

The application of thermal plasma technology to large-scale
pyrometallurgical processes

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SYNOPSIS

The requirements for large-scale applications of thermal plasma in extractive metallurgy are examined. The most likely processes in which plasma may find industrial use in the near future are iron making and ferro-alloy production in the power range from 10 to 100 MW.

The current and voltage characteristics of the various plasma devices discussed are related to the consumption of their electrodes and stabilizing gas, which are of particular importance in large-scale process applications. The implications of these factors upon the interfacing of plasma devices with smelting furnaces is studied, and current process applications are reviewed.

The experience of the Council for Mineral Technology (Mintek) with the open-bath transferred-arc plasma configuration is used in the description and evaluation of this system as a proposed method by which thermal plasma technology can be utilized. The open-bath

configuration is compared with the other major configuration that has emerged, namely the non-transferred-arc shaft furnace. It is pointed out that before one of these two options is selected as being better suited to a particular process, consideration must be given to the thermal efficiency of the process, the electrode consumption, and the possible loss of products in the off-gas stream.

INTRODUCTION

Thermal plasma technology is reaching the stage at which its large-scale application is becoming feasible. Large scale means that power levels greater than 10 MW are generated by the plasma system, which can comprise one or more plasma devices. This high power level is necessary for the processing of relatively large quantities of materials of essentially low value.

The general relationship between the power requirements and the approximate value of the material being processed is illustrated in Fig. 1. Materials of high value generally require only a rather small-scale operation, typically in the range 500 kW to 2 MW. Examples of such materials are the platinum-group metals (PGM) in spent exhaust catalysts or in residues like anode slimes. Certain gold-bearing refractory ores or concentrates containing high levels of this precious metal could also be considered for treatment in a small-scale plasma system and, although no known commercial process for these materials exists, treatment of the PGM is a reality on the industrial scale¹. These high-value materials fall into Group I in Fig. 1.

Medium-value materials, i.e. those falling into Group II in Fig. 1, are priced between 2×10^3 and 10^4 U.S. dollars per ton, and

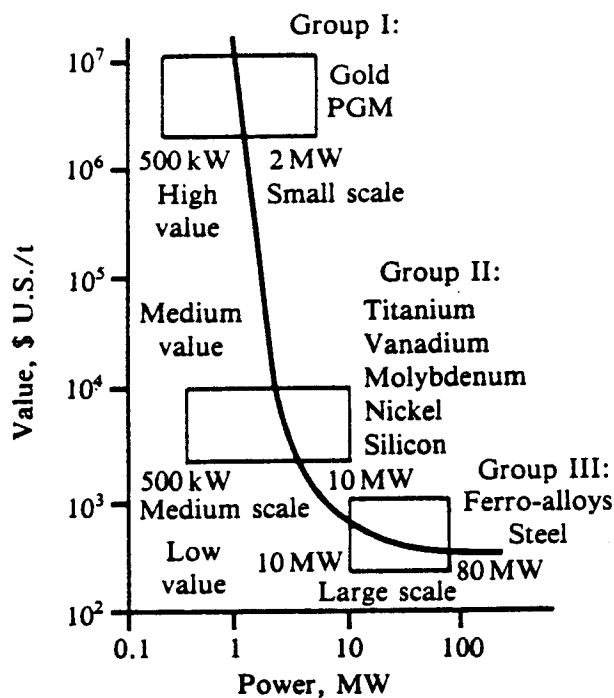


Fig. 1. The relationship between power requirements and the approximate value of the materials being processed

require processing at a small- to medium-scale of 500 kW to some 10 MW, e.g. the melting of titanium and nickel alloys at Daido Steel in Japan.² Proposals for ferrovandium and vanadium^{3,4}, ferromolybdenum and molybdenum⁵, and silicon⁶ have been made in the literature, but no commercial process exists at present.

Low-value materials, i.e. materials priced from 10² to 10³ U.S. dollars per ton fall into Group III in Fig. 1, and include iron, steel, ferro-alloys, and titania-rich slags, which are processed at high throughputs that necessitate operation at high power levels, namely some 10 to 100 MW. This paper is concentrated mainly on this area.

The capital cost of new large-scale plant equipment is very high, and producers of materials of relatively low value, using conventional processes and installed plant, are often strongly

resistant to change. The advantages of a new technology, therefore, must more than offset the major disadvantages of the high capital costs, especially where the existing capacity is still able to meet the demand. However, new undertakings or the expansion of existing ones offer the producer an opportunity to pilot and, if the results are sufficiently convincing, to implement new and improved technology. New technology affords the best opportunity for research, development, and the subsequent transfer of technology right up to plant-scale operation, where present technology does not offer a suitable solution to the processing of a given material or the manufacture of a new product.

The advantages of thermal plasma as a source of high-temperature energy make it potentially suitable for many applications to new and existing processes. The specific advantages to be gained depend primarily on, or relate to, the plasma device used and the manner in which it is interfaced with the reactor in which the given material is processed. Where possible, the advantages should also be assessed in relation to alternative or conventional processing methods.

In extractive metallurgy, thermal plasma technology has more-general advantages, especially when it is compared with systems in which combustion is the temperature source, namely the very high temperatures that are attainable, and the independence of the oxygen potential. These characteristics and conditions are necessary for the reduction of elements that occur in nature, usually as the oxides of, for example iron, chromium, manganese, magnesium, silicon, titanium, and aluminium, i.e. where reactions are highly endothermic or require strongly reducing conditions, or both.

In the context of extractive metallurgy, i.e. smelting, therefore, plasma technology is less likely to be applied to elements like copper, nickel, zinc, and lead, which usually occur as sulphides. These materials are generally processed at lower temperatures, and require less stringent reducing conditions to produce the metal product. However, this consideration does not apply where volatilization or pyrolysis is required and a low oxygen potential is necessary.

