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PILOT PLANT SMELTING OF CANADIAN AND SOUTH AFRICAN CHROMITE IN A DC FURNACE

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ABSTRACT

Ferrochromium smelting in a direct current (DC) furnace for the direct processing of chromite fines has matured in the past four decades from relatively humble beginnings in the 1980s during the development of the technology at Mintek's facilities. The current demonstration-scale facility enables testing of chromite ore from global sources via a systematic test protocol. The aim of the current study was to demonstrate the production of a ferrochromium metal product from a bulk ore sample of Canadian chromite. As a benchmark, the test plan included a comparison with South African chromite. The smelting test was conducted in a 2.5 m diameter pilot furnace configured with a single, solid graphite electrode acting as the cathode and an anode embedded in the hearth. The main objectives of the campaign were to demonstrate at significant scale the feasibility of smelting Canadian chromite ore in an open-arc DC furnace; to evaluate the quality of the ferrochromium product in the context of two slag regimes; to generate sufficient process information for furnace scale-up. About 31 metric tons of South African chromite and 144 metric tons of Canadian chromite ore were successfully smelted to produce 83 metric tons of metal. The results highlighted the flexibility and efficiency of direct processing of DC open-arc smelting of chromite and confirmed the feasibility of DC smelting of Canadian chromite ore.

KEYWORDS

Direct current (DC), Chromite, Ferrochrome, Open-arc, Open-bath, Pilot test, Slag basicity, Smelting

INTRODUCTION

A pilot smelting test was conducted on a bulk sample of Black Thor chromite to evaluate and demonstrate the smelting behaviour of Canadian chrome ore in a direct-current (DC) furnace to produce ferrochrome. Ferrochrome production is basically a high-temperature carbothermic reduction process, aiming to produce an iron-chromium-carbon alloy. Ferrochrome alloy is primarily used in the production of stainless steel. The purpose of the study presented herein was aimed at assessing the smelting behaviour of chromite from the Ring of Fire deposit in Ontario, Canada, in the context of the option to use DC smelting technology.

The pilot smelting facilities at Mintek are ideally suited to evaluate chrome smelting with Mintek's expertise in chrome smelting and pilot plant testing, well-established over the past four decades. An overview of the various chromite pilot smelting tests conducted at Mintek, representing all the major chrome regions in the world, is described elsewhere (Geldenhuys, 2013; Hockaday & Bisaka, 2010). DC smelting for ferrochrome production can no longer be regarded as an emerging technology. Since its first implementation for the smelting of chromite fines to produce ferrochromium more than 35 years ago in 1984 (Jones, 2014), the technology is now well-established globally as an efficient option for ferrochrome production.

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A smelting test of this nature and duration provides valuable information about product quality, process efficiency, and mass and energy balance data, information that is crucial for design and feasibility studies. Aspects of the pilot smelting test results are described herein.

The Ring of Fire

Chromium ore, or chromite, is a mineral of the spinel group. Geologically, commercial chromite deposits in the world are found as three primary types, the most common being the stratiform-type chromite deposits. The most significant example of a stratiform-type deposit is the Bushveld Complex in South Africa (Cramer, Basson & Nelson, 2004). The Blackbird, Black Thor, and Big Daddy chromite deposits in the James Bay Lowlands, Ontario, Canada, are also stratiform-type deposits (Lesher, Carson & Houlé, 2019). These deposits form part of The Ring of Fire region, which is also rich in high-grade nickel, copper, platinum and palladium. The deposits were formally discovered in 2007 by a team of mining executives and geologists who named this region “The Ring of Fire”. They were inspired by the semi-circular shape of rock hosting the mineral deposits and they were fans of Johnny Cash (Wallace, 2019). Noront Resources Ltd. is currently developing the chromite deposits of the Ring of Fire region and recently announced their plans to set up a ferrochrome production facility in Sault Ste. Marie. Their plans for the facility include implementation of direct-current (DC) furnace technology to produce ferrochrome, details of the flowsheet and implementation plans are described elsewhere (Flewelling, Baker, Weston, Desilets, McCaffrey & Cramer, 2020; Mining Weekly, 2019).

DC furnace technology

A ‘DC furnace’ or ‘DC arc furnace’ refers to a pyrometallurgical vessel that comprises a cylindrical steel shell with base (domed or flat), and a roof that is usually conical. The vessel is lined with a refractory material to contain the molten materials. A DC furnace usually has a single central graphite electrode (the cathode) and an anode embedded in the hearth. The molten metal in the furnace is in electrical contact with the anode by design. The energy is supplied by means of an open plasma arc that is generated between the bottom tip of the cathode and the upper surface of the molten slag. The arc is a supersonic super-heated plasma reasonably coherent jet. The surface of the molten bath, at least a portion of the surface in the arc-attachment zone, is mostly clear of unreacted feed material.

These open-arc open-bath DC furnaces have a number of advantageous properties, including the ability to process fine materials directly, that is without some form of agglomeration. Apart from extensive use in the steel industry to melt steel scrap, DC arc furnaces are increasingly used for smelting processes. Mainly where the feed materials are fine, predominantly non-metallic, and significant chemical reactions are involved (Jones, Reynolds, Curr & Sager, 2011). Because the furnace is electrically powered, very high temperatures (in excess of 1500°C) can be attained by adjusting the arc. The open bath allows fine feed materials to be fed into the furnace, without the risk of eruptions in a burden. By contrast, in a blast furnace, or in an AC submerged-arc furnace, coarse feed materials are required in order to provide a porous bed that allows the reaction gases to percolate away and escape from the reaction zone. This additional degree of freedom allows the slag composition to be designed (unconstrained by electrical properties) to achieve the smelting regime most favourable to the process (Geldenhuys, 2013; Jones & Erwee, 2016).

