel production occurs in the EAF[1]. This oxidation will not only decrease the chrome exchange in the EAF, but it will also have negative effect the overall performance of the scrape melting process as well as obstructing the slag to be used as recirculation material due to the environmental problems occurring from the high chromium content in the slag. It is therefore important to prevent the chrome oxidation from the scrape and reduce the chromium content in the slag using a reduction agent. A high chromium content in the slag will also lead to a crusty non-reactive slag, which prevents the formation of a foaming slag and this gives problems with the overall performance of the melting process in the EAF.

The most common way to control the chromium content in the slag is by adding a balanced quantity of ferrosilicon when charging the furnace. Silicon will oxidize before chrome and therefore decrease the chromium content in the slag. This positive effect of silicon oxidation will continue during the entire melting process. During the furnace tapping there will be a vigorous mixing between slag and liquid metal and even further chromium oxide will react with remaining silicon in the metal, lowering the final Cr_2O_3 content. After tapping a final silicon content of ~0.2% in the metal is stated as an optimum concentration.

There are, however, some drawbacks connected with the addition of ferrosilicon. The main problem is that lime must be added to the slag in order to maintain the slag basisity at reasonable levels, CaO/SiO_2, 1.3–1,7. Consequently the total slag amount will increase and this will lead to proportionally larger chrome losses. Another complication with ferrosilicon addition is that amount of the addition must balance the chrome oxidation during the melting. This can be somewhat difficult to estimate as it depends on the quality of the scrape charge to the furnace as well as the steel type produced. If the addition is too small a final Cr_2O_3 content higher then 10% is not unusual. If on the other hand the addition of ferrosilicon is too high this leads to high Si content in the liquid metal and large amounts of slag in the following converter process.

One alternative to ferrosilicon additions is the use of carbon powder injection in order to reduce the chromium in the slag. A substantial benefit of carbon powder over ferrosilicon is the lower price and the fact that the reduction product carbon monoxide gas does not aeffect the total slag amount. The method using carbon injection is not without problems. In order to get an efficient reduction of Cr_2O_3, high temperatures in the slag have to be obtained. This is accomplished by combining the carbon powder injection with injection of oxygen. A practical compromise between these two reduction methods is that it only partly exchanges the ferrosilicon with carbon powder injection. This would lead to gas generation in the gas, which is an important prerequisite to form a foaming slag. The slag foaming may also increase the exchange reaction between silicon chromium.

Taking the technology used today into account, the procedure with calcium carbide injection stands out as an interesting alternative compared to the reduction agents ferrosilicon and carbon powder. When CaC_2 reacts with an oxide, lime is one of the reaction products and this will not lower the basicity, as is the case when using ferrosilicon. Carbon oxide gas is also one of the reduction products and this could improve the slag foaming similar to the situation with carbon powder. It has therefore been the focus of this research activity to investigate the possibilities of substituting carbon powder and ferrosilicon additions with CaC_2 injection during the melting process in the EAF.

Background

During the operation of an EAF an early formation of a liquid slag is desirable in order to improve the process and electrical efficiency. The formation of a liquid slag will reduce the effect of arc radiation, slag splashing onto refractories and water cooled panels, and decrease electrode consumption. By forming a foaming slag, this positive effect of a liquid slag may be further enhanced resulting in a higher productivity and lower tap-to-tap time. Slag foaming is normally described as a process with two basic demands, powerful gas generation in the slag combined with a suitable slag viscosity. The slag viscosity should not be to low as this would give a short hold-up time for gas bubbles in the slag and thus prevent the possibility sustaining an adequate foam. Similarly, if the slag viscosity is too high no foaming slag can be formed.

In the production of low alloy carbon steel by the EAF, route oxygen is injected to form a slag with good foamability. Iron oxide formed by the injection will react with injected carbon powder, providing both a reduction of FeO and the formation of CO gas. This will lead to good slag foaming during the melting process. This strategy to increase the foamability of the slag is not accessible in stainless steel making as the chromium losses to slag would not be acceptable. Further complicating the situation for stainless steel producers is the fact that Cr_2O_3 has a high melting point and a low solubility in $CaO\text{-}FeO\text{-}SiO_2$ slags. The solubility of Cr-oxide in the slags present in the EAF is between 3 to 6 wt%[2] at temperatures normally reached in the furnace. It is therefore of great importance to reduce chromium in combination with gas formation in the slag. This may be achieved by using a reduction agent that forms gas as a reduction product e.g. carbon powder or CaC_2.

Finally, it has been shown that the reduction of chrome oxide is facilitated by the presence of metal drops in the slag phase[3]. Chrome metal formed by the reduction reactions may then go into solution in the present iron droplets and therefore prevent the undesirable formation of solid chrome metal in the slag.

Thermodynamics

As previously mentioned, Cr_2O_3 is normally reduced by silicon or carbon addition to the EAF. The reduction reactions involving chromium, silicon and carbon may be represented as:

$$Cr_2O_3 + 1.5Si = 2Cr + 1.5SiO_2 \qquad [1]$$

$$Cr_2O_3 + 3C = 2Cr + 3CO(g) \qquad [2]$$

Reduction of chromium with calcium carbide may be described by the following reaction:

$$Cr_2O_3 + CaC_2 = 2Cr + 2CO(g) + CaO \qquad [3]$$

The Gibbs energies[4] dependence on temperature for this reduction reactions are presented in Figure 1. From the figure it is clearly seen that reduction of chromium with carbon is favoured by a high slag temperature. The increase in temperature necessary for the reaction is accomplished by oxygen injection as mentioned earlier. The reaction between silicon and Cr_2O_3 does not show as strong temperature dependency and may propagate at lower temperatures. The suitability of CaC_2 as a reduction agent is clearly indicated in the figure as the reaction between CaC_2 and Cr_2O_3 shows the lowest Gibbs energy in the temperature span ~1550°C to ~1850°C.