The Council for Mineral Technology (Mintek) has been involved in research-and-development work on the application of thermal plasma since 1976.⁷ A multi-purpose pilot-plant facility has been installed at Mintek, and experimental campaigns and the ongoing development of equipment are major activities. The key objectives of the work done on these pilot-plant facilities are: the determination of the amenability of various local ores to processing by plasma technology and the determination of whether improved processes (i.e. technically and commercially) can be found.⁸ Mintek's fundamental-research activities are directed towards a better understanding of the efficiency of conversion from electrical to thermal energy. Factors that control the absolute rate of the process are also of great importance, and research has been started in this area. Most of the work has been done on materials of relatively low value, e.g. ferro-alloys, iron, steel, and stainless steel, because South Africa has an abundance of the associated minerals. Hence, the attainment of large-scale plasma systems has been of particular interest to Mintek and to the local pyrometallurgical industry.

THERMAL PLASMA DEVICES

A thermal plasma is described as a plasma in which the bulk of the plasma approaches a state of local thermodynamic equilibrium (LTE). LTE is generally explained as the thermodynamic state approached by an optically thin (the plasma does not absorb any of its own radiation), collision-dominated plasma in regions where spatial variations are small enough to allow the moving plasma species to adjust continually to their environment. When such plasmas are used in large-scale pyrometallurgical processes, they are generated exclusively from a high-intensity arc-discharge configuration. This arc or thermal plasma is always derived from a cathode and terminates at an anode. The specific shape and composition of these electrodes are varied. Electrodes shaped as rods, buttons, tubes, or rings are common. Rod and button electrodes are usually made of thoriated tungsten (2 to 3 per cent ThO_2) or graphite, while tubular electrodes are made of copper or steel. In certain instances, the workpiece (or, specifically, in smelting systems, the molten bath of slag and metal) is an electrode. This has led to the generally accepted categorization of all plasma devices into either transferred-arc or non-transferred-arc systems, as illustrated in Fig. 2. In the transferred-arc system, the workpiece need not necessarily be the anode, but can also be the cathode, or even the anode and the cathode for an a.c. configuration. Numerous general reviews covering the particular configurations of the range of proposed, piloted, and commercial systems are available.⁷⁻¹³

The power generated by a given device is dependent on its operating current and voltage and is required to meet the energy needs of the process. These characteristics of various high-power

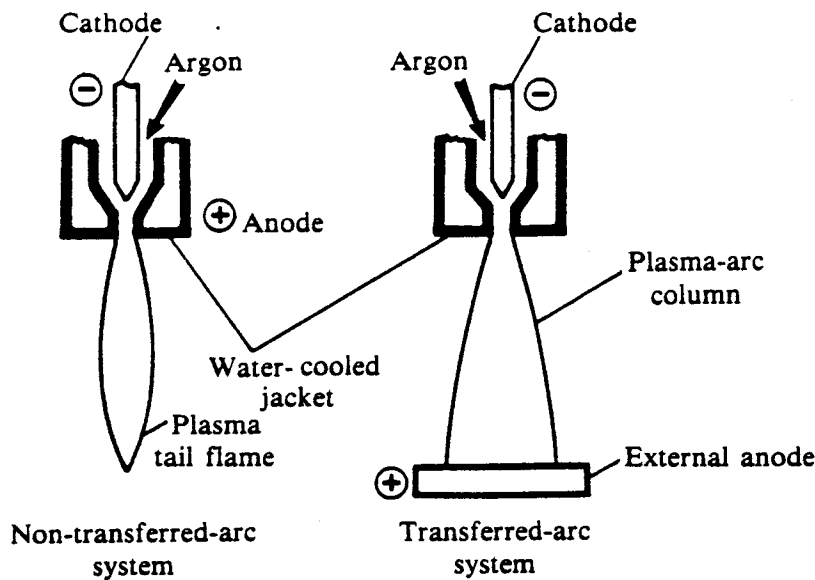


Fig. 2. Transferred- and non-transferred-arc systems using rod and tubular electrodes

plasma devices used in large-scale pyrometallurgical processing are illustrated in Fig. 3. The devices tend to be grouped according to electrical constraints encountered when high-power arcs are generated.

High-current low-voltage devices (group 1)

These devices are all operated in the transferred-arc mode, the arc being struck between a graphite electrode and the surface of an open bath. Rod-type graphite electrodes are desirable thermionic emitters since they can carry up to 100 kA with relative ease. This use of a single, hollow graphite electrode (multiple for an a.c. system) overcomes scale-up problems associated with water-cooled torches in regard to current-carrying capacity.

Intermediate-current, low-voltage devices (group 2)

Although these devices are also normally operated in the open-bath transferred-arc mode, they all rely on a water-cooled plasma torch as one of the electrodes. A typical thermionic-emitting cathode device is shown in Fig. 4. These water-cooled plasma torches

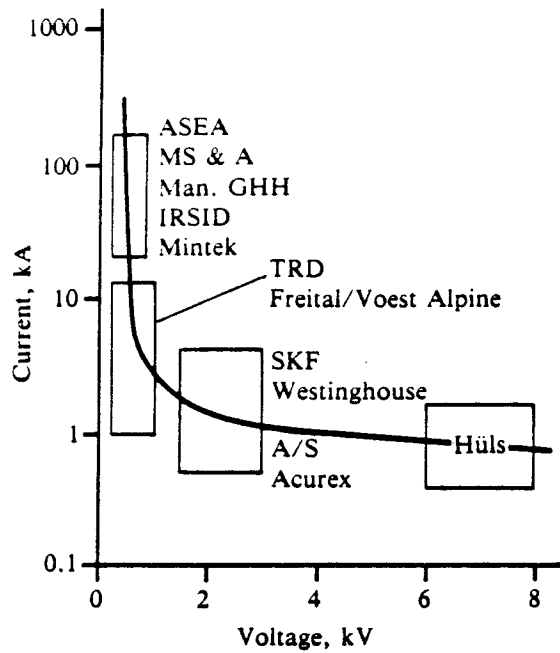


Fig. 3. Characteristics of plasma devices

KEY:

