SMELTING MUSTAVAARA TITANOMAGNETITE CONCENTRATE USING DC-FURNACE AND SELECTIVE OXIDATION OF VANADIUM FROM THE HOT METAL[1]

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Abstract

Mustavaaran Kaivos Oy is currently working on its business objective to put the large Mustavaara vanadium-iron-titanium deposit in northern Finland back into production. As part of the on-going feasibility study, pilot scale test work has been carried out at Swerea MEFOS facilities in Luleå, Sweden. Titanomagnetite concentrate was smelted using the 3 MW DC-furnace with hollow electrode feeding. The principal aim of the test work was to produce hot metal with high vanadium content by treating Mustavaara concentrate and slag formers, thereby establishing the hot metal composition that can be expected in full scale operations. The next target was to produce a vanadium slag with low phosphorus content out of the vanadium rich hot metal containing around 1.7% vanadium and 0.1% phosphorus by selective oxidation using the 6 tons universal converter at Swerea MEFOS. In total 45 tons of hot metal were treated and more than 3 tons of vanadium slag with low phosphorus content and 43 tons of de-vanadized hot metal were produced. Due to the high vanadium content, the vanadium slag has the potential to be either sold as an intermediate product, used for the production of vanadium pentoxide (V_2O_5) or direct production of ferrovanadium alloy. Mustavaaran Kaivos is also investigating a process for pyrometallurgical production of ferrovanadium alloy. This paper will highlight some of the results obtained from the pilot test campaigns.

Keywords: Smelting reduction; Titanomagnetite; Ferrovanadium; Selective oxidation.

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1 INTRODUCTION

Mustavaaran Kaivos Oy (MKOy) is currently working on its business objective to put the large Mustavaaran vanadium-iron-titanium deposit in northern Finland back into production. As part of the on-going feasibility study, pilot scale test work has been carried out at Swerea MEFOS facilities in Luleå, Sweden. Titanomagnetite concentrate was smelted using the 3 MW DC-furnace with hollow electrode feeding. The DC-furnace was operated 24 hours a day for 5 consecutive days. The Mustavaara concentrate was smelted to a hot metal with about 4 % carbon. Anthracite was used for reduction of iron oxide and vanadium oxide from the concentrate. The next target was to produce a vanadium slag with low phosphorus content out of the vanadium rich hot metal containing around 1.7% vanadium and 0.1% phosphorus by selective oxidation using the universal converter at Swerea MEFOS. For 3 consecutive days, nine selective oxidation trials treating 5 tons of iron per test were performed. Pig iron, previously produced in the smelting reduction campaign was melted using a 10 tons electric arc furnace with a 5 MVA transformer (EAF).

2 SMELTING REDUCTION TEST WORK

2.1 Targets

The principal aim of the test work was to produce a metal with high vanadium content by treating Mustavaara concentrate and slag formers, thereby establishing the hot metal composition that can be expected in industrial scale and to identify the process conditions required to optimize the recovery of vanadium while maintaining good reduction selectivity prior to both silicon and titanium.(1) A secondary aim was to produce minimum 18-20 ton of metal for future testing of the downstream processes. The following parameters was considered and evaluated:

- Full chemical analysis of slag, metal and dust
- Slag and metal temperatures
- Distribution of most importantly Fe, P, V, Mn, Si and Ti

As pre-reduced pellets will be used in industrial operations, other design parameters as energy consumption were of less interest.

2.2 Test Materials

The raw materials used for the campaign was Mustavaara concentrate (d80: 37 μm), slag formers with particle size of less than 8 mm and 4% moisture, silica sand with a particle size of less than 2 mm and less than 1% moisture, as well as anthracite with a particle size of 0.5-5 mm. The Mustavaara concentrate was dried from 10 %, as received, to 1-2 % moisture. The chemical analyses of the feed materials are presented in the following Table 1 and 2.