It is of special interest to compare the energy need for reduction of chromium with calcium carbide and reduction of iron oxide with carbon. Calculated per amount of formed gas, the energy need is in the same size range. In analogy with the melting process of carbon steel, it could therefore be assumed that a foaming slag would be able to transport the necessary energy to the reaction surface between carbide particles and slag.

Pre trial investigation at the EAF in Degerfors

A first attempt to reduce chromium with calcium carbide was conducted in the EAF in Degerfors[6]. The study included 10 charges where carbide bags of 5 kg were thrown through the slag door. The addition, approx. 7 kg/tonne steel, was carried out during the last 10 minutes before tapping. Four of these charges showed good slag foaming and for two of these charges a final Cr_2O_3 content in the slag as low as 0.68 wt%. The results from this investigation were found to be promising even if the number of observations was quite small.

Experimental procedure

The electrical furnace at Sandviken is used to manufacture a wide range of different steel qualities including low-alloy materials, stainless- and acidproof-steel. The yearly production is about 200 ktonne. The main part of the produced material is decarburized in an AOD converter followed by subsequent treatment in a ladle furnace and is finally continuous cast to blooms. The main data of the

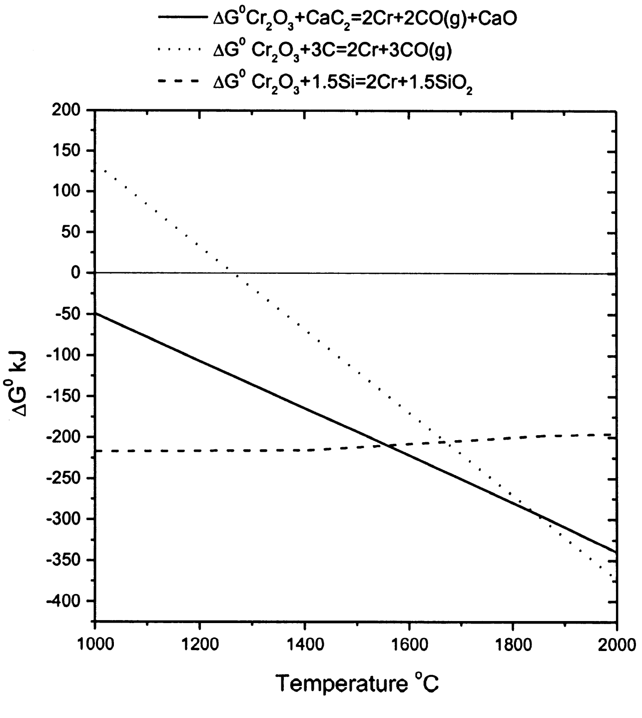

Figure 1. Temperature dependence of Gibbs energies for chromium reduction with calcium carbide, carbon and silicon[4]

EAF at Sandviken are presented in Table I. The melting profile from the electric furnace used in Sandviken is presented in Figure 2. The experiments were carried out using a MEFOS portable powder dispenser and injection equipment. A station for emptying turnbins and, transport containers for CaC_2, constructed by AKZO Nobel, were employed during the experiment in order to assure safe and practical filling of the powder dispenser. A schematic figure of the experimental equipment is show in Figure 3 and the data of the equipment are presented in Table II. An additional lance was assembled on the existing lance manipulator to ensure practical operation of the carbide injection.

Security considerations

The fact that calcium carbide will form acetylene gas if exposed to moisture necessitates special security arrangements. The experimental equipment was mounted and the operational staff were trained in the handling praxis. After some initial trials the experiments were performed by the personnel at Sandviken during the day shift.

Realization and results

In connection to the experimental data collection, data from charges using normal praxis were also collected to be used as reference. A total of three trial campaigns was performed using different injection feed rates of carbide and different reduction praxis. During the experimental series the effect of calcium carbide injection was investigated for five different steel grades, presented in Table III.

Initial trials

The opening experimental series was conducted with the main goal to give experience of the technology and to get a rough understanding of the metallurgy aspects of the injection. In this trial set, normal amounts of ferrosilicon and carbon powder were added to the furnace in combination with CaC_2 injection. Finally, the introductory trials were completed with some experiments where the possibilities of catalysing the reduction reactions were investigated using further additions. A compilation of the results from the first trials is presented in Table IV and an explanation of the different conducted experiments is given in Table V. Total data from 43 experimental charges and

