Pure & Appl. Chem., Vol. 56, No. 2, pp. 209-214, 1984.
Printed in Great Britain.

0033-4545/84 $3.00+0.00
Pergamon Press Ltd.

POTENTIAL, PROBLEMS AND INNOVATIONS OF PLASMA HEAT APPLICATIONS IN THE METALLURGICAL INDUSTRY

G. K. Bhat

Mellon Institute, Carnegie-Mellon University, Pittsburgh, PA 15213, USA

Abstract - Industrial applications of plasma technology are in the spotlight in many countries which offer cheap electric power. The flexibility of coupling electric power in a plasma jet or a plasma arc with energy from fossil-fuels has been demonstrated in selected pilot scale and industrial scale plasma processing systems for extractive metallurgical and pyrometallurgical purposes. This report describes and provides brief assessments of several successful and promising plasma processing innovations.

INTRODUCTION

Materials production using plasma heat applications have gained increased importance and credibility in certain west and east European countries, South Africa and in Japan (1,2). Plasma materials production activities in the U. S. have remained relatively small scale during the past decade. The high cost of electric energy has been a major deterrent to wide scale development and industrial applications of thermal plasma processes.

Where electric power costs are lower than 4 cents per KWh, the flexibility of coupling electric power of the plasma arc with energy from fossil-fuel sources has raised new possibilities of plasma heat applications in primary materials manufacturing industries. This will also provide fresh impetus for extending bench scale plasma technology development studies into pilot scale and industrial scale operations.

This report provides an assessment of four groups of plasma technologies of interest to metallurgical industries as follows: (a) reduction and smelting; (b) melting and consolidation; (c) remelting and refining; and (d) plasma surface dressing, surface modification and surface coating.

PLASMA TORCHES - DESIGN PRINCIPLES AND OPERATION

Three basic types of plasma heat sources are used in the various plasma processes. These include non-transferred arc A.C. and D.C. plasma heat sources, transferred-arc A.C. and D.C. plasma torches and the electrodeless high-frequency induction plasma heating devices. The most important design features and operating parameters of such plasma heat sources are as follows: (a) power requirement, which are determined by the specific energy consumption and productivity of the process; (b) specific enthalpy and mean mass temperature for obtaining the required energy concentration in the system for steady operation of the process; and (c) type of gas, its flow rate and pressure of the plasma effluent required for the process operations.

A most popular plasma torch is the one that utilizes a coaxial electrode as a cathode and nozzle which acts as the anode. The arc stabilization mechanism uses either gas or a magnetic fields. In certain plasma torches, both methods of arc stabilization are employed in order to obtain the desired concentration of heat and rotational movement of the hot spot on the workpiece.

Transferred arc plasma torch operational features

Controllable supply of gas is introduced in plasma torches in order to regulate the stiffness and momentum of the arc and the effluent. The gas flow aids in the transfer of energy to the workpiece. Constriction of the arc in the torch nozzle by changing nozzle area leads to increase of arc voltage and total power at constant current. The selection of proper arc length is an important requirement for obtaining maximum heat transfer efficiency in any plasma arc heating torch. Also, various types of plasma gases differ widely in their ability to dissipate electrical energy as heat energy in the plasma arc.

Systematic characterization data for different types of plasma heat services are not readily available. Therefore, plasma heating systems development and evaluation work has largely proceeded on an empirical basis. The lack of a comprehensive plasma technology data base from pilot scale work has impeded progress in commercial applications of many plasma processes which have been tested and found useful in laboratory studies.

Service life of industrial plasma torches

The service life of plasma torches with electrodes is limited by several factors. Electrode service life is largely determined by (a) the type of materials used for electrodes, (b) the design configuration of the electrodes which affect the current density and ability to withstand shocks during the start-up, (c) reactivity with plasma gases, and (d) the nature of the current, A.C. or D.C.

Plasma torch start-up procedure is in many cases responsible for early deterioration of electrodes. A soft start of plasma torch is essential for maintenance of electrode shape and integrity. In pilot scale plasma torch operations a solid electrode having a round tapered tip has been found to be quite satisfactory to carry current up to 2000 Amps and a dished or hollow electrode for carrying current up to 10,000 Amps.