South African chromite ores are known to be friable, and large quantities of fines are generated during processing. DC smelting technology was initially developed at Mintek to provide a solution to the growing fines problem in South Africa almost four decades ago. A brief history of DC arc furnace technology and Mintek’s role therein has been published previously (Jones, 2014).

Chromite smelting

The chromium spinel mineral is a highly complex mineral with the general form of AB_2O_4 (A = Mg, Fe^{+2} and B = Al, Fe^{3+} ,Cr^{3+}). Magnesium can be substituted in varying proportions by divalent iron, and the aluminium can be substituted, also in varying proportions, by trivalent chromium and trivalent iron.

Chromite ore is, therefore, a combination or a mixture of $FeCr_2O_4$, $MgCr_2O_4$, $MgAl_2O_4$ and Fe_3O_4 (Erwee, Geldenhuys, Sitefane & Masipa, 2018). This spinel mixture accounts for the variations in the total and relative amounts of Cr and Fe, the ore grade and the smelting behaviour of different deposits from around the world. The purpose of smelting chromite is to reduce most of the Cr_2O_3 in the $MgCr_2O_4$ and $FeCr_2O_4$ spinel phases to Cr and separate the chromium from the main gangue components. The main gangue components are MgO, Al_2O_3, and SiO_2, which forms a slag phase. As the Cr^{3+} is reduced to Cr^{2+} it is replaced by Al^{3+} and as an example, stable $MgAl_2O_4$ form in the structure, which needs to be fluxed to facilitate separation between metal and slag.

The slag composition, and therefore the fluxing regime, is designed to achieve the desired metallurgical objectives. The melting point (or liquidus temperature) of the gangue components is lowered by adding fluxes. The first step is to estimate the alloy composition and based on this, estimate the liquidus of the alloy. The fluxing strategy is designed to ensure the slag liquidus matches that of the alloy to ensure the alloy is fluid enough to flow during tapping. The slag melting point is lowered by adding silica, usually as quartz. A small addition of SiO_2 can reduce the melting point of the gangue significantly. For example, the approximate melting point of the gangue components of the UG2 and the Black Thor chromite samples are 2008°C and 1935°C, respectively. The effect of silica addition, based on the normalised gangue constituents, is presented in Figure 1, with the initial normalised gangue composition for UG2 chromite 59% Al_2O_3, 37% MgO, 5% SiO_2, and for the Black Thor chromite 40% Al_2O_3, 41% MgO and 19% SiO_2.

The trend shows that even adding a small quantity of silica can significantly change the melting point. The effect of silica addition is further illustrated in Figure 2 via the ternary projections of the normalised gangue components MgO, Al_2O_3 and SiO_2 (chromite from South Africa, Kazakhstan, India and Zimbabwe is included for comparison).

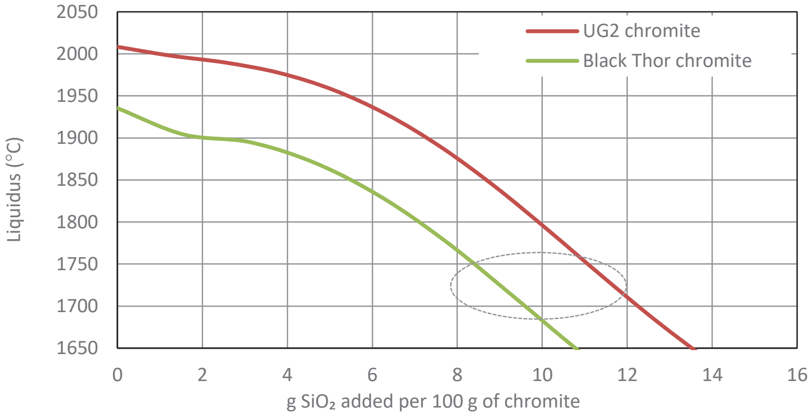


Figure 1. Effect of silica addition on the liquidus of the gangue components from two chromite concentrate samples with initial compositions for the three main gangue components (liquidus via FactSage 7.1)

The relative compositional relationship of the UG2 and Black Thor gangue components is presented in Figure 2. The lines linked to the silica apex represent the compositional change with increased silica addition; MgO/Al_2O_3 ratio remains constant. The dashed elliptical areas in Figure 1 and Figure 2 are indicative of the targeted operating temperature (achieved through silica addition). Compared to the UG2 sample tested during the pilot campaign, the Black Thor sample contained four times more silica.

Silica, as a gangue component, contributes positively to the liquidus in this system. It is worth noting that the gangue composition can contribute as a flux, and there is possibly an opportunity to use the natural gangue constituents as fluxes. Generally, beneficiation aims to maximise grade, and while there are benefits to cleaning up the chromite ore, transport costs and market expectations, there is clearly some benefit in relaxing the targets to retain some gangue components. This may potentially increase the overall metal recovery during processing as less chromium would be discarded to tailings. The opportunity and concept are described in a recent patent (Geldenhuys, 2014) assessing smelting of low-grade chromite feed.