- MS&A - Middelburg Steel and Alloys
- IRSID - Institut de Recherches de la Siderurgique Francais
- TRD - Tetronics R & D Ltd
- A/S - Aérospatiale plasma torch

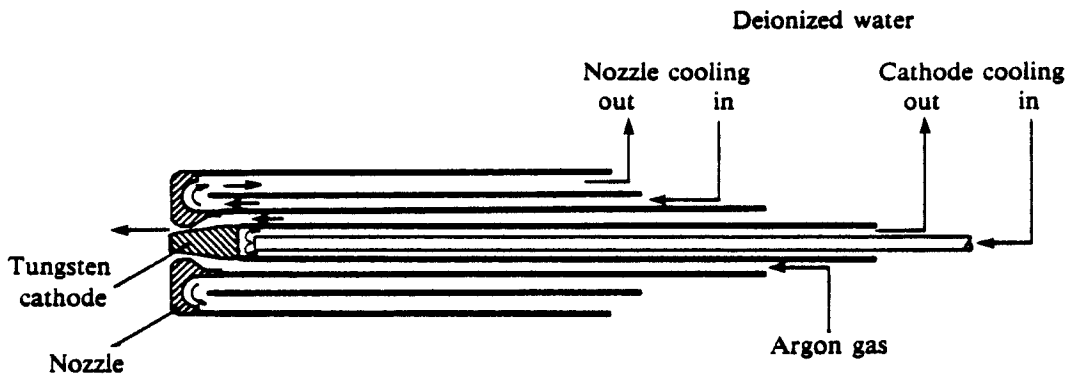


Fig. 4. Tetronics Research and Development Limited water-cooled transferred-arc cathode torch with rod electrode (after Page¹)

usually employ a tungsten electrode, which is surrounded by a copper jacket to direct the gas flow and to stabilize the arc. This jacket is normally at a floating potential. As a result of present restrictions on the current-carrying capacity of these devices (less than 10 kA), more than one cathode is used to effect scale-up to higher power levels. Their geometrical arrangement in the furnace is important, since the magnetic field surrounding each arc affects the directional stability of neighbouring arcs. For example, the Freital furnace system marketed by Voest-Alpine employs multiple 10 kA torches introduced laterally into the side of the furnace to prevent the arcs from converging above the surface of the melt in their high-power (20 MW) furnace.⁸

Low-current, intermediate-voltage devices

A major step forward in the development of these high-voltage devices was provided by the programmes of the National Aeronautics and Space Administration (NASA) in the 1960s, and most of the devices used for large-scale pyrometallurgical processing derive from this period. Tubular water-cooled copper electrodes are generally used. These field-emitting cathodes and the specific arc-stabilizing technique employed allows these devices to operate at relatively high voltages (1 to 3 kV). Magnetic stabilized arcs (e.g. the Westinghouse arc heater¹⁴), wall-stabilized cascade arcs (e.g. the Tioxide arc heater¹⁵), or combinations of these (e.g. the SKF arc heater¹⁶, which is illustrated in Fig. 5) are generated entirely within the device. In the transferred-arc devices discussed previously, these high voltages are not attainable since the arc voltage is controlled more by the process than by the device itself. The generation of the arc in the device also facilitates scale-up to the higher power levels (greater

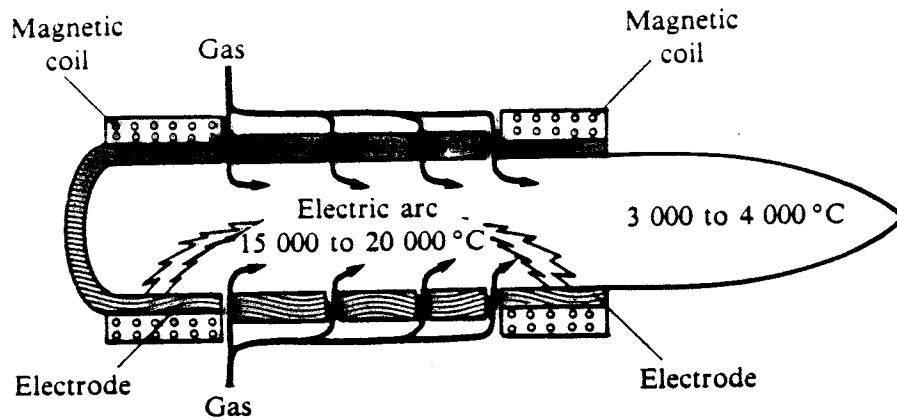


Fig. 5. The SKF tubular arc-heater device for operation up to 6 MW (after *Metallurgical Plant Technology*¹⁶⁾)

than 8 MW) required for large-scale pyrometallurgical processing by the use of multiple independent devices.

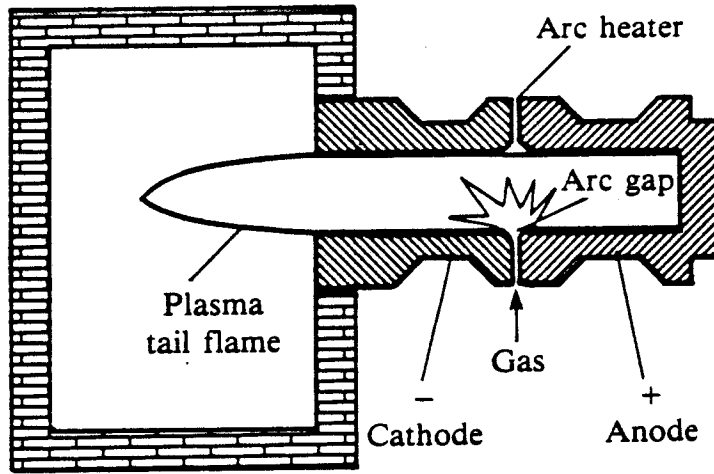
Low-current, high-voltage devices

The Hüls arc heater¹⁷ is unique since it operates at very high voltages (7 kV), and is the ancestor of the devices used in the NASA programmes. Although similar in design to the intermediate-voltage devices, this device achieves the higher voltage as a result of the long arc length obtained at high gas velocities. As these devices can attain high powers (8,5 MW) at low currents, they have very good electrode life - up to 1000 hours.