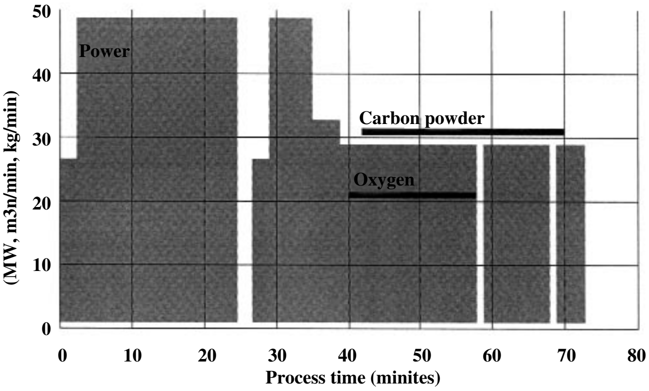

Figure 2. Melting profile of EAF in Sandviken

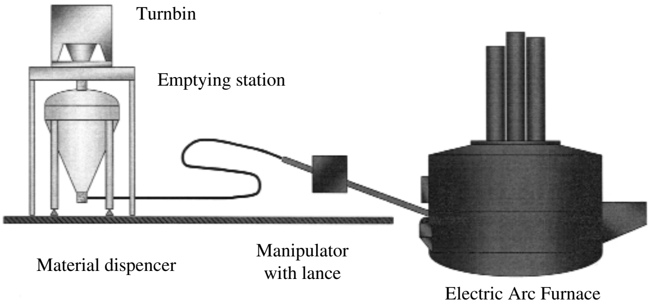

Figure 3. Schematic figure of the experimental equipment, EAF in Sandviken

Table I
Furnace data of the EAF in Sandviken

Construction year	1973
Modernization	1994
Supplier	ABB
Type	AC, conventional tapping
Charge capacity	80 tonne
Inner diameter	5.6 m
Furnace volume	70 m³
Electrode diameter	500 mm
Transformer:	
Capacity	50/60 MVA
Secondary voltage, max	855 V
Lance manipulator	BSE, oxygen gas and carbon powder with consumable lances
Steering	3 porous plugs
Charging	2 baskets
Key factors:	
Energy consumption	500 kWh/tonne
Tap-to-tap time	115 min
Power on time	75 min
Carbon powder	10 kg/tonne
Oxygen gas	5 m3n/tonne
Lime consumption	37 kg/tonne

Table II
Data of experimental equipment

Turnbins:	
Volume	1.5 m^3
Weight, capacity	1800 kg carbide
Material transmitter:	
Volume	3 m^3
Injection host inner diameter	32 mm
Injection lance carbon steel inner diameter	36 mm
Injection gas	Argon

Table III
Steel grades

1	Steel 18.8 type
2	Special steel without Mo
3	Steel 18.8 with Mo
4	Special steel with Mo
5	Cr-steel 13–20% Cr no Ni

Table IV
Results from the initial experiment

Exp. no.	Charge	Steel grade	Type exp.	Added carbide (kg)	kWh/ton total load	Temp. läppsk. (gr C)	Oxygen ğas (Nm^3)	C total (kg)	Steel 52			Slag			
									C (%)	Si (%)	Cr (%)	FeO (%)	MnO (%)	Cr_2O_3 (%)	Bas.
1	451172	1	Inj	230	497	1650	442	712	1.55	0.02	16.95	1.2	0.9	2.1	1.69
2	451174	1	Inj	210	450	1646	399	362	1.23	0.01	17.93	1.2	1.9	4.2	1.62
3	451210	5	Inj	570	446	1622	442	318	1.55	0.28	11.83	2.8	0.6	2.4	1.67
4	451211	5	Inj	570	501	1680	458	448	1.88	0.15	12.67	1.6	0.5	1.3	1.67
5	451248	3	Inj	531	517	1697	439	626	1.22	0.08	21.47	1.1	0.3	0.8	1.96
6	451249	3	Inj	540	523	1699	305	796	1.37	0.07	17.15	1.2	0.7	1.1	1.79
7	451250	3	Inj	524	513	1701	323	804	1.38	0.01	16.63	1.3	1.5	2.2	1.64
8	451260	4	Inj	520	521	1654	390	948	2.23	0.01	29.72	3	1.4	7.3	1.60
9	451261	1	Inj	547	540	1692	359	846	1.39	0.09	19.05	1.8	0.6	2.2	1.71
10	451262	1	Inj	530	502	1660	364	724	1.35	0.05	18.2	1.2	0.6	1.4	1.66
11	451269	1	Inj	535	558	1713	349	764	1.46	0.07	17.5	1.9	0.4	1.4	1.96
12	451270	3	Inj	530	516	1679	365	720	1.03	0.22	15.56	1.4	0.4	1.2	1.92