Table 1. Composition of the anthracite specified by the supplier and an independent laboratory, unit mass%

	Supplier Analysis	**Laboratory Analysis**
C-fix	86.7	89.8
Sulphur	0.860	0.813
Volatiles	3.7	3.8
Ash	9.6	5.6

Table 2. Main components of Mustavaaran concentrate, slag formers, silica sand and the ash from anthracite, unit mass%

	Fe_{tot}	**V_{tot}**	**MgO**	**Al_2O_3**	**SiO_2**	**P_2O_5**	**CaO**	**TiO_2**	**MnO**
Concentrate	62.2	0.84	0.67	1.11	3.03	0.003	1.10	7.19	0.23
Slag Formers	14.3	1.97	1.55	1.57	12.2	0.87	46.3	1.27	2.68
Silica Sand	<0.10		<0.1	0.14	99.3	<0.01	<0.10	0.15	
Anthracite Ash	1.51	0.05	2.12	25.9	56.1	0.54	5.78	0.81	1.08

2.3 General Description of the Test Equipment and Pilot Setup

A schematic view on the DC-furnace and a picture of Swerea MEFOS DC-furnace are presented in following Figure 1 and 2. The DC-furnace at is designed with a conductive hearth. For the working lining in the bottom, magnesite is used with L-shaped stainless steel plates between each brick. The walls are lined with mag-carbon bricks. The bottom of the furnace is air-cooled with a fan. Cooling panels are used in the walls and in the cast roof. Above and on the sides of the tap-hole copper blocks are used for cooling. The furnace gases exit through a port in the furnace roof where a gas probe and a thermocouple are installed for continuous sampling of the furnace gas atmosphere and temperature respectively. The graphite electrode has an outer diameter of 250 mm and an inner diameter (feeding-hole) of 70 mm. Two overhead hoppers equipped with precision feeders are used to feed the fine grained materials into a screw conveyor and further through a telescopic pipe into the hollow electrode. The material in the third bin is fed directly into the telescopic pipe. Silica sand was manual charged through the inspection hole in the roof or via the hollow electrode.

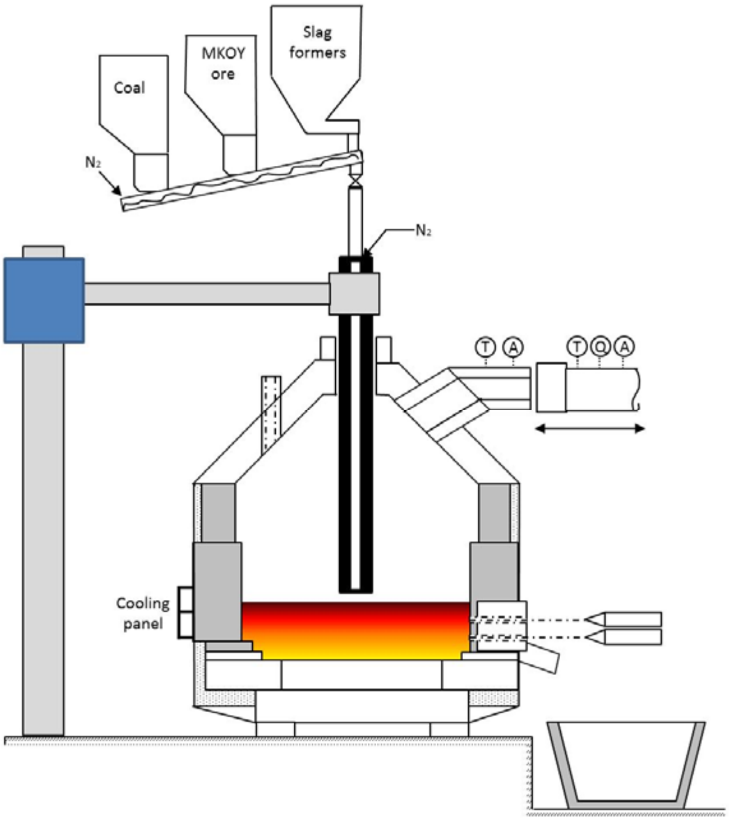


Figure 1. Schematic view of the DC-furnace.

Figure 2. Picture of Swerea MEFOS DC-furnace.