THERMAL PLASMA FURNACES

From the point of view of the process metallurgist interested in carrying out metallurgical reactions, the coupling of a specific plasma device with the process in a furnace is of prime concern. The interfacing of the device in large-scale pyrometallurgical furnaces is accomplished in one of two basic ways, as illustrated in Fig. 6. This has extended the terminology 'transferred-arc' and 'non-transferred arc' to the furnace. Transferred-arc furnaces are

Non-transferred-arc system



Transferred-arc system

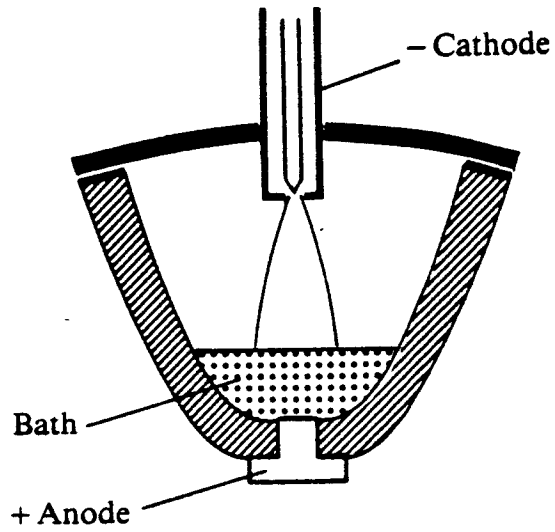


Fig. 6. Schematic arrangement of the interfacing of plasma devices with furnaces

generally open-bath reactors in which the device usually comprises the cathode, and the bath constitutes the anode connection to the plasma arc. Non-transferred-arc furnaces rely on the device to heat a process gas to temperatures higher than those attainable by the conventional combustion of fossil fuels. The arc-heated gas is then conveyed to the reactants to provide the energy required by the metallurgical process. Although various configurations can be used to accomplish this coupling, the shaft-furnace approach is used exclusively in large-scale pyrometallurgical processing.

Open-bath furnaces

Large-scale open-bath systems can be based on water-cooled metallic devices or on solid graphite electrodes. The water-cooled devices produce very stable, well-directed plasma-arc columns that can be readily transferred to an open bath. However, multiple water-cooled devices might be required to achieve the desired level of power, and the use of a single graphite electrode operating at higher currents could be favoured. In many instances, there is no need for a sophisticated water-cooled metallic electrode with gas support to be used as the plasma device. A simple graphite electrode will suffice, although improved arc stability can be realized by the introduction of some plasma-supporting gas down a small hole in the solid electrode and by the shaping of the end of the electrode to improve the directional stability of the arc to the bath. Direct-current operation and a high-temperature environment improve arc stability even further. Conventional three-phase a.c. open-arc furnaces use three graphite electrodes, which do not have the manoeuvrability of water-cooled devices. Arc deviation as a result of the magnetic field surrounding each arc can cause

energy to be directed to the side wall of the furnace rather than to the bath, especially when open-bath and long-arc conditions prevail.

Shaft furnaces

Large-scale shaft-furnace systems are usually based on multiple high-voltage devices that are either directly or indirectly interfaced with the process.

Direct interfacing is accomplished as follows. The super-hot gases from the 'tail flame' of the device, or devices, are directed into the reaction zone or cavity at the base of a coke-filled shaft furnace.¹⁸ The coke in the shaft is essentially a refractory shield or cover for the tail flame and the surface of the bath, and also permits the product gas to escape. The bulk of the carbonaceous reducing agent (e.g. coal fines) for the smelting process is fed, with the optionally prereduced feed, into the lower part of the shaft. (The ratio of the reducing agent to the coke is about 5.)

Indirect interfacing refers to an arrangement in which the device is used merely to reform or superheat a gas stream that is subsequently directed into the base of the blast or shaft furnace. The arc-heater device is not directed into the blast furnace itself but into the gas stream before the latter enters the tuyères.

PROCESS APPLICATIONS

At present, the open-bath and shaft-furnace systems are both being applied commercially on a large scale to accomplish metallurgical smelting reactions. These processes include: iron making, the smelting of ferro-alloys, and the smelting of ilmenite.

Iron making

Cockerill Steel employ an indirect interfacing with a shaft furnace in their Pirogas process¹⁹ to superheat the gas blast to a conventional blast furnace.

The conventional blast furnace for the production of pig iron uses only chemical energy, which is derived from the combustion of relatively expensive coke in the tuyère region by the injection of a hot-air blast. The rate of coke consumption in the blast furnace is normally 400 to 600 kg/t, but the use of electrical energy can lower the rate of coke consumption to less than 200 kg/t. Testwork has been carried out by Centre de Recherches Metallurgiques (CRM) on an experimental blast furnace pilot plant in Belgium. Subsequently, testwork was carried out on an industrial-scale blast furnace at Cockerill Sambre Company in Belgium, using a single Westinghouse (intermediate-voltage) arc heater rated at 3,5 MW. Air and natural gas have been heated with the plasma device so that the decrease in coke rates on this industrial scale could be evaluated. The performance so far has been satisfactory, and further developments are awaited.