13	451271	3	Inj	535	516	1715	361	700	1.13	0.07	15.73	1.1	0.6	2.3	1.73
14	451285	1	Inj	540	545	1643	382	514	1.5	0.12	20.74	2.7	1.3	12	2.25
15	451286	2	Inj	540	556	1656	410	558	1.36	0.02	24.12	2.5	1.3	9.2	2.09
16	451287	1	Inj	520	512	1662	416	584	1.13	0.01	16.69	1.7	1.3	3.6	1.77
17	451318	3	Inj	540	490	1633	349	752	1.13	0.05	16.39	2.1	2	6.8	2.08
18	451319	4	Inj	540	487	1609	429	798	1.62	0.09	25.3	1.1	0.8	3.7	1.93
19	451320	3	Inj	520	496	1655	339	762	1.54	0.12	16.39	1	0.6	1.7	1.81
20	451330	3	Inj	540	467	1702	350	764	1.48	0.13	17.34	1.1	0.9	2.1	1.53
21	451331	3	Inj	540	488	1721	396	756	1.38	0.07	16.23	1.1	0.7	1.2	1.62
22	451332	4	Inj	520	492	1630	376	574	1.8	0.04	0.85	2.3	2.2	9.4	1.40
23	451349	5	Inj	540	493	1640	529	574	1.78	0.01	15.46	4.1	1.6	4.5	1.57
24	451350	5	Inj	540	488	1627	441	634	2.17	0.04	18.91				
25	451351	5	Inj	520	469	1634	428	506	1.55	0.06	12.26	3.3	1.1	4.9	1.57
26	451362	1	Inj	540	544	1684	402	746	1.47	0.07	17.16	2.5	0.6	1.9	1.89
27	451363	1	Inj	540	459	1623	364	752	1.35	0.16	17.29	1.6	0.6	1.8	1.81
28	451364	1	Inj	520	489	1635	395	710	1.33	0.07	17.44	1.4	0.5	1.3	1.88
29	451424	5	Inj	540	462	1612	356	440	1.69	0.03	13.64	2.5	1.1	3.4	1.44
30	451425	5	Inj	540	470	1643	350	514	1.74	0.16	12.43	1.3	0.3	0.7	1.55
31	451426	5	Inj	520	470	1610	480	514	1.76	0.06	15.38	2.9	0.6	3.4	1.60
32	451551	4	Inj, Rjg 40	560	484	1640	396	768	1.74	0.02	24.94	1.2	1.4	5.7	1.29
33	451552	1	Inj, SiC 50, Rig 40	520	449	1575	367	762	1.41	0.31	17.69	0.9	0.8	1.1	1.50
34	451553	1	Inj, Rjg 130	520	481	1627	407	534	1.14	0.1	17.63	1.8	1.9	3.5	1.29
35	451554	1	Inj, SiC 100, FeO 40	540	550	1616	269	342	1.2	0.09	18.03	1	1.8	2.9	1.40
36	451555	1	Inj, FeSI 80	540	533	1654	451	732	1.35	0.03	18.2	1.8	1.7	4.1	1.52
37	451556	1	Inj, SiC 50, FeSi 80	520	485		366	720	1.52	0.15	17.84	1.2	1	1.6	1.53
38	451582	3	Inj, CaC_2 25-50 200	740	520	1649	356	808	1.36	0.05	16.77	2.4	1.1	2	1.86
39	451583	3	Inj, CaC_2 25-50 200	740	539	1702	470	844	1.37	0.04	16.62	1.5	0.9	1.4	1.61
40	451584	4	Inj, CaC_2 25-50 200	720	472	1651	345	838	1.1	0.01	19.9	1.5	1.3	6	1.62
41	451591	3	Inj, CaC_2 4-7 166	710	474	1645	367	806	1.51	0.12	17.13	1.4	0.9	1.4	1.70
42	451592	3	Inj, CaC_2 4-7 166	710	484	1664	388	860	1.32	0.19	17.25	1.4	0.6	1.6	1.93
43	451593	3	Inj, CaC_2 4-7 166	690	479	1644	394	746	1.49	0.23	15.61	0.7	0.1	0.4	2.13