By adding silica, the liquidus is adjusted, but usually, the resulting slag would be highly viscous (due to the high in SiO_2 content). For this reason, a basic oxide, CaO, is usually added to lower the viscosity of the slag. In many operations, CaO levels of between 10 and 15% are maintained to ensure that the slag is sufficiently fluid for tapping and contributes to the efficacy of slag/metal separation. A very viscous slag can lead to entrainment of chrome-containing metallic droplets in the slag. It is, therefore, necessary to design the operating conditions with the appropriate fluidity to achieve the best possible slag-metal separation. It is worth noting that the addition of CaO to the slag results in a slight increase in liquidus temperature, but for South African chromite smelting slags the positive effect of CaO on the viscosity of the slag is larger than the increase in liquidus temperature.

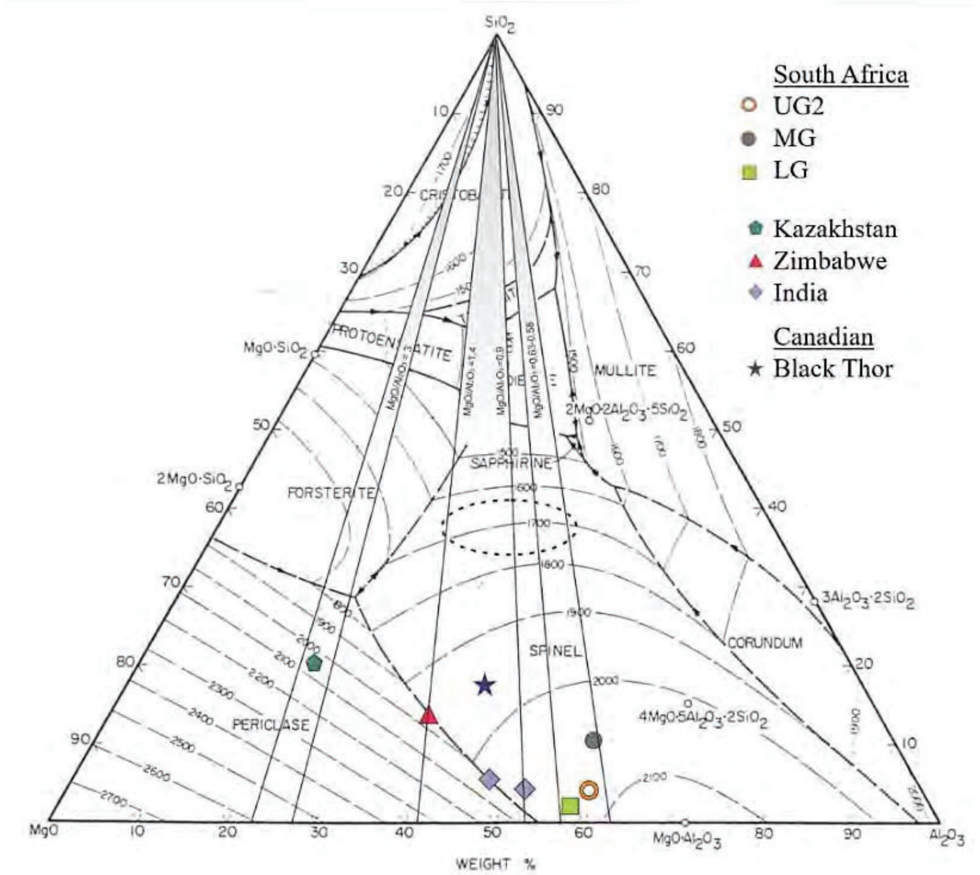


Figure 2. Ternary projection of the unfluxed, normalised gangue components $MgO–Al_2O_3–SiO_2$ for chromite ores together with UG2 and Black Thor chromite (Slag atlas, 2nd Edition, 1995: 569)

Table 1 summarises the relative impact of the slag and temperature on the viscosity of typical ferrochrome slags - $MgO–Al_2O_3–SiO_2$ systems. It is worth noting that the Cr^{2+}/ Cr^{3+} ratio is sensitive to the slag composition, slag liquidus and the smelting conditions. Divalent chromium increases with increasing temperature, decreasing oxygen potential and slag basicity (Erwee et al., 2018; Holappa & Xiao, 2004). The relative abundance of the different spinel forms in a specific deposit has an impact on the relative ease of smelting. For example, increasing amounts of magnesium compared with iron in the divalent site will make the spinel harder to reduce. Conversely, increasing amounts of iron in the trivalent site, replacing aluminium, will increase the reducibility of the spinel.

Table 1. Typical slag viscosity trends for ferrochrome slags

Lowers viscosity (*impact*)	Increases viscosity
Temperature (*intermediate*)	SiO_2
CaO, MgO (*strong*)	Undissolved spinel
FeO (*intermediate*)	Al_2O_3 (potential to increase)
CrO_x (Cr^{2+}) (*very strong*)	Cr_2O_3 (Cr^{3+})

In practice, chromite smelting recipes vary, depending on the type of furnace open-arc or submerged-arc, and metallurgical objectives, such as Cr recovery, and the composition of the chromite being processed. In a DC furnace, the recipe can be optimised for metallurgical purposes, and it is usual to achieve Cr recoveries of at least 90% in a DC ferrochrome furnace.