Gas heating, non-transferred arc plasma torches are preferably operated at voltage levels in the range 600 V to 5000 V. On the other hand, transferred arc plasma torches used in scrap melting and consumable electrode remelting purposes are operated in the range 80 V to 1200 V.

The reason for the application of different voltage levels is the arc length required to melt the charge and the need for avoiding severe wear of the hearth (or the transfer) electrode embedded in the bottom lining of the furnace. The higher the current, the greater is the tendency of hearth electrode erosion.

To a certain extent, this electrode wear can be minimized through the use of soft metals around the electrode and by using high pressure deionized cooling water circulation within the electrode. Nevertheless, the safety of the bottom electrode is a constant source for concern. Sensors are employed to provide advance warning of non-uniform erosion of bottom electrode in scrap melting furnaces.

PROGRESS IN PLASMA HEAT APPLICATIONS IN EXTRACTIVE METALLURGY

Interest in plasma extractive metallurgy has recently increased because of an urgent need to develop low capital investment, smaller, flexible, efficient and economical extractive metallurgical processes.

This report will focus on examples of successfully piloted plasma reduction and plasma melting processes.

The Plasmared process developed by SKF Stal (2) represents a coal based direct reduction process of considerable industrial promise for the production of sponge iron in amounts less than one-half million tons per year.

The iron ore reduction reactions using coal provides either CO_2 or CO as a reaction product besides iron. The iron ore (Fe_2O_3) reduction process which provides CO_2 takes place at 1000°C at an energy consumption rate of 538 Kwh per tonne iron. On the other hand, reduction to CO requires 1166 Kwh or twice as much energy per tonne iron. A smelting reduction process at 1600°C would require more than 2000 Kwh per tonne of energy. Very large quantities of gas are evolved when the reduction process is conducted at higher temperatures. Therefore, the prereduction of ores at lower temperatures is an exceedingly important consideration in reducing the total energy materials costs.

The Plasmared process uses a plasma reformer because only 40% of the reducing agents in the gas are used. The spent gas has to be regenerated and used again. Because of this, energy consumption in the process is comparatively high and a mix of fuel to adjust energy costs is a prerequisite for economical operation of the Plasmared process. Despite this energy cost drawback, plasma technology has the potential of making the sponge iron production feasible for both large and small markets.

In most extractive metallurgical operations manufacture of liquid metal is more important than the production of sponge iron. Some of the more promising applications of plasma heat are smelt-reduction of iron ores, mineral dusts and carbo-thermal reduction of metal oxide concentrates.

Some examples of plasma smelt reduction technology include SKF's Plasmasmelt, Plasma Zinc(3) and Bethlehem's plasma iron making (4), and Foster Wheeler-Tetronics Expanded Precessive plasma furnace processing (5) of iron ore and other types of ore concentrates.

Plasmasmelt processes, in order to be commercially successful require solutions to five of their inherent problems. These problems may be listed as follows: (a) to supply heat to the smelting zone without generating excessive amounts of gas; (b) to heat the charge undergoing reduction above the temperature range 950-1500°C without conversion of the charge into a semi-molten doughey mass in the furnace; (c) to use the thermal energy and reducing power of the gas without a reformer; (d) to use all charge materials without agglomeration; and (e) to utilize a mix of fossil-fuels.

Experimental data are required to find effective solutions to the above problems of the smelt reduction processes. Also, in order to use plasma heating systems effectively, their service performance characteristics should be extended beyond the 100-hour present limit.

Our understanding of the heat transfer and chemical reaction kinetics of many important plasma metallurgical processes in the temperature range 2500 K to 10,000 K is incomplete. An independent high heat source allows for the organization of the smelt-reaction process in many ways. There is scope for much fundamental research in the areas of plasma extractive metallurgy using different types of plasma heat sources and reductants.

Edstrom (6) has performed extensive, economic comparison of emerging smelt reduction processes. His conclusions indicate the advantages of Plasmasmelt process of producing crude steel in countries which offer electric power at cost levels below 4 cents a Kwh.

Plasmasmelt is a relatively much cleaner process compared to the blast furnace iron making and other metal reduction processes.

For carbo-thermal reduction of non-ferrous metals, the energy consumption estimate is 1 to 2 Kwh per kg and required enthalpy of the gas jet effluent from the plasma torch is of the order, 5 to 20 kcal/g. For these thermal reduction applications, it is convenient to use hydrogen, natural gas or carbon dioxide as working gas. The power capabilities of plasma torches need not be higher than 100 to 300 KW. The number of plasma torches needed can be estimated by the productivity requirements for each installation.