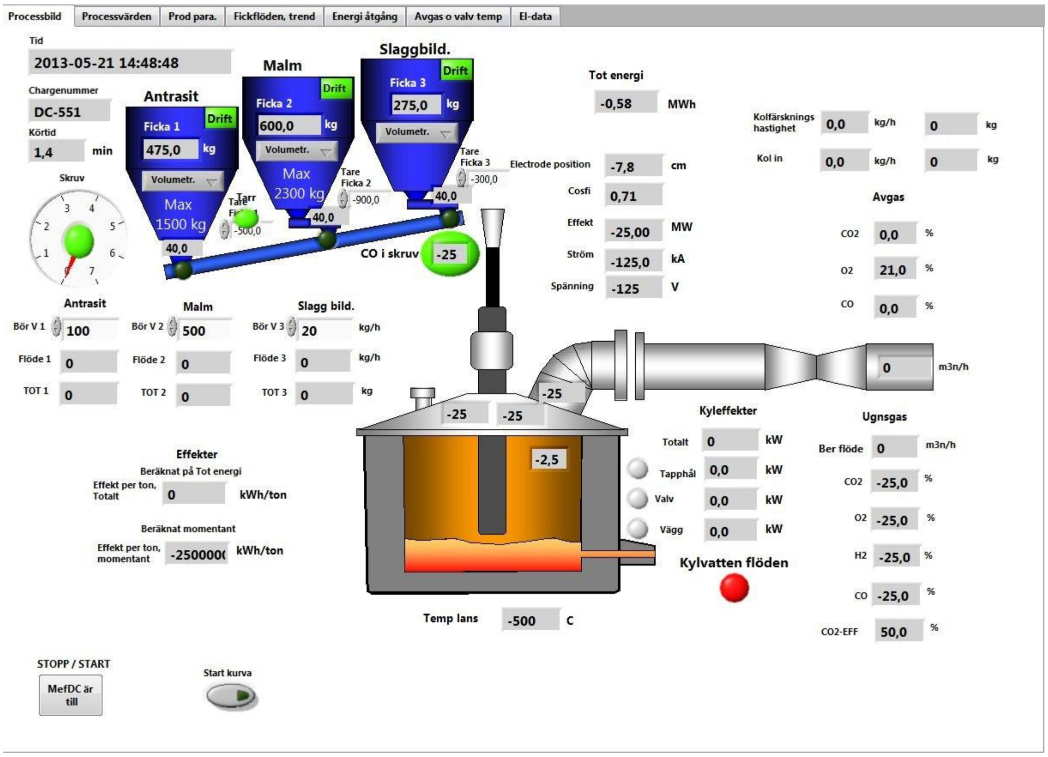
The furnace gas was combusted by leakage air entering through a slit in the duct. A venturi is utilized for volume measurements. The volume of the furnace gas was calculated based on the carbon balance. The off-gas was first cooled and then the dust was collected in a bag house filter. The furnace- and off-gas analysis was carried out for CO, CO_2, O_2 and H_2.

A tapping machine was used for drilling and a mud gun for plugging. The furnace is equipped with tap holes in three levels; one tap hole for slag, one tap hole for metal and slag and a lower tap hole for draining the furnace in the end of the campaign. The level of the metal bath after tapping was about 110 mm corresponding to roughly 1.5 tons of metal.

Metal and slag was tapped into the same ladle. The weight of the ladle was recorded, before and after tapping, using the overhead crane. The ladle was then transported outside for cooling. After cooling, the slag on top of the metal was removed before the weight was recorded for the metal.

2.4 Measurements

The operational parameters were recorded every fifteen second in the process computer, most importantly power, current, voltage, feeding rates, composition- and temperature of the furnace gas, composition-, temperature- and volume of the off-gas, heat losses (based on the temperature difference between the cooling water in roof, wall and tap-hole) and C- efficiency/balance. The overview screen in the control system is shown in the following Figure 3. Specific electrode consumption during effective test time was determined by weighing incoming and outgoing electrodes. The refractory profile before and after the test campaign was also measured. Temperature measurements of the slag and/or metal were carried out every 15-30 min. Metal was sampled through the inspection-hole in the furnace roof with an argon probe. Slag was sampled either using a metal rod with wooden handle inserted through the inspection hole or by using a slag sleeve during slag tapping. The dust was weighted and sampled after each tap. A selected number of samples from the steady state periods were analyzed.