EXPERIMENTAL

Equipment description

The installed furnace consisted of a refractory-lined cylindrical shell, a domed base, a conical roof and a refractory roof plug resting on top of the conical roof. It is important to note that the feed is fed via the roof ports not via the electrode. During the early years of DC arc smelting, hollow-electrodes had been used to feed the materials, but over the past three decades, Mintek has repeatedly tested alternative arrangements and found that the potential benefit of feeding via the electrode is outweighed by the operational challenges associated with the hollow electrode, e.g. blockages and plant availability. Ferrochrome smelting, in particular benefits from distributed feeding (Geldenhuys, 2013; Jones et al., 2011).

The furnace shell has an unlined internal diameter of 2.5 m (shell diameter or outer diameter). The conical roof design includes an off-gas port or opening to allow for the extraction of the process gasses. The shell has two openings, in which the taphole blocks for the slag and metal tapholes are seated during the installation of the refractories. The operating diameter, after the installation of the refractory lining, was about 2 m. The sidewall and hearth refractories consisted of high-MgO refractory materials. The conical roof and upper shell area are cooled by means of forced water-cooled circuits while the furnace lower shell is designed to utilise film water-cooling. Water-cooled copper inserts were installed in the metal taphole area. A general view of the pilot plant furnace is shown in Figure 3, highlighting the relative positions of key design features.

Slag and metal are usually extracted from the furnace at regular intervals, typically after a predetermined feeding period. Each batch is fed at the desired feeding rate, determined to achieve the desired metallurgical outcomes. During the batch, the targeted recipe is fed to the furnace at a controlled feeding rate matching the power input. The power-to-feed balance control is a crucial part of operating an open-bath furnace and power input, energy losses, and feed rates are monitored throughout a pilot test. The principles of power-to-feed control is described elsewhere (Geldenhuys, 2017).

During the pilot test, slag was tapped into cast metal pots, and metal was tapped into refractory lined ladles (see Figure 3). Once the liquid product solidified, the ladles were moved to a cooling area until the content could be safely tipped out. The slag and metal were sampled during tapping by taking cross-stream spoon samples, and the samples were subsequently analysed. The samples and the ladle content were weighed and logged for mass balance purposes. During tapping, a calibrated pyrometer is used to establish the slag or metal tapping temperature. The pilot furnace is operated with a combustion system for the off-gas, mainly for safety purposes. The CO-rich off-gas is combusted before the dust is separated from the gas stream via a bag filter system. The off-gas dust is therefore collected as a dry dust. The dust collected from the off-gas system is weighed, sampled and assayed as part of the mass balance.

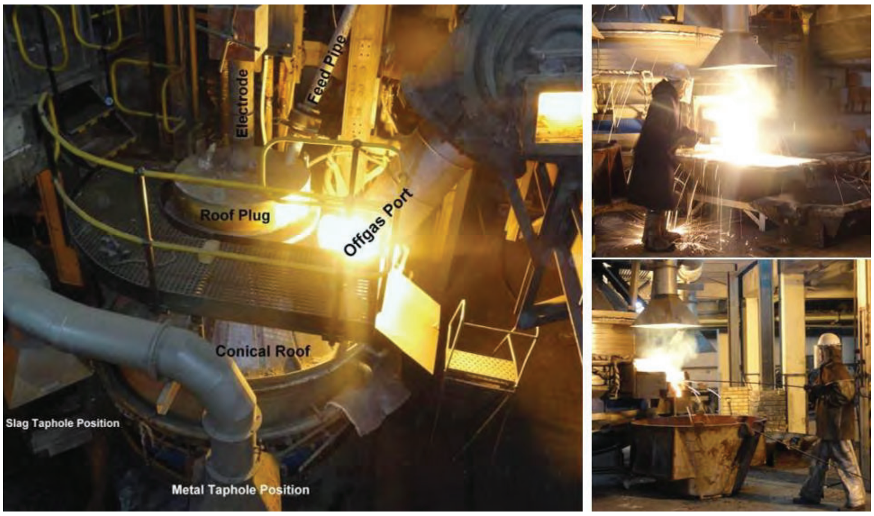
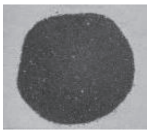


Figure 3. View of the pilot furnace in operation (left) - annotations indicate relevant aspects of the furnace, and a metal and slag tap in progress (top and bottom right), photographs by author

Raw materials

The use of UG2 chromite concentrate as feedstock in ferrochrome production has increased dramatically over the past two decades. The ‘discard’ streams from platinum producers (so-called UG2 tailings) have become a valuable raw material for ferrochrome producers, as predicted by Cramer et al. (2004). A bulk sample of UG2 chromite concentrate was acquired for the pilot test to provide a reference point and to use a known chromite during the warm-up of the furnace. The Black Thor chromite was prepared specifically for the pilot smelting test. Table 2 summarises the chemical composition of the raw materials processed during the pilot smelting study.

