# OPEN-BATH PRODUCTION OF FERROCHROMIUM IN A DC PLASMA FURNACE

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## ABSTRACT

From 1983 a 16 MVA dc open-arc furnace has been used to produce charge chrome at the Krugersdorp Works of Middelburg Steel & Alloys (Pty) Ltd. The paper opens with the reasons for selecting the technology, and a description of the installation. A section on furnace operation shows that the principal function of the measurement and control systems is to match furnace feed rate and electric power input. An account of operational features illustrates the versatility of the furnace with regard to raw materials, demonstrates the process's tolerance to widely differing metallurgical conditions, and indicates some of the differences between open-arc and submerged-arc processes. Strong emphasis on research and development directed at mastering the technology has resulted in a decision to up-rate the operation to 40 MVA, and the paper closes with a description of the scope of this undertaking.

## INTRODUCTION

Middelburg Steel and Alloys (Pty) Limited owns and operates two plants that produce ferrochromium alloys, and a stainless steel plant. At its Krugersdorp Works, adjacent to Johannesburg, charge chrome is produced in two 20 MVA submerged-arc AC furnaces and one 16 MVA open-arc DC Plasma furnace. The latter furnace was built in 1983 and replaced a 9 MVA submerged-arc furnace.

The Company had progressively installed increased capacity at both its ferrochromium plants, generally by uprating existing units, this proving to be a capital-effective method of containing operating costs. It had become evident, by the late 1970s, that there was a need to examine alternative technologies and production methods, particularly those that addressed the variable elements of production cost.

During these studies it became apparent that the Elred process, based upon the single electrode DC arc furnace developed by Asea AB, might be adapted for producing ferrochromium. Metallurgical feasibility was proved by extensive sponsored pilot-scale testwork designed and conducted by the Council for Mineral Technology (Mintek), near Johannesburg, where it was demonstrated that good chromium recovery could be achieved from Transvaal chromite fines in a furnace using dc transferred arc technology.

Accordingly it was decided to convert the existing 9 MVA submerged-arc furnace at the Krugersdorp plant. Asea AB provided the engineering and equipment to install a 16 MVA DC arc furnace, to be fed through a single hollow graphite electrode, to produce charge chrome.

The furnace was commissioned from December 1983. Earlier operation as an industrial unit was hampered by low levels of availability, perhaps not an uncommon occurrence when new technology is put to commercial use for the first time.

## DESCRIPTION OF FURNACE INSTALLATION

### Raw Materials

Raw materials for all three furnaces are stored in fourteen day bins, from which they are drawn for weighing and premixing in a central batching plant, prior to conveying to individual furnaces.

The DC arc furnace is at present using dried chromite fines, fluxes, and anthracite reductant, which are conveyed to a buffer storage bunker placed above the furnace. From here material flows to a feed-bin, mounted on load cells, and thence into the furnace via a vibrator and the hollow graphite electrode.

## Electric Power

Electricity is received from the supply commission at 132 kV and is stepped down to 11 kV prior to transmission to the 16 MVA furnace transformer and the silicon diode rectifier. This configuration provides open-circuit dc voltage range from 300 - 520 v, and a maximum current of 38 kA. Connections to the electrode and the hearth anode plate are by means of suitable bustubes, flexible cables and clamps.

Electrical input to the furnace is controlled through a 17-step transformer tapchanger and 8-step automatic current controller, both on-line.

## Furnace Proper

The furnace tank consists of a cylindrical section 7,5 m diameter, 2,4 m high, mounted on a flanged dished bottom plate. A copper anode plate is fitted to the inside of the bottom plate.

Electrically conductive refractories are employed for the current path through the hearth, and the hearth lining has a thickness of 1,1 m. Sidewall refractory thickness reduces from 1,2 m at the level of the hearth skewbacks to 0,3 m at the top of the shell.

The shell supports a watercooled steel ring structure that carries the furnace roof, consisting of nine watercooled panels, refractory lined, and a sprung, annular centre dome. The graphite electrode passes through the annulus. The roof is provided with sand-seals and the electrode with a gas seal to maintain gas-tight conditions and hence allow control of the furnace atmosphere and pressure.

The single taphole is sited so that a permanent heel of molten alloy is present at all times. This serves to protect the hearth refractories from the potentially destructive action of the arc.