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Chargenummer DC-551
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Ficka 1 475,0 kg Volumetr.
Ficka 2 600,0 kg Volumetr.
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Tare Ficka 1 -500,0
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Tare Ficka 3 -300,0
40,0
40,0
40,0
CO i skruv -25

Antrasit: Bör V 1 100; Flöde 1 0; TOT 1 0
Malm: Bör V 2 500; Flöde 2 0; TOT 2 0
Slagg bild.: Bör V 3 20 kg/h; Flöde 3 0 kg/h; TOT 3 0 kg

Tot energi -0,58 MWh
Electrode position -7,8 cm
Cosfi 0,71
Effekt -25,00 MW
Ström -125,0 kA
Spänning -125 V

Kolfärsknings hastighet 0,0 kg/h 0 kg
Kol in 0,0 kg/h 0 kg

Avgas
CO2 0,0 %
O2 21,0 %
CO 0,0 %
0 m3n/h

-25
-25
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Effekter
Beräknat på Tot energi
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Kyleffekter
Totalt 0 kW
Tapphål 0,0 kW
Valv 0,0 kW
Vägg 0,0 kW

Ugnsgas
Ber flöde 0 m3n/h
CO2 -25,0 %
O2 -25,0 %
H2 -25,0 %
CO -25,0 %
CO2-EFF 50,0 %

Temp lans -500 C

Figure 3. The overview screen in the control system.

2.5 Main Results

Although many challenges were encountered during the campaign, it was shown that it is possible to meet the test work targets by optimization of the furnace process conditions. In total 26 tons of hot metal and 4 tons of titanium rich slag were produced and 1.8 tons of dust was generated. The vanadium-, phosphorus- and manganese-content in hot metal can be expected to be about 1.7%, 0.1% and 0.3%. Complete analysis of the hot metal is shown in the Table 3 below.

Table 3. Analysis of the Mustavaaran Kaivos hot metal, unit mass%

	Fe	**V**	**C**	**Si**	**Ti**	**P**	**Mn**	**Cr**	**S**
Hot Metal	93	1.7	3.94	0.28	0.25	0.1	0.3	0.08	0.03

2.6 POWER INPUT AND FEED RATES

The reduction degree was controlled by balancing the feed rates and power input and by the anthracite to concentrate ratio. The C-, Si-, Ti- and V-content (%) in the metal, the anthracite feed rate (kg/t) and the specific power consumption (MWh/t concentrate) are plotted in Figure 4 below. It is shown that a simultaneous increase of the power input and the anthracite to concentrate ratio resulted in higher Si-, Ti- and V-contents in the metal and vice versa. An active power of about 1.2 MW and 130-140 kg of anthracite per hour were found suitable, when operating at 500 kg concentrate per hour, to obtain highest possible vanadium recovery while maintaining good reduction selectivity prior to silicon and titanium. A manageable slag which could easily be tapped from the furnace was obtained based on this recipe. The furnace gas volume was about 200 Nm^3/h or 400 Nm^3/t concentrate and had a typical composition of about 10-15 % H_2, < 5 % CO_2 and > 60 % CO. The specific gas volume will be significant less for the industrial case treating pre-reduced pellets. The furnace was typically operated with an actual power of about 1.2 MW, a secondary current and voltage of 8-9 kA and 125-150 V, respectively.