SKF use direct interfacing with a coke-filled shaft furnace in their Plasmadust and Plasmasmelt processes.¹⁸

In the Plasmadust process, the arc heaters are installed in the base of a coke-filled shaft furnace. Dust from the production of special steels, which are high in chromium, nickel, molybdenum, and iron oxides, and powdered coal are injected directly into the lower regions of the furnace close to the arc heaters. Successful pilot operations with a 1,5 MW arc heater have led to the building of a commercial 18 MW demonstration plant in Landskrona in Sweden. Three 6 MW intermediate-voltage arc-heater devices are required to



process 70 000 t of steel-plant dust per year to produce 35 000 t of pig iron, containing chromium, nickel, and molybdenum, per year.

Instead of the conventional blast-furnace process, the Plasma-smelt route is based on the direct use of iron oxide ore fines. These ore fines are dried, preheated, and prereduced in fluidized-bed reactors to some 60 to 70 per cent metallization, and then injected directly into the lower region of a coke-filled shaft furnace. The thermal energy is supplied by arc-heater devices located in what would be the tuyère region of a blast furnace. The prereduced ore fines and plasma tail flame interact directly on the coke layer in the base of the shaft furnace. Coal fines and fluxing agents are added with the prereduced feed to complete the smelting process. The coke consumption is minimal at about 50 kg per ton of pig iron produced. The optimum relationship between the degree of prereduction and the generation of the process gas required for prereduction from the smelting stage can be achieved by the balancing of the coal-to-oxygen ratio and the input of electrical energy. Proposals for an industrial plant were made recently in Sweden but, as yet, the plant is only a paper study and no testwork, apart from the pilot-plant work at SKF, has been done.

ASEA have opted for the transferred-arc open-bath furnace approach in their ELRED²⁰ process to produce pig iron. This process, like the SKF Plasmared route, has been used only on a small-scale (12 t/d) pilot plant but it, too, has the potential for scale-up to a large industrial-scale operation (40 to 60 MW producing 600 000 t/a). ASEA uses a single hollow graphite electrode as the arc-generating device, and is thus able to increase the power input to the furnace by increasing the arc

current up to 100 kA. Prerduced ore fines metallized to about 60 per cent are fed hot (700°C) to the furnace via the hollow electrode. The process produces surplus gas, which could be used for other purposes, for example the generation of electricity.

Ferro-alloy production

Middelburg Steel and Alloys (MS & A) employs the transferred-arc open-bath furnace approach for the smelting of chromite ore.²¹

The final configuration was arrived at after extensive pilot-plant investigations by MS & A, ASEA, Mintek, and Tetronics Research and Development Limited. Initial work involved the use of an intermediate-current water-cooled device. This original pilot-plant work was carried out up to power levels of about 750 kW at Tetronics in the United Kingdom.²² However, it was decided that further testwork was required on the use of a high-current device (namely a hollow graphite electrode) that would readily facilitate scale-up to the power levels required for this commercial plant.

Numerous subsequent campaigns, in which a hollow graphite electrode was used, were undertaken at Mintek. Limited tests were also carried out on Mintek's 3.2 MVA facility at power levels of up to 400 kW as a 'training' exercise for the 20 MVA furnace. The design of the commercial furnace was based on the ASEA d.c. arc furnace that had been developed for the ELRED process discussed earlier, but was modified in the light of the experience gained in the pilot-plant work.

Patents²³, held jointly by Mintek and MS & A, cover the smelting of chromite (including the co-melting of metal fines) and the refining of high-carbon ferrochromium containing 7 to 8 per cent carbon and some 3 to 5 per cent silicon to medium-carbon ferrochromium containing 3 to 4 per cent carbon and less than 1 per cent

silicon.

The MS & A furnace has been in operation since the end of 1983, and has produced several thousand tons of ferrochromium. Thus the d.c. arc-furnace process has been scaled up to an industrial operating level. Feedback on performance factors like efficiency, etc., are still not available to the outside World, but should be disclosed in due course.

SKF have opted for the alternative furnace configuration in their process for ferrochromium smelting.¹⁸ Following pilot-plant work at the 1,5 MW level in a coke-filled shaft furnace with an arc-heater device, SKF have proposed several processes, including the smelting of chromite fines to produce ferrochromium alloys. Although no plants have been built on the industrial scale for either Plasmasmelt (iron) or Plasmachrome, the demonstration plant in Landskrona will also be used in demonstration-scale tests on the Plasmachrome process (as well as other processes, e.g. for ferromanganese²⁴ and ferrosilicon²⁵). A plant using the SKF process to produce some 78 000 t of ferrochromium per year is expected to go into production in 1986 near Malmo in Sweden.¹⁶

Ilmenite smelting

Richards Bay Minerals²⁶ (RBM) and Quebec Fer et Titane (QIT) employ 6-in-line graphite electrode furnaces for the smelting of ilmenite.

Physically the furnaces are 19m long and 8m wide and are supplied with three transformers rated at a total of 105 MVA per furnace.

The process originally developed by QIT (who smelt Allard Lake ore, a coarse-grained pegmatite) has been adapted at RBM to smelt fine ilmenite obtained from a beach-sand deposit on the north-eastern coast of South Africa. The process employs a relatively open-bath approach, for which careful control is required to avoid

refractory erosion of side and end walls.

The installed electrical capacity has the potential to make these furnaces the largest scale transferred-arc plasma operation to date and gives hope for the scale-up of similar processes to the same level.

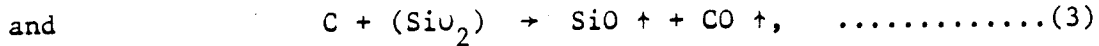
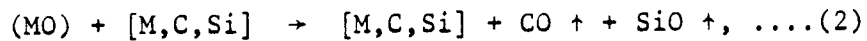
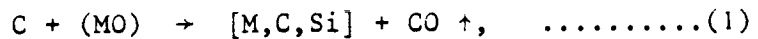
OPEN-BATH PROCESSING

The general features of an open-bath processing configuration described below are based on the experimental work done at Mintek over the last 4 years. The conceptual model of the furnace, which forms part of this treatment, has not been verified quantitatively, but has formed the basis of several successful applications^{22,27} of open-bath plasma smelting.