data from 113 reference charges were collected. The final chromium content varied with the different steel grades manufactured. This could partly depend on effects from alloys additions. It was also found that the ejector of the material transmitter limited the feed speed of calcium carbide. This restricted the reaction velocity in the slag and therefore the ejector was changed to a type with 3 times greater capacity.

The results from the 18:8 steel (type 1) shows a modest difference between the carbide and reference charges. The foam formation on the other hand was found to be somewhat stronger for the carbide charges than for the reference charges. The lower final chromium content for the experimental charges does not correspond to the larger amount of reduction agent added to the charges. A total of 14 experimental charges was performed for this steel grade and they are compared with 56 reference charges in Figure 4. In the figure the charges are in chronological order and charges for other steel types, as well as charges without analysis, are not presented.

Table V
Different experiments

Experiment types	
Inj	Injection of CaC_2
Rjg	Crude iron granular with bags 4 kg
FeSi	Ferrosilicon with bags 2 kg
SiC	Silicon carbide with bags 2 kg
CaC_2 25–50	Calcium carbide in barrel 25–50 mm, 100 kg
CaC_2 4–7	Calcium carbide in barrel 4–7 mm, 83 kg

The results for 18:8 steel alloyed with Mo (type 3) shows

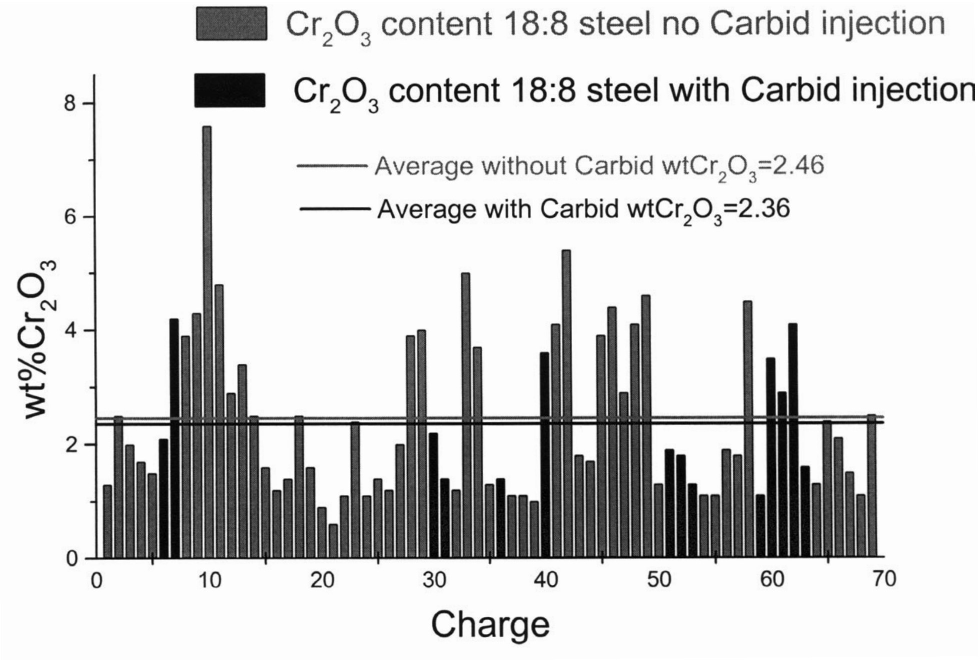

Figure 4. Final chromium content in slag for 18:8 steel without Mo (type 1)

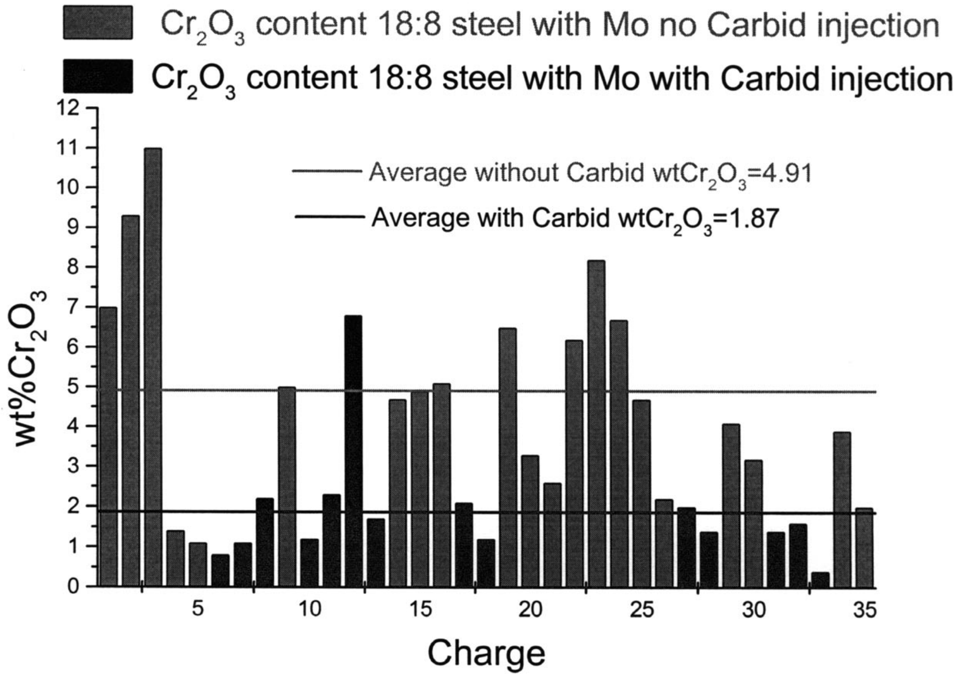

Figure 5. Final chromium content in slag for 18:8 steel with Mo (type 3)

a more positive picture with respect to the final chromium content. An apparent improvement of the chrome exchange is observed. The results are even better than the result for the corresponding 18:8 steel, which is clearly seen in Figure 5. A part of the explanation may be due to the uncertainties in the quality of charge scrape and alloying material. Another contribution to the improved results could be the fact that the total amount of reduction agent added to these steels (type 3) is larger than the amount added to the 18:8 steel charges. The average value of added reduction agent to the reference charges for both steel types is ~62 kmol/charge. The value for the carbide charges is 71 kmol/charge for the 18:8 steel and 83 kmol/charge for 18:8 steel alloyed with Mo. This could probably also explain the positive results for Mo alloyed steel. The final chromium content shows a cyclic variation probably ascribed to variations in the quality of the charge scrape. That this is the case may be seen in Figure 6 where the results of the final Cr_2O_3 content from all charges are presented in chronological order. Generally, the results for the other steel grades are positive for the final chromium content but the low number of charges for each steel grade makes it difficult to perform any further analysis of the results. For example, only one charge with carbide injection and 6 reference charges were accessible for the special steel without Mo, type 2.