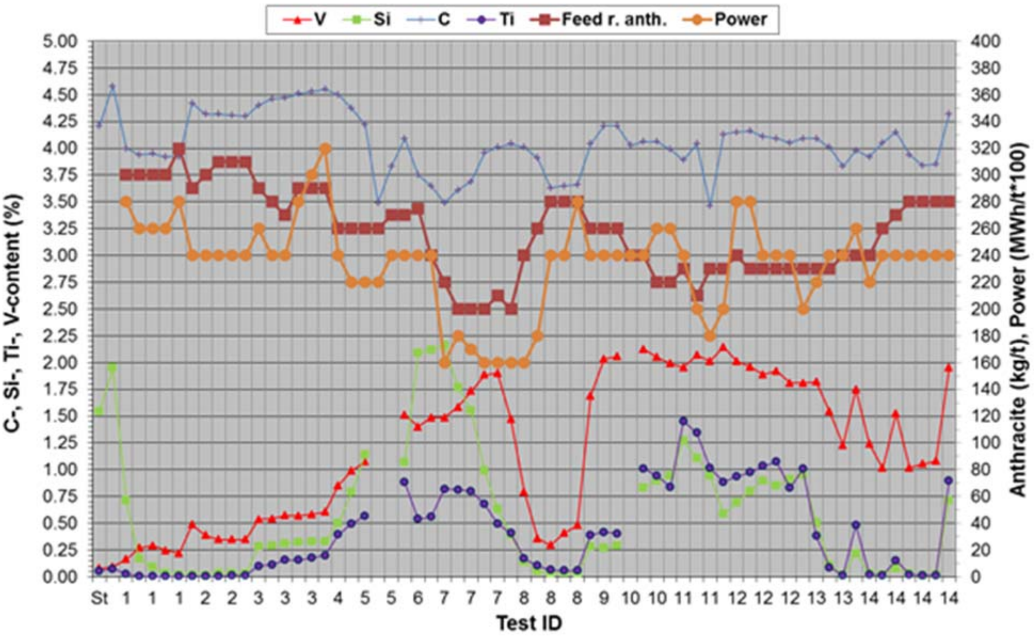

Figure 4. The C-, Si-, Ti- and the V-content (%) in the metal, the anthracite feed rate (kg/t) and the specific power consumption (MWh/t*100).

2.7 Slag Analyses

The final slag analysis is shown in Table 4 below. The Fe-content is presented as total iron. Basicities B2 (CaO/SiO_2) and B4 ($(CaO+MgO)/(SiO_2+Al_2O_3)$) were targeted to 0.9-1.2 and 0.8-1.2, respectively. There was relatively large fluctuation in the slag basicity that was due to strongly reducing conditions resulting in Si-losses to the dust and metal. The losses were controlled to acceptable levels by balancing the feed rates and power input.

The MgO-content could be kept at around 3-4 % by operating with a proper freeze lining covering the furnace refractories. However, in the end of the campaign, a very good and fluid slag was obtained and the freeze lining was melt which dramatically increased the MgO content in the slag. Therefore it can be concluded that either a proper freeze lining and/or MgO-containing slag modifier is required for the future industrial furnace operations.

Table 4. Analysis of the titania-slag, unit mass%

	CaO	**SiO2**	**MgO**	**MnO**	**Al_2O_3**	**Na_2O**	**P_2O_5**	**K_2O**	**TiO_2**	**Cr_2O_3**	**Fe_{tot}**	**V_{tot}**
TiO_2-slag	33.7	31.8	3.39	1.15	5.09	0.16	0.025	0.02	23.1	0.07	0.55	0.42

2.8 Dust Analyses and Dust Load

It can be concluded that there is an enrichment of SiO_2, MgO (from refractory), MnO, K_2O, Na_2O and P_2O_5 in the dust samples compared to the concentrate, especially during periods that were operated with a high slag temperature. The iron- and vanadium- concentrations are also lower than in the concentrate, all indicating that the dust fraction partly consists of chemically formed dust. The high phosphorus content could as well be caused by slag former carry-over since slag formers contain relatively high amount of phosphorus as a comparison to the concentrate. A chemical analysis of the dust fraction is presented in Table 5.

Typically 20-30 % of the manganese was distributed in the dust during the smelting campaign. As manganese evaporation is enhanced by high temperature and is a common element in dusts and sludges in steel production. Low manganese distribution to the metal is an advantage in the downstream processes, in case the direct pyrometallurgical production route of a ferrovanadium alloy is considered. The total dust load was about 3 % of ingoing materials. The dust carry over will be lower for the industrial case treating pre-reduced pellets instead of concentrate fines and due to coarser particle size and lower specific gas volume.

Table 5. Analysis of the dust fraction, unit mass%

	CaO	**SiO2**	**MgO**	**MnO**	**Al_2O_3**	**Na_2O**	**P_2O_5**	**K_2O**	**TiO_2**	**Fe_{tot}**	**V**
Dust Fraction	5.84	29.8	0.59	12.9	0.88	2.79	0.33	2.53	4.17	36.8	0.8

2.9 Summary of Smelting Reduction

The process parameters that were found to be the most important as listed as follows:

- Power input and feed rate: The objective was to find the operation conditions with highest possible vanadium recovery while maintaining good reduction selectivity prior to silicon and titanium. The reduction degree could be controlled by balancing the feed rates and power input and by the anthracite to concentrate ratio. The reduction degree was found to be sensitive to comparable small changes of these parameters. The Si- and Ti-content in the metal was a suitable indicator for the vanadium recovery and reduction selectivity. A vanadium recovery of about 90 % can be anticipated while maintaining good reduction selectivity prior to both silicon and titanium. The overall iron recovery was 98 to 99 %. The carbon content varied between 3.5 % and 4.5 %, any clear impact on the reduction degree was not found for this quite narrow composition range. The reduction degree can be expected to be easier to control with pre-reduced pellets as most of the reduction work has already been done prior to the electric furnace.

- Slag load: As the slag is conductive and consequently the arc was struck between the electrode tip and the liquid slag, the slag load in the furnace was important.(2) In the initial heats, tapping was done after about 3 tons of concentrate had been fed. However it was found out that frequent tapping practice facilitates furnace operation
- Slag basicity: Control of the slag basicity was more complicated than anticipated since too reducing conditions not only resulted in silica losses to the metal but also to the dust, by formation of gaseous SiO. Silicon losses lead to larger fluctuations in the slag basicity than was expected which in turn restricted basic slag former feed rate. Target slag basicity (CaO/SiO_2) of 0.9-1.2 was learned to operate by minimizing the Si-losses to the metal and dust (by controlling of the reduction degree). The targeted value for B2 was based on available data for the $CaO\text{-}SiO_2\text{-}Ti(IV)O_2$ system;(3) thus possible formation of titanium nitrides and carbides as well as Ti^{3+} has a large impact on the slag properties.(4)
- TiO_2-content in the slag: As both the slag conductivity and the slag liquidus temperature are dependent on the TiO_2-content in the slag, operating furnace at high TiO_2-contents (>40 %) was challenging. Difficulties of reaching sufficient metal temperature and consequently difficulties with metal tappings were encountered as an effect of a too high TiO_2-content. The utilized slag former material is suitable as slag modifier and also as a diluting component. By diluting the TiO_2-content in the slag to 30% or less, slag temperature of 1550-1600°C was required to reach metal temperature of about 1450°C.

3 SELECTIVE OXIDATION USING CONVERTER

In the next step of the concept, the target was to produce a vanadium slag with low phosphorus content out of the vanadium rich hot metal that was produced during smelting reduction test campaign. For 3 consecutive days, nine selective oxidation trials treating 5 tons hot metal per test were performed using the universal converter at Swerea MEFOS. Metal containing around 4% carbon, 1.7% vanadium and 0.1% phosphorus, previously produced in the smelting reduction campaign was melted in a 10 tons electric arc furnace (EAF). Oxidation of vanadium was carried out with penetrating oxygen jet introduced by a water cooled lance. Iron oxide was added as additional oxygen source and as coolant. Nitrogen was flushed through a bottom tuyere to improve stirring and process stability in the converter.

3.1 Test Work Targets

The main aim of the test campaign was to demonstrate the vanadium selectivity prior to phosphorus during selective oxidation. V-slag had a following targeted composition: >12% V (as V), ≤ 0.05% P, ≤ 6% CaO and ≤ 18% SiO_2. Targeted metal composition after selective oxidation was ≥3% C and ≤0.1% V, corresponding to a V-yield of about 90-95%.

Important design information required through the test work was the following:

- The amount and full chemical analysis of metal and slag
- Off-gas composition
- Dust load and composition
- Operational metal temperature
- Oxygen consumption (Nm^3 O_2/t)
- Consumption of cooling scrap (indicative figure)
- Refractory losses
- Blowing practice including oxygen lance height and tapping procedure

3.2 TEST MATERIALS

The feed materials for the test campaign were previously smelted Mustavaara hot metal and iron ore pellets with low phosphorus content. The chemical analyses of the feed materials are presented in the following Table 6 and 7.

Table 6. Typical hot metal analysis, unit mass%

	V	**C**	**Si**	**Ti**	**P**	**Mn**	**Cr**
Hot Metal	1.6 - 1.8	4.0 - 4.2	0.2 – 0.3	0.2 - 0.3	0.1	0.3	0.05

Table 7. Chemical analysis of the iron oxide source, unit mass%.