Description

Open-bath processing can be defined as a process in which a liquid surface is maintained on the top of which a single layer of solid material may exist at any instant. This ideal definition is clearly violated by the necessity for feed to be added at discrete points. Nevertheless, observations of furnace conditions have shown that the particles tend to spread out over the slag surface to form such an ideal layer. Once the heaping of the feed exceeds the capacity of the bath to absorb the feed, a transition to a shaft or submerged-arc configuration has started.

The metallurgical consequences of such an ideal open bath for the general carbothermic reduction of a metal oxide in the presence of a silicate slag can be illustrated by the following simplified reactions:



where

M is a transition metal,

() represents the liquid slag phase,

[] represents the liquid metal phase, and

↑ represents gas evolution.

The plasma source is assumed to be a well-directed stable d.c. electric arc that can be approximated by the model of Szekely.²⁸

A general arrangement of the furnace configuration under these conditions and the assumed behaviour of the various feed particles in the liquid slag are shown in Fig. 7.

The reaction sequence would be as follows:

- (a) dissolution of the metal oxide into the slag phase at the slag surface and within the bulk,
- (b) the reaction of the dissolved metal oxide with the carbon according to reaction (1) at the slag surface,
- (c) the descent of the metal droplets formed through the bulk slag phase,
- (d) the further reaction of these metal droplets according to reaction (2), including gas evolution, and
- (e) final equilibrium at the interface between the bulk slag and the metal.

The extent to which these various reactions take place clearly depends very strongly on the local temperature, and given the high-temperature, high power-density nature of plasma arcs, large temperature gradients may well be a feature of such configurations.

The model of Szekely²⁸ predicts that a large proportion of the

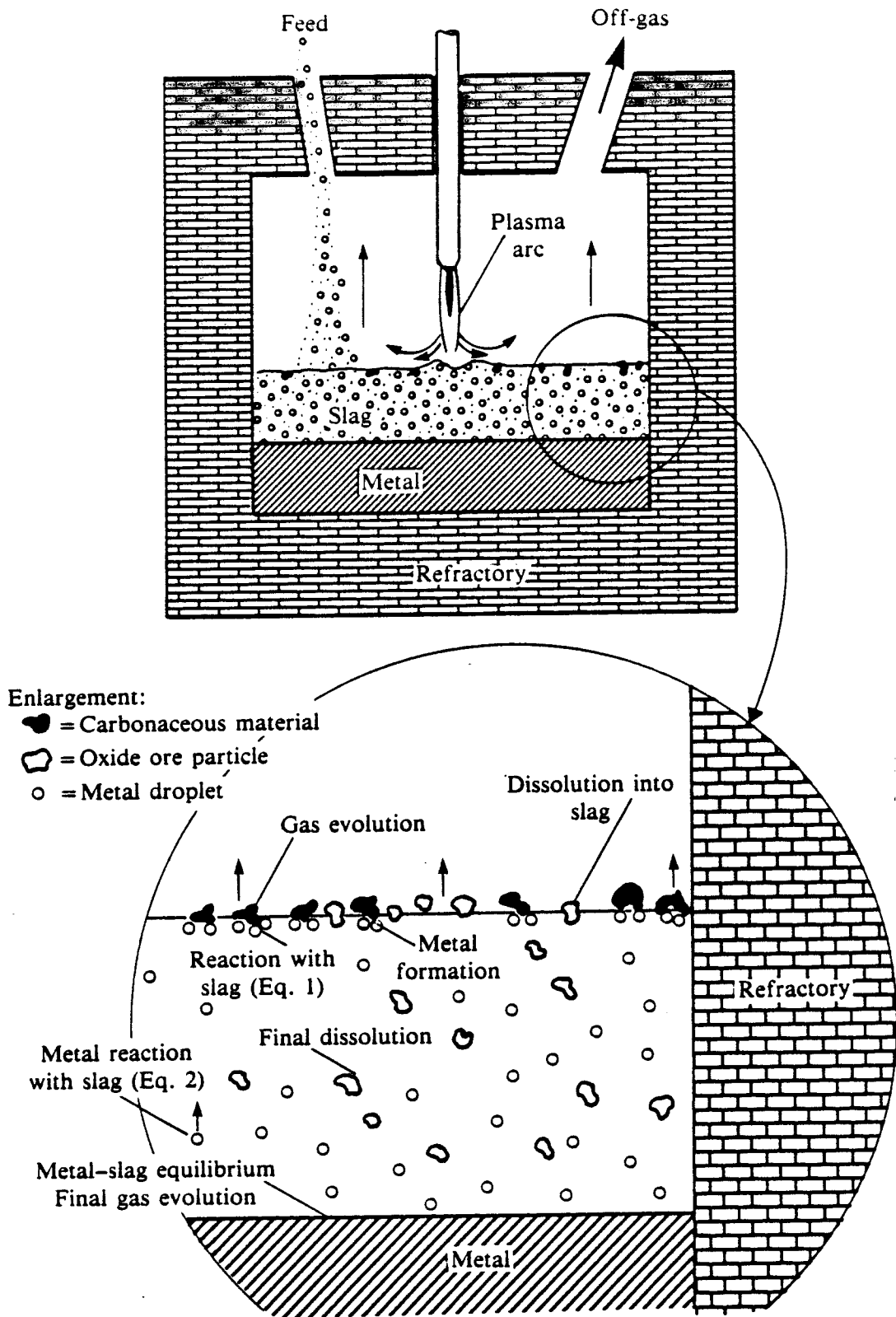


Fig. 7. Schematic view of an open-bath plasma process

plasma energy is dissipated in the high-temperature 'pumped' gas diverging from the anode-attachment region (corresponding to the well-known 'arc flare' observed in a.c. open-arc furnaces). However, the contribution made by radiation from the arc is considered to be relatively small. In a contained furnace environment, a complex interaction of the convective component, the radiative component, the evolved process gas, and the liquid slag bath would be expected. Observations of the behaviour of a 120 kW test furnace may be a useful starting-point.