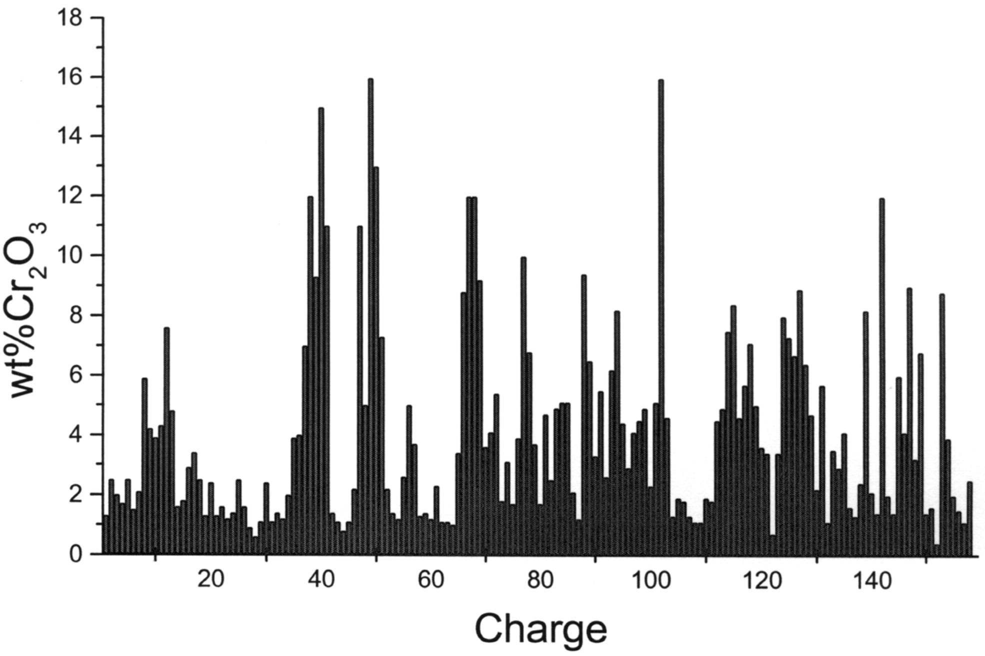

Figure 6. Final chromium content in slag for all reported charges in chronological order

The injection of calcium carbide had to start early, during the over heating period when oxygen is also injected due to a low material feed of CaC_2, < 40 kg/min. This awakened the suspicion that there could be a risk of calcium carbide reacting with oxygen gas instead of oxides in the slag. In order to corroborate this doubt, calcium carbide in barrels was charged in the furnace for three charges. The addition was done just before tapping and resulted in powerful slag foaming in combination with a substantial reduction of the final chromium content. Therefore the material transmitter ejector was replaced with a new one with greater capacity. The maximum material velocity was increased nearly three times with the new equipment.

Trials with higher injection rate, series 1 and series 2

The replacement of the ejector meant that a material feed of over 100 kg/min of calcium carbide could be achieved during the injection trials. Consequently, the carbide injection could start at a later stage of the process after the oxygen injection.

During the first trials with the new equipment, series 1, nine trials were performed and compared with 18 reference charges. The results were considerably improved for the trial heats, with lower final chromium content and also better slag foaming. However, the total amount of reduction agent added during this trials was somewhat larger then for the earlier trials and this could to some extent explain the better results obtained. An additional experimental series was performed to investigate how the amount of reduction agent affects the slag foaming and final chromium content. Extra slag samples were taken as:

- Slag sample 1. After ~150-200 Nm^3 oxygen, before carbide injection
- Slag sample 2. After completion of oxygen injection, (~400 Nm^3), approx. half carbide
- Slag sample 3. Immediately before tapping
- Slag sample 4. Sample in transport ladle.

During these trials the carbide content in one turnbin was evenly distributed between two charges, 800 kg per charge. The first six charges were carried out without any carbon powder injection. The injection of calcium carbide started when ~150–200 Nm^3 of oxygen had been injected, approx. 20 min. before tapping. The carbide was then injected in small portions until tapping. The amount of added ferrosilicon was also reduced for some charges. The total amount of reduction agent is significantly lower for this trial than for those previously performed, in the size range of 25 kmol/charge. Unfortunately, these six experimental charges were of different steel grades, which makes an elaborated analysis difficult as it has been shown earlier that the final chromium content varies considerably among different steel types. A result from these charges with only carbide injection, was a lowering of the carbon (~0.2–0.4%) content in the steel at the AOD converter. This shows that a large amount of the added carbon will not react with oxides in the slag but rather alloy the steel with carbon.

In order to somewhat compensate for the lower amount of reduction agent, the following four charges were completed with carbon addition until the carbide injection was started and no reduction of the ferrosilicon additions was made. Approximately 300 kg carbon powder was added for each charge. Roughly 50 kmol/charge of reduction agent was added for these trials, which is lower than for the initial trials. The average final chromium content was 6.1 % which is higher than the result observed earlier.

Finally, two charges were accomplished with full a carbon powder addition of approx. 750 kg and an addition of 800 kg carbide. For these two charges a total amount of reduction agent of ~85 kmol was added. This is only marginally higher than the amount of reduction agent added during the initial trials for steel type 3, 18:8 with Mo. A somewhat lower final chromium content was accomplished compared to the previous charges in the series, but the result from the earlier trials produced an even lower final chromium content. This could depend on cyclical variations in the final chromium content observed during the initial trials.

As mentioned earlier four extra slag samples were taken for the 12 charges with carbide injection and also for 2 reference charges. The results from these samples are presented in Table VI. The information from the different slag samples gives a possibility to investigate the efficiency of the different reduction agents used, carbon, calcium carbide and a combination of carbon and CaC_2. In Figure 7 the chromium reduction in the slag between slag sample 1 and slag sample 4 is presented as a function of the total amount of reduction agents supplied. In the Figure the different steel types produced during the trials are indicated to distinguished the results of the reduction between different steel types. The low number of charges performed makes a thorough analysis somewhat difficult. However, the calcium carbide shows the highest efficiency as reduction agent of chromium in the slag, independent of investigated steel type. Most of the charges with combined injection of carbon and carbide were carried out with Mo alloyed steel, steel type 3, and display a low reduction of chromium in the slag, especially in comparison with the result of the charges with only carbide for the same steel type. Finally, it is clearly seen in the Figure that for charges with only carbide injection, the chromium is reduced by 90% for 18:8 steel with a low addition of reduction agent, ~25 kmol/charge. Furthermore, these results shows that calcium carbide has not to any greater extent reacted with the injected oxygen.