## Tapping

The furnace is tapped at four-hourly intervals, metal and slag flowing together into a cascade system consisting of a refractory lined teeming ladle and cast steel slag pots. Slag temperature is normally 1620 - 1640°C, and metal is at 1550°C. After tapping, the ladle is transferred to teeming station by an overhead travelling crane. Alloy is cast in moulds to form ingots weighing approximately 3 tonnes, and the slag is tipped into a pit for cooling and disposal.

## Gas Handling

Off-gas from the furnace passes through a refractory-lined offtake and duct to a vertical cylindrical water-quench chamber. Cooled gas passes from the top of the chamber into a horizontal duct where a steam/water injection nozzle wets and agglomerates the remaining solid particles, and these are separated from the gas phase in a cyclone chamber. Both the scrubber and cyclone are provided with underflow pipes and gas seals. Cleaned gas is combusted via a flare stack, and the slurry is treated for water/solids separation.

## Temperature Measurement

Twelve thermocouples in the furnace hearth are arranged in a concentric pattern radiating from the centre, and a further three are situated in the hearth area below and adjacent to the taphole. Fifteen thermocouples in the sidewall refractories are situated at five points on the circumference at three levels.

Gas temperature is measured in the refractory-lined ducting and in the scrubber. Inlet water temperature to the roof and outlet water temperature from each panel are measured by RTD.

All thermocouple readings are displayed on continuous chart recorders. All measured temperatures are recorded and displayed in the main control system, described later in this paper. This latter system has the capability of indicating pre-set alarm conditions.

## OPERATION AND CONTROL

Operation of the furnace is effected from a control room where all the required information is displayed in digital, analogue or mimic form. The heart of the control system is a combination of a programmable ASEA MP 260 front-end, and an IBM PC-AT information processor. The Asea MP is programmed by means of an intelligent unit which can program offline and perform online testing.

Front-end software is very task specific, while the IBM PC-AT is well suited to information processing, reporting, and graphics generation for a well-developed furnace operation mimic. Communication between the IBM and a Data General MV20 000 mainframe multi-user system allows remote access to online furnace data, as well as processing of the stored data.

The system's principal control function is to maintain the required ratio between raw materials feed rate and electric power input, i.e. kg/kWh. The prescribed ratio is set into the system via the IBM PC keyboard.

There are some 60 digital input signals into the system from the various process areas; these are generally characterised as status and/or alarm. Some fifty analogue input signals are concerned mainly with temperature measurement, e.g. 29 furnace refractories thermocouples, furnace electrical parameters, and furnace feed system status.

Analogue outputs are directed to controlling raw materials feed rate and displaying rate-related parameters on meters mounted in electrical panels in the furnace control room.

Summarising, the required power level (normally maximum) is set by transformer tap and current controller step selection, and the prescribed feed/power ratio is keyed into the control system.

## METALLURGICAL AND OPERATIONAL FEATURES

Some of the advantages claimed for thermal plasma-type processes have been realised in the DC arc furnace.

The process uses cheaper raw materials than those required by the submerged arc process, leading to a reduction in variable cost of production.

The use of a hollow graphite electrode is well suited to treating unagglomerated fines. Carry-over of chromium into the gas handling system has been less than 1% when using chromite fines having wide ranges of size distributions.

The process is not dependent on metallurgical coke, anthracite being used as a reductant in the present furnace. The use of bituminous coal has also been successfully demonstrated, but the limitations of the gas handling plant prevent its utilisation at full furnace load.

Reduction of chromite is more complete and chromium recovery is higher in the DC arc furnace than in our other furnaces, giving another cost advantage.

It is relatively easy to strip all the $Cr_2O_3$ from the slag phase, and it is a feature of the process that $SiO_2$ will not remain reduced to any great extent until the oxide chromium content of the slag is below 3%. Chilled slag contains up to 3% chromium in a metallic form, both as prills and as small blebs of metal that have not been released from the remains of the spinel. These losses also occur in slag from our sub-arc furnaces.

An open-bath process allows more freedom in selecting slag composition regimes than does the sub-arc process, particularly because there is no restriction imposed by considerations of electrical resistance. This freedom, together with the consistency of raw materials composition, results in the ability to control silica reduction more closely, and to produce alloy compositions that cannot be achieved in our other furnaces. In addition, freedom from concern with electrical resistance means that electrical input to the furnace does not deviate from the prescribed level.

Table 1 illustrates the conditions for producing two typical alloy compositions from Transvaal chromites.