	CaO	**SiO_2**	**MgO**	**MnO**	**Al_2O_3**	**Na_2O**	**P_2O_5**	**TiO_2**	**Fe_2O_3**	**FeO**	**V**
Iron Oxide	0.45	1.8	1.3	0.05	0.32	0.04	0.027	0.35	95.5	0.5	0.13

The converter was equipped with a water cooled lance with a single nozzle, designed for gas flow of 17 Nm^3/min and one bottom tuyere, designed for gas flow of 0-600 dm^3/min. A mixture of oxygen and nitrogen was used in the lance and only nitrogen in bottom tuyere.

3.3 Test Programme

Even though carbon (C), silicon (Si), titanium (Ti), manganese (Mn), chromium (Cr) and vanadium (V) all have higher affinity for oxygen than iron, most of the oxygen blown into the converter through the lance reacts to form iron oxide in the slag. The iron oxide in the slag in turns reacts with Si, Ti, Mn, V and Cr in the metal to form their oxides that dissolve in the iron oxide slag. It was therefore decided prior to the campaign that only iron oxide should be used as cooling agent. Dissolution of iron oxide pellets is also faster than for cooling scrap. The oxygen equivalent for the used iron oxide source was 0.211 Nm^3 O_2/kg pellets.

Oxidation of vanadium is also promoted by low bath temperatures controlled by the addition of cooling agents. The targeted hot metal temperature was 1350 to 1400°C; which was one of the reasons that the targeted carbon content after selective oxidation was set to ≥3% to not risk scull formation in the transfer ladle or in the converter.

The most important control figure was the total oxygen consumption (oxygen and iron ore) defined as Nm^3 O_2/t iron; this is however to a large extent depending on the degree of decarburization and the vanadium oxidation state. $V_2(III)O_3$ was assumed as vanadium is known to be distributed in vanadium spinels with mainly iron, Fe_3O_4-$Fe(II)O$-$V_2(III)O_3$ spinel. A 100% oxygen yield (calculated based on recovery of 97% Ti, 97% Si, 95% V, 95% Mn and 95% Cr and an initial metal analysis of 0.3% Ti, 0.4% Si, 1.7% V, 0.3% Mn and 0.06% Cr) corresponds to 11.0 Nm^3 O_2/t iron. The equation used was:

$$O_2 - \text{yield}(\%) = \frac{0.07 \cdot M_O \left(\frac{Ti_i \cdot Ti_{yield}}{M_{Ti}} \cdot 2 + \frac{Si_i \cdot Si_{yield}}{M_{Si}} \cdot 2 + \frac{V_i \cdot V_{yield}}{M_V} \cdot 1.5 + \frac{Mn_i \cdot Mn_{yield}}{M_{Mn}} + \frac{Cr_i \cdot Cr_{yield}}{M_{Cr}} \cdot 1.5 \right)}{\text{Oxygen consumption}}$$

whereas M_x is the molar mass of the elements (g/mol), Me_i is the initial metal content (%), Me_{yield} is the metal yield to the V-slag (%) and the oxygen consumption is the total amount of oxygen added to the system (Nm^3 O_2/t).

Media to the lance was oxygen enriched air with 50% of O_2, and with specified gas flow of 17 Nm^3/h. The reason that oxygen enriched air was selected was that it was expected, that longer blowing time was needed to dissolve the relatively large amount of iron oxide and also to permit more frequent sampling which is important for evaluation of the test results.

3.4 Main Results

In total 45 tons of vanadium rich hot metal containing around 4% carbon, 1.7% vanadium and 0.1% phosphorus has been successfully treated in a pilot campaign using the 6 tons converter. More than 3 tons of vanadium slag and 43 tons of de-vanadized hot metal have been produced. Vanadium recovery up to 94% was achieved while maintaining good oxidation selectivity prior to phosphorus. The vanadium slag consisted of 16.8-20.1% V, 0.014-0.028% P, 5-6% MnO, less than 18% SiO_2 and 24-30% Fe. The vanadium content in the hot metal, after selective oxidation, was as lowest 0.1%. Chemical analyses of the pig iron as well as the vanadium slag are shown in the Tables 8 and 9.