Discussion

Slag foaming is favoured by high gas generation in the slag in combination with a suitable slag viscosity. The slag foaming has been better for most of the charges using calcium carbide injection. This may be due to the more efficient reduction of chromium in the slag with calcium carbide, offering a reduction of the slag viscosity in combination with gas generation. Normally, the melting starts with a crusty non-reactive slag with high concentration of CaO and Cr_2O_3 in combination with low concentration of silicon. During carbon powder injection, chromium will be reduced at the same time as silicon from the added ferrosilicon is oxidized which leads to a lower slag viscosity. This means that it will take some time before

Table VI
Slag analyses for the different slag samples

Charge number		452086	452087	452208	452210	452259	452260	452261	452269	452270	452352	452353	452363	452364	452377
Slag sample 1	%SiO_2	26.6	13.4	17.8	24	22	18.3	22	21	24	27	22	21	21	20
Before CaC_2	%Al_2O_3	4.9	5.6	3.5	2.6	4	3.1	3.4	4.2	4.6	4.2	4.7	5.5	4.9	4.4
addition	%FeO	6.7	16.1	8.8	6.1	7.5	11	5.2	16	4	3.7	3.6	5.9	7	16
O_2 blown	%MnO	3.3	2.2	4.8	5.4	4.5	7.6	5.4	7.2	5.1	2.7	3.4	4.1	3.8	3.8
150–200 Nm^3	%CaO	38.7	20.2	29	31	35	27	37	25	37	39	38	28	30	30
	%MgO	9.2	6.2	11	11	5.6	4.4	5	5.5	6.1	7.8	11	16	12	5.5
	%TiO_2	0.9	0.38	1	1.1	2.8	1.4	1	1.4	1.3	1.4	1.5	1.6	1.3	3.6
	%Cr_2O_3	14.1	34.4	23	20	18	30	17	26	14	18	15	20	22	19
	CaO/SiO_2	1.45	1.51	1.63	1.29	1.59	1.48	1.68	1.19	1.54	1.44	1.73	1.33	1.43	1.50
Theoretical slag weight		4738	11787	8022	7763	6467	8270	7758	8742	6201	6244	5823	8546	8010	7976
Slag sample 2	%SiO_2	31	18.3	18.7	23	23	21	23	24	26	29	21	19.8	23	23
End of O_2	%Al_2O_3	5.4	9.5	3.6	2.9	4.3	3.6	3.6	5.7	4.8	4.1	5.3	5.6	5.2	5.7
blow	%FeO	2.3	9.7	5.2	4.3	2.4	6.4	5.7	5.2	4	2.9	3.2	6	4.1	9.7
	%MnO	2.6	1.6	4.5	4.5	3.7	6.1	5.6	5.4	5.4	2.3	3.3	3.8	3.4	4
	%CaO	45.3	33.3	32	36	43	37	38	38	39	44	42	31	38	33
	%MgO	9.8	7	11	8.5	5.8	4.7	5.5	7.6	6.2	7.7	14	16	13	6.3
	%TiO_2	0.9	0.51	1	1.2	2.9	1.3	1	1.5	1.4	1.3	1.4	1.5	1.3	4.4
	%Cr_2O_3	6.5	24.2	21	17	12	21	18	15	15	10	11	17	14	15
	CaO/SiO_2	1.46	1.82	1.71	1.57	1.87	1.76	1.65	1.58	1.50	1.52	2.00	1.57	1.65	1.43
Theoretical slag weight		5005	8315	7959	7644	6332	7130	7554	6677	6746	6018	5962	8642	7243	7251
Slag sample 3	%SiO_2	31.2	23.6	20	25	24	23	24	24	27	28	22	19.3	23	26
Immediately	%Al_2O_3	5.4	11.7	4.1	3.4	4.5	4	3.6	5.6	4.9	4.3	5.6	5.6	5.5	5.2
before tapping	%FeO	1.2	3.6	4.9	2.5	1.5	3.1	4.6	2.1	2.1	2.6	4	5.5	4.5	8.6
	%MnO	1.4	1.4	4.2	4	2.1	4.4	5.3	3.2	4.3	2	2.3	3	2.9	3.7
	%CaO	49.1	41.3	39	43	50	37	40	38	44	47	45	37	39	37
	%MgO	9.5	7.5	12	9.8	7	6.1	5.8	9.2	7.2	7.8	13	15	13	7.7
	%TiO_2	0.83	0.6	1.1	1.3	2.7	1.1	1	1.2	1.3	1.2	1.3	1.5	1.2	3.9
	%Cr_2O_3	2.6	11.4	18	12	6.4	14	16	7.4	11	9.3	6.9	13	13	10
	CaO/SiO_2	1.57	1.75	1.95	1.72	2.08	1.61	1.67	1.58	1.63	1.68	2.05	1.92	1.70	1.42
Theoretical slag weight		5180	7528	7703	7359	5935	8025	7176	7696	6797	6769	6491	8510	7915	6467
Slag sample 4	%SiO_2	31	24.7	22	27	26	27	29	27	30	31	26	24	25	33
In transfer ladle	%Al_2O_3	6.2	11.7	11	3.8	4.9	4.9	4.3	5.6	5.3	6.1	7.1	6.6	6.2	6.7
	%FeO	0.9	1.9	1.7	1.5	1.3	1.6	1.4	1.8	1.5	1.4	1.8	2.4	2.3	1.4
	%MnO	0.9	1.1	2.3	2.9	1.6	3.9	3	2.8	3.4	1.4	2.2	3	2.8	1.8
	%CaO	48.9	42.5	42	43	48	43	47	42	43	48	45	41	42	46
	%MgO	10.1	9.2	14	11	8.4	7.2	7.5	9.6	8.4	8.2	12	15	13	10
	%TiO_2	0.9	0.62	1.2	1.3	2.6	1.5	1.1	1.4	1.4	1.3	1.3	1.5	1.3	3.9
	%Cr_2O_3	1.7	7.5	8	8.5	4	13	7.8	6.7	6.2	3.8	4.1	7	7.1	2.6
	CaO/SiO_2	1.58	1.72	1.91	1.59	1.85	1.59	1.62	1.56	1.43	1.55	1.73	1.71	1.68	1.39
Theoretical slag weight		5202	7315	7153	7359	6182	6905	6107	6963	6955	6628	6491	7680	7350	5202