**Table I : Typical alloy composition, slag composition and furnace feed ratio for low and medium silicon alloy**

| | low silicon alloy | medium silicon alloy |
|---|---|---|
| **Alloy composition** | % | % |
| Cr | 53.5 | 52.0 |
| Si | 1.0 | 4.0 |
| C | 8.5 | 7.5 |
| S | 0.020 | 0.010 |
| P* | 0.010 | 0.010 |
| **Slag composition** | | |
| $SiO_2$ | 26.0 | 28.0 |
| MgO | 22.0 | 23.0 |
| CaO | 18.0 | 14.0 |
| $Al_2O_3$ | 34.0 | 35.0 |
| **Furnace feed ratio** | | |
| chromite | 100.0 | 100.0 |
| limestone | 15.0 | 12.0 |
| quartz | 7.0 | 12.0 |
| anthracite | 32.0 | 33.0 |

* Phosphorus content is lower than in alloy from our sub-arc furnaces (.015%), but this is due to freedom in selection of raw materials, in particular the reductants.

The sidewall refractories become lined with a protective layer of partly-reacted material, slag, or frozen alloy. The thickness of the layer is controlled by varying the slag composition within the range selected for producing a particular alloy. There is freedom to manipulate the $SiO_2$ and CaO contents of the slag independently so as to obtain the required furnace condition. The process responds promptly and predictably to changes imposed upon the metallurgical regime.

Although the furnace has generally smelted Transvaal chromite, a campaign was run on an ore with Cr:Fe ratio of 3:1. One interesting feature was that the content of MgO and $Al_2O_3$ in the ore were significantly different from normal Transvaal ore levels (Table 2).

The differences required that a slag composition be employed that was far removed from the normal operation to maintain comparable slag to metal ratios. In particular the slag would contain 22 - 25% $Al_2O_3$, compared to 35% when smelting Transvaal chromite. This necessitated employing higher than normal $SiO_2$ levels in order to remain within the spinel field and away from the periclase field of the $SiO_2$ - MgO - CaO - $Al_2O_3$ quarternary system. The liquidus temperatures of the slags were approximately 100°C below those of the typical operation.

The smelting campaign did not cause difficulties, and the mean compositions of alloy and slag are shown in Table 3.

The furnace has been used for co-melting alloy fines, also unagglomerated, thus converting off-grade material to a saleable commodity.

**Table II : Chemical Composition of Chromium Ores**

| | $Cr_2O_3$ | FeO | $SiO_2$ | MgO | CaO | $Al_2O_3$ |
|---|---|---|---|---|---|---|
| Transvaal ore | 43.5 | 25.2 | 4.0 | 10.0 | 0.5 | 14.5 |
| High ratio ore | 49.5 | 13.7 | 5.3 | 18.7 | 0.1 | 10.9 |

**Table III : Composition of Alloy and Slag Produced from 3:1 Ratio Chromite**

| Alloy | Mass % | Slag | Mass % |
|---|---|---|---|
| Cr | 63.7 | Cr (total) | 2.3 |
| Fe | 23.9 | Cr (oxide) | 0.4 |
| Si | 3.5 | $SiO_2$ | 32.9 |
| C | 8.6 | MgO | 29.1 |
| S | 0.009 | CaO | 12.2 |
| | | $Al_2O_3$ | 22.2 |

Turning to some negative aspects of performance:

- Energy requirements are higher than for our other furnaces because of inherently higher levels of heat losses from the system - through the rectifier, the refractories, the watercooled roof, and in the off-gases. The topic is further addressed in the last section of this paper.

- Furnace availability has been lower than for the sub-arc furnaces, but has steadily improved over time, through correcting inadequacies in the feed system, improving the performance of ancillary equipment, and better management of refractories through re-design and the installation of many more thermocouples than in the original design. The main cause of downtime then became the gas handling and cleaning system, where blockages necessitate switching out the furnace for manual cleaning of the ducting.

Fig 1 - 3 illustrate progress made in furnace availability, power input and alloy production during the period 1984 - 1988.