The vanadium slag was viscous and had a consistency of a paste because the temperature was below liquidus. The V-slag was dry and could easily be tapped from the converter, no build-ups in the converter could be observed. Prior to the campaign, one concern was that too “soft” oxygen blow could cause oxidation of Fe(II) to Fe(III); which would increase the liquidus temperature and cause the slag to be excessively “dry”. By maintaining a gas flow of 17 Nm^3/h to the lance (de Laval flow – penetrating jet) and by adjusting the lance height accordingly no such phenomenon was observed.

Table 8. Chemical analysis of the vanadium slag, unit mass%.

	CaO	**SiO_2**	**MgO**	**MnO**	**Al_2O_3**	**P_2O_5**	**TiO_2**	**Cr_2O_3**	**FeO**	**V_2O_3**	**V**
V-slag	0.55	10.7	1.6	5.0	0.37	0.04	7.2	1.5	40.8	32.3	21.9

Table 9. Chemical analysis of the pig iron, unit mass%.

	C	**Si**	**Ti**	**P**	**Ni**	**Mn**	**Cr**	**S**	**V**	**Cu**
Pig Iron	3.04	0.009	0.006	0.1	0.06	0.018	0.003	0.02	0.1	0.01

3.5 Dust Analysis and Dust Load

The dust was sampled in the off-gas before the wet venturi scrubber; the results from the measurements are shown Table 10 below. The dust amount varied between 1-3 kg/t of hot metal. The dust amount was calculated based on the dust load in the off-gas, dry off-gas flow and on the duration time. Higher pellet addition resulted in higher dust load and the composition of the dust for the analyzed samples is very close to that of the pellets; it can therefore be assumed that a large part is mechanically formed dust. Still the dust loads can be considered to be low compared to a normal steel converter. Some chemical dust has been generated, for example there is a slight enrichment of manganese and phosphorus.

Table 10. Chemical analysis of the dust fraction, unit mass%.

	CaO	**SiO_2**	**MgO**	**MnO**	**Al_2O_3**	**P_2O_5**	**TiO_2**	**Fe_2O_3**	**Na_2O**	**K_2O**
Dust Fraction	0.29	0.91	0.39	0.48	0.08	0.27	0.02	97.1	<0.05	<0.1

3.6 Summary of Selective Oxidation Test Campaign

A vanadium recovery of up to 94% could be achieved while maintaining good oxidation selectivity prior to phosphorus. The vanadium slag was composed of 16.8-20.1% V, 0.014-0.028% P, 5-6% MnO, less than 18% SiO_2 and 24-30% Fe. The vanadium content in the hot metal, after selective oxidation, was as lowest 0.1%.

The developed converter practice for the selective oxidation concept can be summarized as follows:

- Iron ore / iron oxide was used as cooling agent for high iron oxide activity in the slag and low bath temperature (≥1400°C).
- Stirring was of essential importance to ensure that the iron oxide in the slag reacted with the vanadium in the metal bath.
- The formed V-slag is dry and do not cause violent slag foaming (boiling) and could easily be tapped from the converter, no build-ups in the converter could be observed.

4 CONCLUSIONS

Mustavaaran Kaivos Oy has demonstrated its concept for production of vanadium containing hot metal as well as high titania slag and then further refining the hot metal to produce high vanadium containing slag and pig iron using Swerea MEFOS 3 MW DC-furnace with hollow electrode feeding and universal converter.

During smelting reduction test campaign both hot metal and high titania containing slag were produced. Vanadium recovery of over 90% into hot metal can be anticipated while maintaining good selectivity prior to both silicon and titanium. The overall iron recovery was 98 to 99%. It was also noted that both phosphorus and manganese partly evaporated as an effect of the open bath operation. The phosphorus and manganese contents can be expected to remain below 0.12% and 0.4%, respectively.

During the converter test campaign, a blowing practice was successfully developed and both vanadium slag and pig iron were produced. The blowing practice was proven by high reproducibility of test results. A vanadium recovery of up to 94% could be achieved while maintaining good oxidation selectivity prior to phosphorus. The vanadium slag was in general composed of 16.8-20.1% V, 0.014-0.028% P, 5-6% MnO, less than 18% SiO_2 and 24-30% Fe. The vanadium content in the hot metal after selective oxidation was as low as 0.1%.

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