Table 2. Composition (mass %) of chromite, fluxes and reductant

	Black Thor	UG2	Silica	Limestone	Anthracite
Cr_2O_3	44.0	42.0			0.01
FeO	18.2	28.5	0.24	0.57	0.46
MgO	12.8	8.8	<0.05	0.70	0.1
Al_2O_3	12.5	15.7	0.36	1.2	3.1
SiO_2	5.9	3.5	99.3	5.3	5.7
CaO	0.60	0.44			0.14
P (ppm)	166	71	170	10	80
$CaCO_3$				92.4	
Fixed Carbon					81.6
Ash content					10.2
Volatiles					4.6
General appearance of the materials					
Cr/Fe	2.13	1.30			
(Cr_2O_3 + FeO)	62.2	70.5			
(MgO + Al_2O_3 + SiO_2)	31.2	28.0			

The most notable compositional differences between the two chromite materials are the Cr/Fe ratio, and the composition of the gangue. The Cr/Fe ratio of the Black Thor and UG2 chromite is 2.13 and 1.3, respectively. The Black Thor sample is regarded as an intermediate grade (Cr/Fe ratio above 2, but below 3), while UG2 chromite falls in the low-grade category (Cr/Fe ratio below 2). The reductant, anthracite, was selected on the basis of a relatively low ash phosphorous content. The silica sand and limestone were sourced from South African suppliers and sized for purposes of the test to -6 mm. The general appearance of the raw materials is included as photographs (not to scale).

Overview of smelting test

The experimental plan for the pilot test included the objective to adjust the slag composition from a basic to acid slag, or changing from a high flux to a low flux condition, also referred to as "basic" versus "acid" fluxing conditions. A basic slag (targeting slag with a basicity ratio of approximately 1.4 to 1.5) was achieved via the addition of limestone and silica as slag modifiers. During the low flux condition, only silica sand was added, resulting in slag with a basicity ratio of about 1. The basicity ratio is defined as the mass ratio of $(MgO+CaO)/SiO_2$ of the feed or the slag. The changeover had to be managed carefully to manage the change in slag properties as the limestone addition was lowered and eventually omitted completely. Transition periods were required to firstly change from UG2 chromite to Black Thor chromite, and subsequently to change the slag composition from basic to acidic.

After each transition period, the operating parameters, recipe and power input, were kept constant to collect adequate data points to describe the metallurgical condition. About 31 tons of a UG2 chromite concentrate was processed first to achieve stable operation, this included heating up the furnace and establishing a molten bath of slag and metal that could be tapped regularly. The start-up and stabilisation period is typical for all pilot smelting tests, as the furnace is a bespoke installation for a pilot study of this nature. Following the UG2 smelting period, Black Thor chromite was introduced, and over a period of about three weeks, about 144 tons of Black Thor chromite was processed. The smelting campaign produced about 83 tons of ferrochromium metal and 89 tons of slag from more than 220 furnace taps (slag and metal). The average power on availability for the furnace was 94%, which is very good for this scale. Power-off events were mainly associated with normal taphole, electrode and off-gas maintenance, while power input and feeding continues during tapping, which benefits the overall metallurgical operation.

RESULTS AND DISCUSSION

The smelting recipe, besides the chromite, comprised of silica sand and limestone fed in conjunction with anthracite. The combination of silica and limestone flux is generally referred to as a basic fluxing while the silica only is referred to as acid fluxing. The basic flux regime resulted in a slag with the following four dominating gangue components Al_2O_3, CaO, MgO and SiO_2 (for both UG2 and Black Thor chromite), while the acid flux regime resulted in slag consisting predominantly of Al_2O_3, MgO, and SiO_2 (for the Black Thor chromite).

Table 3, summarises the flux and reductant addition for the three main operating regimes. Figure 4 presents the evolution of the metallurgical results (metal composition (Cr, Si and C content), and residual chrome and iron in the slag) as an overview of the pilot test. The dramatic shift in the Si content of the metal highlights the sensitivity of the process to the fluxing regime. The transition from basic to acid fluxing was successfully navigated, without major process interruptions, a benefit of the DC technology.

Table 3. Smelting recipe for the four operating periods

Recipe (batches)	UG2 Basic fluxing (1-28)	Black Thor Basic fluxing (50-79)	Black Thor Transition (80-99)	Black Thor Acid fluxing (100-122)	
Silica	94	80	114	111	kg/t chromite
Limestone	232	200	38	0	kg/t chromite
Anthracite	272	309	309	299	kg/t chromite

Flux additions were adjusted to achieve a suitable slag liquidus and viscosity to facilitate the smelting of the chromite concentrate, but there is scope for optimisation. The operating temperature was adjusted accordingly to enable efficient slag/metal separation and slag and metal tapping during the pilot plant. The temperature can be changed by adjusting the ratio of energy input (kWh) per ton of feed; customarily known as the specific energy requirement.

The tapping temperatures of the slag was managed to ensure the metal was fluid enough to tap. It was determined that a metal tapping temperature of greater than 1700°C was required to tap the Black Thor metal. Slag containing about 3.5% Cr_2O_3 and 1.5% FeO was consistently produced regardless of the slag basicity (see Figure 4).