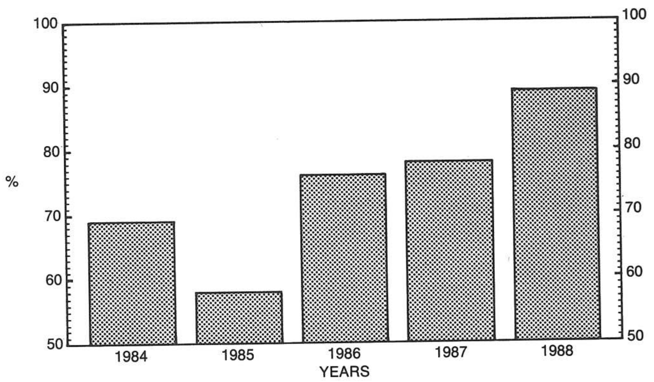


FIG 1: FURNACE AVAILABILITY PERCENT

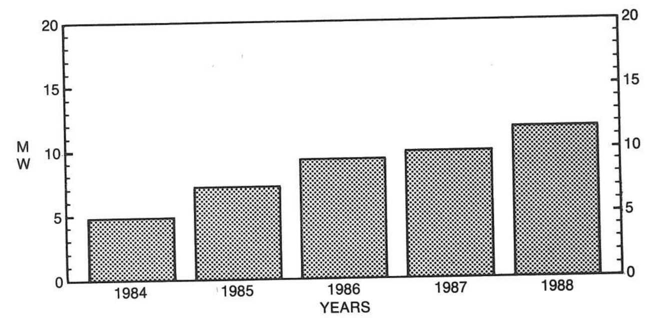


FIG 2: MEAN LOAD (MW)

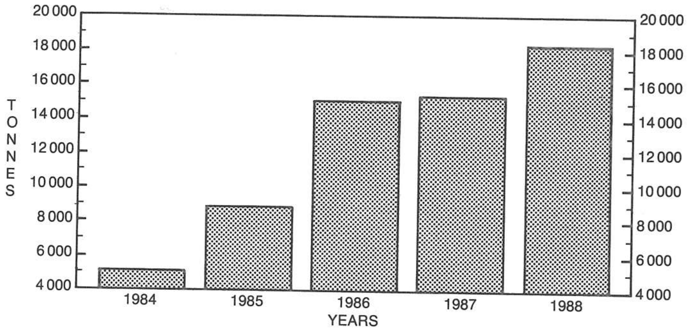


FIG 3: ANNUAL PRODUCTION ALLOY TONNES

- The carbon content of the alloy produced is higher than that of our sub-arc furnaces at equivalent silicon levels. Typically at 3,5% silicon the carbon content is up 0,5% at 7,8 which is closer to the expected equilibrium level. In the sub-arc process a limited degree of refining is effected as the metal droplets filter through the viscous chromium oxide-rich slag above the alloy. However, the slag in the dc operation is rapidly stripped of chromium oxide as a result of the favourable reduction kinetics and as such does not permit the slower refining reactions to proceed to any significant extent. Moreover, the lower viscosity of slags employed in the dc operation further reduces the possibility of affecting the refining reactions.

- Stringent control is necessary in order to remain at the optimum power/feed ratio. Cold conditions cause difficulty in feeding and in tapping the furnace, while imbalance in the other direction leads to wasted energy in overheating slag and refractories, and driving unwanted reactions.

The following are some further differences between dc open-arc and submerged-arc furnace operating characteristics:

| | Open bath | Submerged Arc |
|---|---|---|
| Time constants | short | long |
| Response to change | rapid | slow |
| Feed/energy matching | minute to minute | self-regulating |
| Energy recovery within the process | none | by the burden |
| Metal temperature | low | higher |
| Sulphur control | good | not as good |
| Refractories management | critical | easier |
| Self-baking electrode | no | yes |

## FUTURE PLANS FOR THE FURNACE

### Uprating

Towards the end of 1987 the decision was taken to uprate the furnace from 16 MVA to 40 MVA. There were several reasons for adopting this option:

- The Company's requirement for additional charge chrome capacity; uprating the present furnace is a capital-effective and rapid means of doing so.

- Improved energy efficiency can be expected at higher power input levels because losses will not rise in proportion to the increased power input. This, when coupled with the already demonstrated advantages with regard to cost and improved utilisation of raw materials, will give the unit a considerable variable cost advantage over a sub-arc furnace.

- Attention has been given to the selection and design of ancillary plant and equipment which, it is believed, will result eventually in a higher furnace availability.

At the time of writing (November 1988), plans are well advanced; the 16 MVA furnace was switched out at the end of September 1988, and the uprated furnace will be commissioned from December 1988. It is expected that full power on a continuous basis will be achieved some 18 - 21 months from that date. A photograph of the new furnace is shown in Fig. 4.