Little evidence of refractory damage due to high temperatures has been observed on the side walls of such furnaces, but the roof refractories are prone to fairly severe damage. The extent of this damage increases markedly towards the centre of the roof, which tends to imply that radiation from the open bath is more severe than that from the open-arc column.

It would also appear that a significant radial-temperature gradient across the open bath can be expected.

Evaluation

The advantages and disadvantages of the open-bath process are discussed in the context of process running costs.

Raw materials

The most obvious consequence of open-bath processing, as defined is the freedom with which the particle size of the feed can be selected. For example, a finely sized material can be used because it is not necessary for a fixed bed to be maintained at a minimum porosity to allow the process gases to escape, as is the practice in conventional submerged-arc furnaces.

Products

The final analysis and mass of the metal product will be determined by the degree of completion of reactions (1) and (2). Some of the consequences of an open-bath configuration are as follows.

- (a) The reaction rate is faster if smaller particles are used, and therefore the degree of conversion is higher for the same residence time.
- (b) The vapour loss from the hot zone of the furnace is higher because of the rapid and direct evolution of gases from the surface reaction layer, and there is little possibility that vapour will condense on cooler, incoming solid material.

These two factors make the control of an open-bath process extremely critical because of the ease with which unwanted reactions, like reaction (3), can become significant if a suitable temperature and feed distribution are not maintained.

Energy consumption

The thermal efficiency of open-bath processes has a critical dependence on the rapid dissipation, into the bath, of the energy developed in the plasma arc. Some of the mechanisms contributing to thermal losses from the open bath are as follows:

- (i) radiation from the open bath to the roof, particularly in the area of the arc attachment at the slag surface,
- (ii) the loss of vaporized material from the arc-attachment zone, and
- (iii) convective heat transfer from the high-temperature arc flare to the side walls and roof refractories.

These losses can be limited by the maintenance of a completely covered (with feed) slag surface at all times (to lower the surface

temperature of the open bath) and of a well-directed, controlled plasma arc (for the avoidance of arc skewing, which leads to local overheating of the side-wall refractories).

The overall energy cost of a process per unit of product depends on the production of the furnace, which, in turn, depends on the maximum feed rate attainable and the furnace availability. There is considerable scope for the achievement of high throughputs in open-bath processes²⁹ because of the higher reaction rates attained by the use of finer feed particles. The reliability of such furnaces has not been demonstrated as yet for extractive processes at the industrial level, but the ready accessibility and low inventory of material would reduce the time required for repairs.

Electrode consumption

Any kind of plasma device could be used in an open-bath configuration, but all the current projections for large-scale extractive processing propose the use of the transferred-arc type, for which the electrode materials are generally graphite and thoriated tungsten. Copper electrodes are commonly used for non-transferred-arc devices. In all instances, the major factor affecting electrode erosion is the arc current³⁰⁻³³, as shown in Fig. 8. Consequently, for a constant power requirement, any decrease in the current arising from an increase in the voltage implies a decrease in electrode consumption. The plasma devices developed during the last 20 years have demonstrated that it is possible for the stability of high-intensity arc discharges to be improved, which extends the range of usable voltages. This can have a significant effect upon electrode consumption. For example, an increase in arc voltage

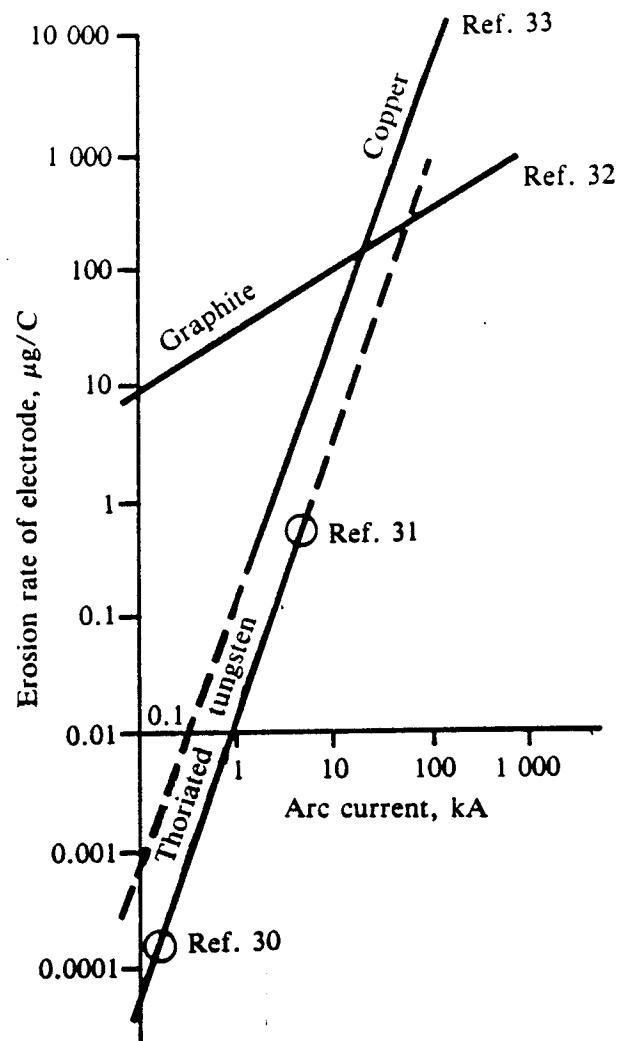


Fig. 8. Electrode erosion as a function of arc current

from 300 to 500 V for a graphite electrode operating at 10 MW should result in a decrease in the erosion of the electrode tip from 19.0 kg/h to 8.3 kg/h. This is of particular importance in energy-intensive smelting processes where the electrode costs per ton of alloy produced are higher than, for example, those for scrap remelting. However, the improvements in arc stability have usually been accompanied by additional costs like inert-gas injection, water-cooling of the plasma device, or rectification of the power supply. The effects of the use of these plasma devices upon furnace performance in a large-scale smelting operation have

not been determined as yet.