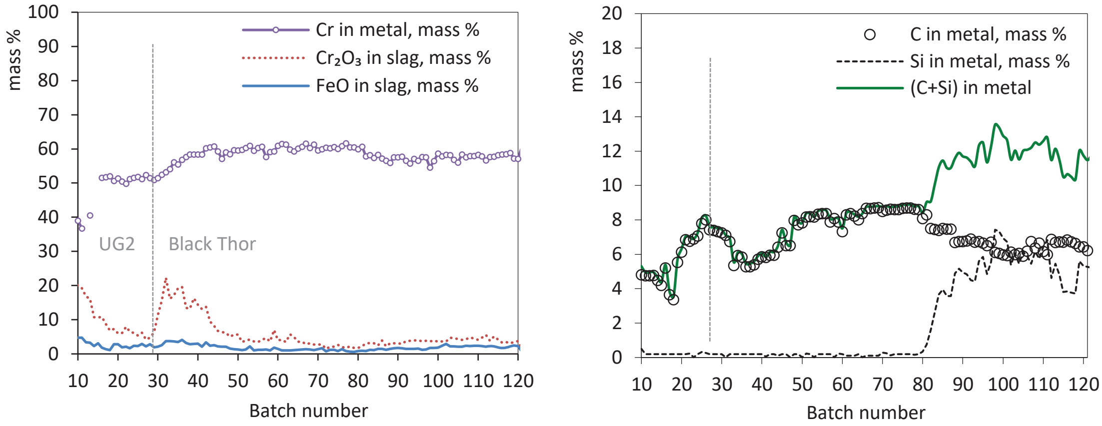


Figure 4. Evolution of the Cr grade, residual Cr_2O_3 and FeO in slag, and the C and Si content of the metal product (mass %), all taps

Aspects of the operational outcomes

Overall, 12.2 tons of dust was collected from the off-gas handling system, which is typical for the scale of operation and the fine nature of the feed materials. Off-gas dust usually consists of a combination of feed carry-over and the reaction products from the process. About 40% of the dust collected during the pilot test was direct feed carry-over with the remainder consisting of reaction products from the process; Mg and Si predominantly. Feed losses to the off-gas are expected to be higher at pilot scale than for a commercial furnace. The off-gas extraction point on the pilot furnace roof is located close to the feed points (Figure 3), which is a function of the furnace size and the layout of the facility.

The pilot plant furnace is set up to use prebaked graphite electrodes as the cathode (200 mm diameter). The electrodes are manufactured with matching threaded sections, and a new electrode is added to the top of the string as the graphite is consumed. The open-arc mode means that the dominant mechanism of consumption is surface oxidation as the electrode is seldom in contact with the molten materials. The overall electrode consumption for the test was 1.8 kg/MWh, which is very good for the scale of operation. The rate of wear is relatively slow if compared to other consumables, and it is therefore not practical to isolate the effects of different operating regimes on electrode wear.

Elemental mass balance

Mintek's experimental protocol for pilot plant tests includes verifying the veracity of the results through an elemental mass balance. The mass balance is based on the law of conservation of elemental mass, stating that the mass of an element entering the system is equal to the sum of the mass of the element leaving the system and the accumulation of the element in the system. At the end of the test, the furnace is excavated, and all smelting product masses are collected, and the elemental composition is included in the overall mass balance. The quality of the test results is reflected as a positive or negative accumulation. As with all experimental results, the measurements involved suffer from uncertainties, associated with sampling, weighing, and assaying the feed and product streams. For purposes of the mass balance, only the solid product and by-product streams are assessed. All the feed and product streams are weighed and sampled at regular intervals throughout a pilot test. The overall elemental mass balance is used to verify whether these measurements provide a reasonable reflection of the test results.

The elemental accountabilities for all the components of the system were found to be excellent. The quality of the mass balance, via the high elemental accountabilities, provides confidence in the results. Accountability is defined as the ratio of the mass of a specific element in all the feed streams and the mass of the element in the product streams. The accountability of the major components in the system, namely Cr and Fe was 99.3% and 100.2% respectively. For Al, Ca and Si, the accountabilities were 99.8%, 99.4% and 103%, respectively. A large proportion of the smelting campaign resulted in metal with low Si content, and these reported values are therefore very close, or at the detection limit, of the analytical technique. It is therefore likely contributing to the overestimation of the Si content in the alloy accounting for a small cumulative error in the mass balance. The accumulation, namely 3%, is therefore within the acceptable uncertainty boundaries and do not negatively impact the quality of the overall results and conclusions.

The MgO-based refractory lining installed for the test performed well. As MgO is the main component of the refractory lining, any refractory wear could contribute to a positive accumulation in the mass balance. While the refractory lining was found to have performed adequately, some wear is normal, especially during the start-up periods, and in the tidal zone of the bath. The accountability of 111.8% for Mg is, therefore, likely due to refractory wear. The total mass of the refractories used in the installation of the furnace hearth and sidewalls construction was about 16.6 tons, with a weighted average of 85% MgO content. During the furnace excavation, only 14 tons of refractory materials were recovered, which is equal to about 2.2 tons of MgO loss, and if this MgO loss is taken into account in the elemental mass balance, the accountability of Mg can be reconciled quite well. The resulting recalculated Mg accountability, including refractory wear, namely101.5% is very reasonable for the scale of operation, and supports the hypothesis that refractory wear is the major contributor to the excess Mg in the system.