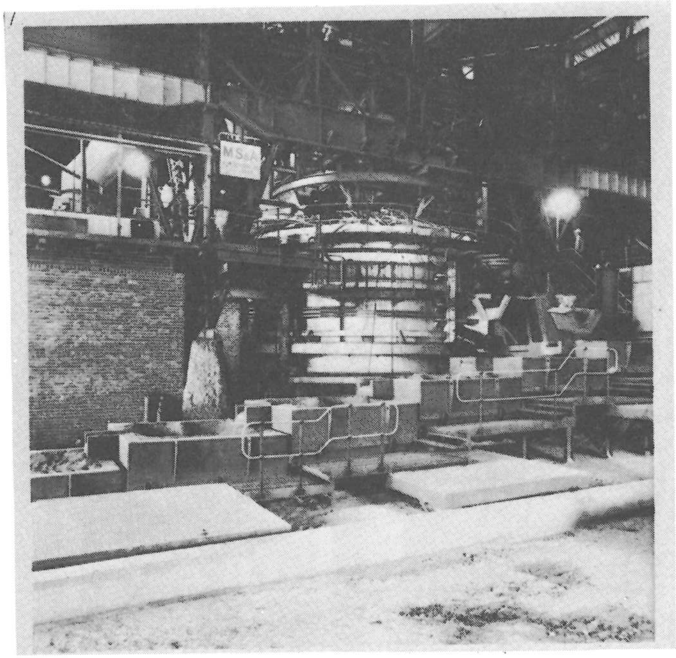

Fig. 4 40 MVA DC Plasma Arc Furnace

The scope of the undertaking is summarised briefly below.

The electrical system comprises two furnace transformers plus a spare, each rated at 20 MVA, two banks of thyristor rectifiers each rated at 30 kA, filters for harmonic suppression, and the necessary switchgear, etc.

The existing plant for drying, storing, and batching raw materials has been extended to provide a dedicated system for the DC arc furnace. New hardware and software provides for feeding the furnace through the hollow electrode and through additional (new) feed ports in the roof.

Metal and slag handling facilities are being extended, and a 40 ton overhead travelling crane has been installed to cope with the increase in production.

A high-energy venturi scrubber has been installed to clean the off-gas. This unit has sufficient capacity to allow the use of bituminous coal reductant.

Furnace shell diameter has been increased from 7,5 m to 9,0 m, and the height (roof to top of hearth) from 3,7 m to 4,7 m. The slope of the roof has been reduced from 30° to 20°. These measures will allow the depth of the permanent metal heel to be increased from 0,5 m to 1,0 m, and there is a considerable increase in the freeboard above the surface of the melt.

A number of criteria were examined when selecting the dimensions of the new furnace, among which were:

- the required lining thickness
- power and current density through the hearth
- materials feed rate
- tapping interval, and volumes of alloy and slag
- superficial gas velocity and rate of displacement.

Modifications to measurement and control systems will result in a number of enhancements, including the following:

- Current control by thyristors and voltage control by electrode movement will result in a more stable arc than in the 16 MVA furnace.

- It will be possible to control the feed rate in terms of kg/kWh at each of the individual feed points.

- A programmable logic controller will be installed to serve as back-up, in case of failure of the Asea MP260.

**Process Development**

Over the life of the furnace the Company has placed strong emphasis on directed research and development aimed at rapidly developing this novel technology to the level it has now achieved. Until very recently the furnace has been under the control of a dedicated Process Development Division at the

Krugersdorp works. Much of the initial work was undertaken in conjunction with Mintek on their pilot facilities. Numerous and diverse sponsored projects have been undertaken which together with the daily production results from the furnace have led to a clearer understanding of the process chemistry of open bath reduction smelting of chromite. Our staff have access to a powerful computerised statistical package which has led to the development of reliable predictive and analytical process models. This emphasis will continue and develop with the operation of the uprated furnace.

## CONCLUSION

The authors have attempted to describe the application of the single-electrode DC arc furnace to open-bath smelting reduction of chromite ore fines. Some of the expected benefits have been amply realised, and the additional advantages that will accrue from operating at 40 MVA, together with improvements in furnace and ancillary equipment, should lead to an efficient and cost-effective operation.

Looking further into the future, there is still the challenge and opportunity of combined melting/smelting of pre-reduced chromite, for which this type of furnace is well suited.

## ACKNOWLEDGEMENT

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