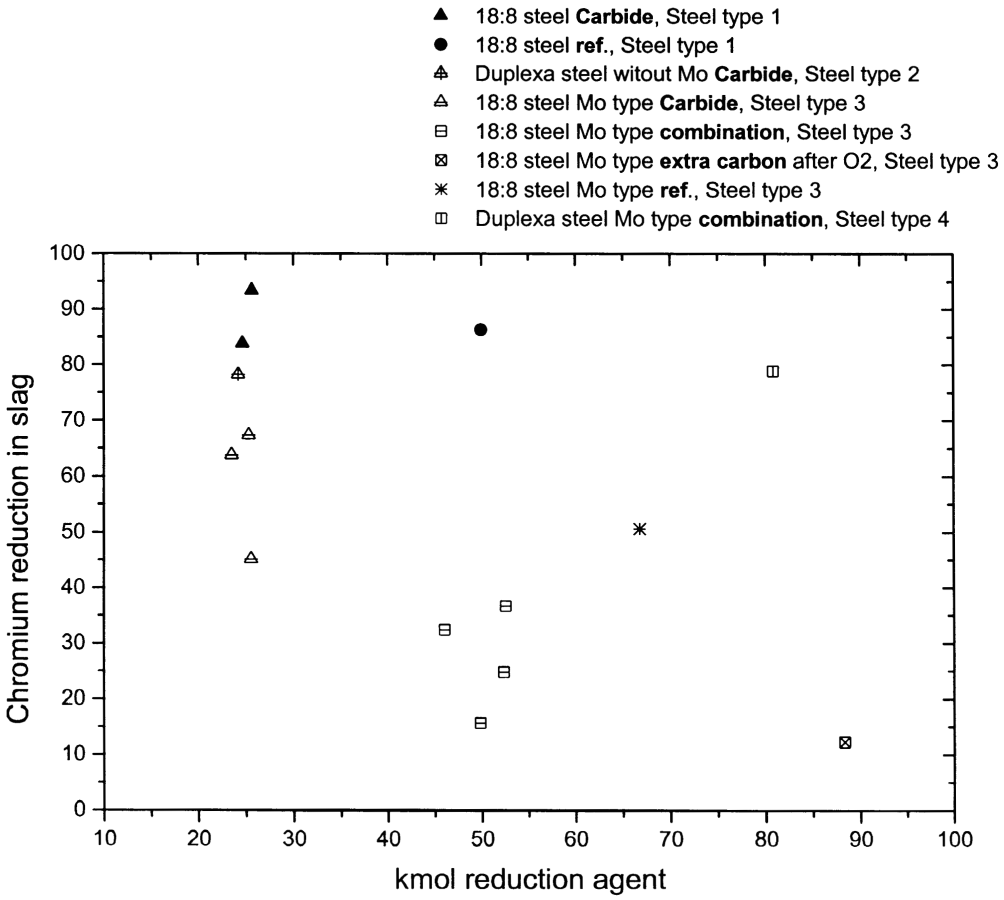

Figure 7. Chromium reduction in the slag as a function of the total amount of added reduction agent

a suitable slag with good foamability is formed. In the case of the trial charges, the injected calcium carbide will simultaneously alter the slag composition and generate gas. This could lead to a shorter time before the condition for slag foaming is fulfilled. Another aspect of the better foamability observed could be the fact that the reduction of chromium with carbide does not consume as much heat as the reaction between carbon and chromium. This would give a higher slag temperature during the trial charges than in the normal case.

The energy consumption has increased for the trial charges with carbide injection and consequently this has lead to an increase in power-on time. On the other hand, if the initial trials are excluded from the analysis, a saving of electrical energy is found of between 3 and 11 kWh/tonne and also a shorter power-on time with 1–2 minutes. Larger energy savings cannot be expected if the foaming slag is not utilized in a more efficient distribution. In order to not complicate the evaluation of the experimental results, no adjustment of the power input was performed during the trials. The final chromium content varies considerably among the production of different steel grades. Normally, higher chromium content is observed for steel grades alloyed with Mo. The improvement of the Cr exchange is also greater for steels alloyed with Mo than for other steel grades. Without going into any details considering energy consumption, it may be assumed that the economical benefits of carbide injection would be more easily fulfilled for Mo alloyed steels. The savings in chrome losses to the slag could compensate for the higher cost of calcium carbide compared to carbon powder. For the other steel grades a deeper analysis of the energy consumption and productivity changes, due to the improved foamability, have to be considered in order to evaluate the economical conditions for calcium carbide injection.

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