Small-scale tests (1 kA) at Mintek have shown that the consumption of graphite electrodes similar to those shown in Fig. 8 are attainable at voltages of 140 V in a smelting environment. In this instance, the average arc resistance of 140 m Ω was much larger than that considered in the 500 V arc mentioned previously (25 m Ω), but the effects of arc length and diameter were not considered in this comparison. No evidence of damage to the side-wall refractories as a result of arc instabilities was observed at this high resistance, but such damage has been observed in other tests in which the arc stability was poor, and resulted in frequent deviation of the arc from a central vertical position.

Refractory consumption

If the conceptual model presented earlier is correct, an open-bath process for smelting would be limited ultimately by the available open-bath area (as the primary reaction zone) in terms of the maximum feed rate attainable. This implies that the maximum throughput and furnace efficiency would be attained if a liquid slag layer were maintained right up to the side walls, and would be expected to result in high refractory costs due to slag erosion of the side-wall refractories. A controlled 'freeze lining' of minimum thickness would be the ideal solution to these conflicting requirements, which would require a high degree of control.

Comparison with shaft-furnace processes

There are two major differences between these configurations, namely the presence of a burden of material and the use of non-transferred-arc plasma devices. The consequence of these differences are examined separately.

Burden

The presence of a porous bed of slowly descending material (usually coke) ensures the following.

- (a) Volatile species can be condensed and returned to the liquid bath, e.g. SiO in reaction (3), by the selection of an appropriate height of burden material to achieve the desired off-gas temperature.
- (b) The high-temperature (greater than 3000°C) tail flame or arc flare produced by the non-transferred-arc plasma device is contained within a reaction space; hence, damage to the refractories is limited and the temperatures of the off-gas is reduced.
- (c) The radiant energy from the molten bath of products is contained in the same manner as in (b) above.
- (d) No direct control can be exercised over the possible reactions of the burden material with the feed materials that are injected into the reaction zone.
- (e) Because the rate of descent of the burden materials is intentionally slow, the burden must be cooled extensively by the radial transfer of heat through the side walls to lower the off-gas temperature to the desired level.

Non-transferred-arc plasma devices

These devices differ from transferred-arc devices in the following major respects.

- (1) Process conditions within the reaction zone do not affect the performance of the arc heater directly.
- (2) A large additional mass of gas must be added to the process via the arc heaters as an energy carrier and, as this gas

stream leaves the top of the burden, its residual energy content is lost, unless used elsewhere.

- (3) The anode and the cathode electrodes both require water cooling which results in a typical energy-transfer efficiency to the carrier gas of 85 per cent.

FURTHER DEVELOPMENTS

It is clear from Fig. 7 that the use of only the surface of the slag in the furnace as the reaction zone imposes a constraint on open-bath processing. The distribution of the feed particles throughout the slag volume would be expected to greatly increase the capability of the furnace to accept higher feed rates. Such distribution could be achieved in a number of ways, e.g. by stirring of the bath with inert gas, pneumatic injection of the feed materials into the bath via a vertical lance, or bottom or side tuyères, electro-magnetic stirring of the bath, etc. This would mix the contents of the bath thoroughly, increase the rates of mass and heat transfer to the feed materials, trap volatile reaction products in the slag, and possibly directly utilize the carbon and hydrogen in the volatile materials in the coal. These conditions could give rise to refractory problems and alternate techniques such as distribution of arc attachment could be considered. All these factors would contribute to an increase in furnace throughput and process efficiency.

CONCLUSIONS

Thermal plasma devices have greatly increased the stability of high-intensity arc discharges, and operation at a much larger range of currents and voltages has been made possible.

The two extremes of the current-voltage spectrum occupied by plasma devices, namely high current (greater than 30 kA), and high voltage (greater than 2 kV), are characterized by a high rate of electrode erosion and high gas consumption respectively.

The disadvantages of these characteristics have been minimized as far as possible by the adoption of a single-electrode configuration for high-current devices where feasible, and the application of high-voltage devices to processes requiring a high gas input.

Large-scale extractive metallurgical applications consist principally of several demonstration-scale facilities (greater than 10 MW) for the production of iron units and ferro-alloys. These plants fall into two broad categories, which reflect the plasma devices used: open-bath, high-current, transferred-arc systems, and shaft-furnace, intermediate-to-high-voltage, non-transferred-arc systems.

The open-bath system provides opportunities for excellent process and product control but is limited by the loss of volatile materials to the off-gases and by the relatively high heat losses of the roof (120 to 150 kW/m²).

The shaft-furnace system can process volatile materials very effectively (e.g. by the Plasmadust process), but high heat losses due to water-cooling and the high gas consumption of the plasma devices lowers the thermal efficiency of the process substantially (10 to 20 per cent).

Improvements to these processes to overcome these disadvantages would be expected to include the following: increased power per unit area of hearth in the open-bath system and, hence, decreased roof area (with its associated high heat losses), and increased net energy per cubic metre of gas produced by the plasma device

and, hence, decreased carrier-gas load for shaft furnaces.

The potential for future applications of plasma technology to large-scale extractive metallurgy may well be realized in the treatment of the very abundant elements silicon, aluminium, and magnesium, and others e.g. titanium, which suit the high temperature and energy intensity of plasma devices. A suitable means for the separation of the products in the vapour state at high temperatures remains the major obstacle to be overcome.

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