Metallurgical results

The slag and metal compositions for the three main metallurgical conditions are summarised in Table 4. The three periods evaluated are for stable periods represented by a sequential number of slag and metal taps, thus excluding the transition periods from one condition to the next. The number of batches included in the calculation is included in the table. The composition of the slag and metal produced during the UG2 and the two Black Thor periods (Table 4), compares well with expected outcomes.

Table 4. Weighted average UG2 slag and metal composition for basic fluxing conditions (mass %)

Slag	MgO	Al_2O_3	SiO_2	CaO	Cr_2O_3	FeO
UG2 slag	15.7	28.5	24.3	20.8	5.5	2.5
Std. dev. (n=5)	0.20	0.23	0.73	0.75	0.88	0.33
Black Thor slag	23.6	24.6	27.1	18.7	2.9	1.1
Std. dev. (n=20)	1.04	1.17	1.35	0.70	1.12	0.29
Black Thor slag	31.1	33.2	27.9	1.1	4.2	2.3
Std. dev. (n=19)	0.80	1.14	1.67	0.33	0.65	0.24

Metal	Cr	Fe	Si	C	Cr/Fe
UG2 metal	51.6	39.4	0.25	7.5	1.3
Std. dev. (n=5)	0.47	0.49	0.05	0.37	
Black Thor metal	60.7	29.0	0.14	8.5	2.1
Std. dev. (n=20)	0.68	0.78	0.07	0.33	
Black Thor metal	57.8	27.4	5.4	6.4	2.1
Std. dev. (n=19)	0.70	0.95	1.00	0.34	

The basicity ratio for the Black Thor basic and acid fluxing conditions, as fed, was 1.44 and 0.73, respectively. It is worth noting that the basicity ratio of the resulting slag during the acid fluxing period was 1.15 (compared to the much lower recipe ratio of 0.73). Figure 5 plots the basicity of each batch as fed and the corresponding slag tap. The trend from batch 80 onwards clearly shows the offset between the feed and the slag basicity as the recipe composition was changed. The difference observed during the acid fluxing period can be attributed to the fact that a significant proportion of the Si, from the flux, reported to the metal phase. It is thus worth also assessing Si deportment as a function of the basicity of the recipe. It is essential to understand the various interdependencies when implementing changes, in an attempt to optimise ferrochrome smelting.

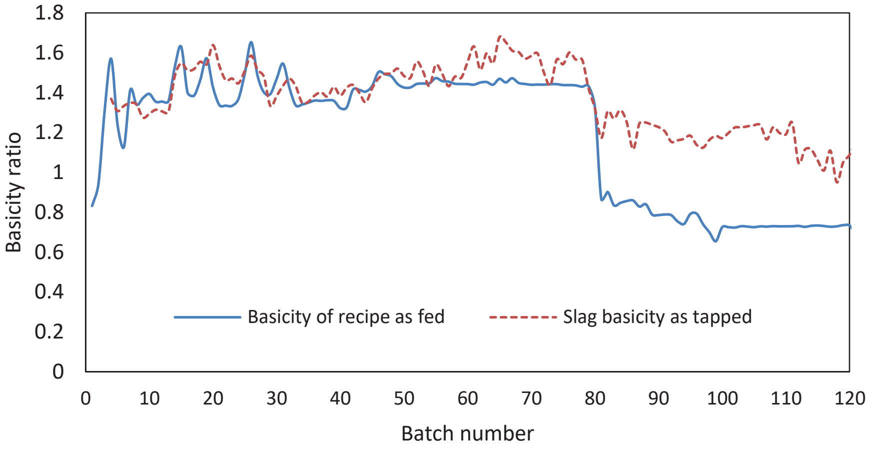


Figure 5. The basicity ratio of the feed and slag for all conditions per batch (as fed and tapped)

Figure 6 presents plots of the individual metal tap compositions produced during the campaign. There is a clear distinction between the acid and basic flux conditions. During the basic fluxing periods, low-Si metal was produced from the UG2 and Black Thor chromite. As the limestone was removed from the recipe, the Si content of the metal increased rapidly, diluting the Cr, Fe and C in the metal. The testwork demonstrated that given the right operating conditions, Si and C content of the metal might be manipulated by modifying slag composition.

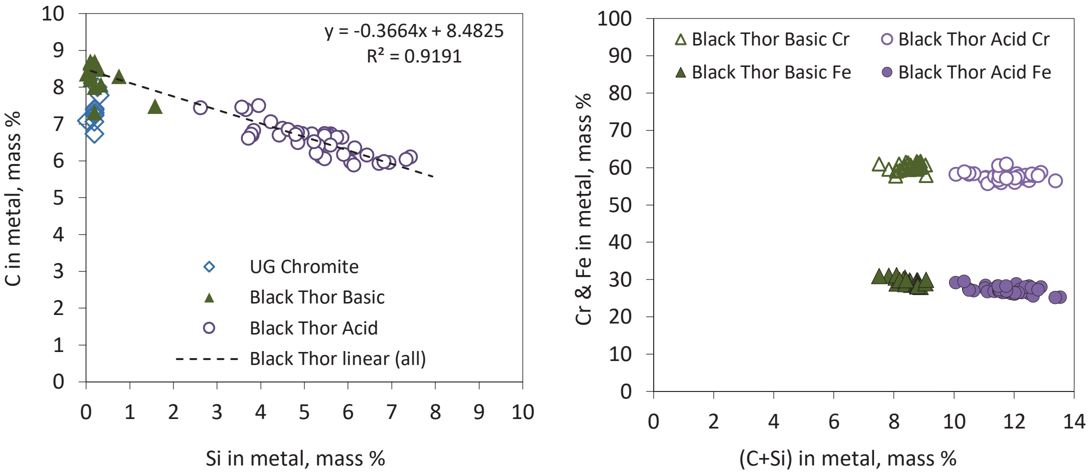


Figure 6. Comparison of metal composition for basic and acid fluxing conditions

The Cr/Fe ratio was consistent during both conditions, namely 2.1, while the lower Cr grade and C content can be attributed to dilution as a result of the increased Si deportment to the metal phase during the acid fluxing period. The Cr/Fe ratios for the metal produced were generally very close to that of the feedstock. Indicative that the bath conditions were close to equilibrium; this is typical for open-bath ferrochrome production. Slag containing less than 4% Cr_2O_3 and about 2% FeO was consistently produced regardless of the fluxing regime. High Cr recoveries were achieved during both the basic and acid fluxing periods, with no statistically significant difference in terms of recovery, which is confirmed by the consistent Cr/Fe ratio of the metal product. Table 5 summarises some of the aspects of the operational outcomes for the two fluxing regimes.

Table 5. Comparison of the basic and acid fluxing periods smelting Black Thor chromite

Aspect	Basic fluxing	Acid fluxing	
Average Cr in metal	61%	59%	
Cr extraction	94%	93%	
Fe extraction	91%	91%	
Recipe basicity ratio	1.44	0.73	
Slag basicity ratio	1.56	1.15	
Silica addition	80	110	kg/t chromite
Limestone addition	200	-	kg/t chromite
Fixed Carbon addition	253	238	kg/t chromite
Average slag temperature	1776°C	1795°C	
Average metal temperature	1732°C	1751°C	
Slag/metal ratio	1.15	0.9	
Metal production	456	477	kg/t of chromite
Energy consumption	2.1	1.8	kWh/kg chromite
	4.52	3.75	kWh/kg of FeCr
	7.31	6.34	kWh/kg Cr in FeCr

During the acid fluxing condition, temperatures were adjusted higher for the sake of fluidity; in the absence of limestone addition, the higher silica content tends to increase the viscosity of the slag. The average slag and metal tapping temperatures during the acid fluxing condition were 1795°C and 1747°C, respectively, about 50°C higher than during the basic fluxing period. The average energy consumption (excluding thermal efficiency), per ton of chromite, was significantly lower during the acid fluxing condition. The basic oxide portion of the recipe, limestone ($CaCO_3$), would have contributed to the difference. While it is common practice to use limestone, it is worth noting that the higher energy requirement for the basic fluxing period, can in part be attributed to the energy consumption associated with the decomposition of $CaCO_3$. In an open-bath furnace, the energy required would be part of the process energy, as there is no burden in which process gas contributes to preheating, for example. There is thus scope to optimise the energy consumption for the basic fluxing condition by not using limestone or to use the process heat from the off-gas to offset this effect, via a pretreatment step. It is usual for ferrochrome smelters to focus on pretreatment of the feed, and a significant electrical energy saving can be achieved via preheating for example.

The specific energy consumption was evaluated and found to agree well with thermodynamic predictions. The average specific energy consumption for the basic fluxing period condition was about 2.1 kWh/kg chromite, while the average energy consumption for the silica only condition was lower, namely about 1.8 kWh/kg. The specific energy consumption excludes thermal efficiency factors and only reflects the process energy requirement. The energy consumption is comparable with literature data for ferrochrome production.

The smelting recipes formulated for the pilot test were selected to demonstrate smelting of Black Thor chromite and to evaluate the boundaries of the operating window. The testwork highlighted that significant opportunities for optimisation exist when designing a ferrochrome smelting recipe. The testwork also successfully demonstrated that production of ferrochrome from Black Thor chromite in a DC open-bath furnace is robust, flexible and efficient with high Cr and Fe recoveries achieved throughout. The pilot test confirmed that a wide range of chromite compositions can be processed using DC technology and that options to optimise the smelting recipe are feasible without compromising Cr recovery.

CONCLUSIONS

The pilot plant testwork conducted at Mintek demonstrated at a significant scale that the Black Thor chromite is suited for the production of good quality ferrochrome and that DC smelting technology would offer significant efficiency and process benefits. The testwork showed that given the right operating conditions, energy consumption and flux addition could minimise energy consumption Cr losses in the slag. In a contained system, such as the DC furnace, the process is both efficient and emissions are containable. The study highlighted the importance and impact of various interdependencies in the ferrochrome system. It is crucial for an operator to understand the sensitivities related to fluxing, and the impact even small adjustments to the fluxing regime may have on operability, refractory life, slag properties, and energy consumption.

The test successfully established that a high degree of Cr recovery, greater than 90%, is achievable when smelting chromite ores in a DC furnace, and demonstrated that slag composition by virtue of the fluxing regime could be optimised to achieve specific objectives, such as Cr recovery, energy reduction or any number of environmental objectives. Ferrochrome with about 61% Cr and low Si content, and metal with about 58% Cr and 5-7% Si was produced, while maintaining a high degree of recovery. The study provides an excellent user reference for the planned ferrochrome production facility in Ontario, Canada.

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