The energy consumption of the plasma reduction process for refractory metals, and rare-earth metals are of the order 5 to 10 Kwh/kg. The enthalpy of the exit gas should be in the range 15-50 kcal/g. Such enthalpies can only be obtained with hydrogen as plasma gas. The mean-mass temperature of the plasma determines, in this case, the useful life of electrodes. The torch design is more complicated and the technical solutions needed are design related.

The linear plasma torches with laminar gas flow seem to be most appropriate for carbo-thermal reduction applications. Design testing of torches which provides electrode life exceeding 165 hours have progressed to power capabilities in this range 1 MW to 3 MW. There is urgent need for continuation of these torch design evaluations to power levels up to 10 MW. Such a technology base is desirable for the promotion of wider-scale applications of plasma arc heating devices for smelt-reduction of copper, tantalum, and titanium concentrates.

PLASMA ARC PRIMARY MELTING AND REMELTING

Plasma arc furnaces

In the U. S., Union Carbide Company was the first to demonstrate in 1962 the feasibility of plasma arc primary melting of scrap in a furnace with a refractory hearth and sidewall. Such a plasma furnace did not become a commercial reality in the U. S. Design simplification of the bottom electrode and the reduction of its cooling water requirement remains a big challenge.

Research engineers in the German Democratic Republic (GDR) were the first to find acceptable solutions to this and other practical problems relative to the plasma heat source and the plasma furnace refractories. A 10-ton plasma furnace was commissioned at the VEB Edelstahlwerke in Frietal in 1973. This plasma arc scrap melting furnace has since been in continuous operation on a three-shift basis. During 1977, a second 30-ton plasma arc melting furnace was put into industrial operation at the same plant.

Plasma torches of 6 KA to 10 KA current transfer capability have been fully tested and optimized in these two plasma furnaces. The current density in the tungsten electrode is not permitted to exceed 2000 A/cm^2. Tungsten electrode and copper nozzle service life of more than 200 hours has reportedly been achieved at torch operation current level of 9 KA.

Operating results of plasma arc scrap melting furnaces at Frietal for the past seven-year period have confirmed the expected technical advantages. However, certain design problems relative to the bottom electrode and location of the plasma torches still seem to be unresolved.

Plasma induction furnaces

Another type of plasma primary melting system is the plasma induction furnace mostly used in foundaries for the preparation of molten alloys in quantities up to 3 tons.

Plasma induction furnaces now in operation are fitted with one plasma torch of power capacity 100 KW up to 400 KW, which heats the charge from a vertical overhead position. Argon used as plasma gas is consumed at a rate of 5 to 6 m^3/hour in a 200 KW torch operating at current level around 2000 A. A problem with these plasma induction furnaces is the bottom electrode. Advantages gained by the use of plasma heat are nullified to a large extent by the cooling and excessive maintenance requirements of the bottom electrode.

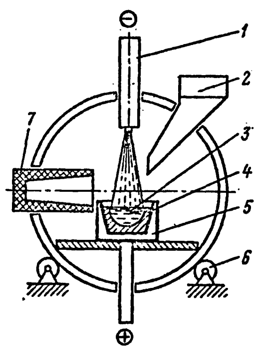
The use of uncooled bottom electrode is possible, but has its own limitations of melt contamination. Multiple torches are utilized in larger plasma induction units. The plasma arc heat is introduced in a tangential mode through ports located in the sidewall of the melt containment crucible. Multiple plasma arc interactions have limited enlargement of the melting capacity of various types of plasma induction furnaces.

The metal quality levels achieved through plasma induction processing are about the same as from vacuum induction melting system. Plasma induction melting systems are more desirable for recycling scrap and for the production of special alloys, such as, magnetic and resistance alloys, ultra-low carbon stainless steels, and alloys required for high temperature, extremely corrosive and cryogenic applications.

Plasma arc remelting and casting

Plasma remelting furnaces are multi-duty systems. They can be utilized for the production of simple and complex castings or near-net and finished shapes. The finished weight capabilities of these plasma remelting and casting systems have not exceeded 8 tons for scrap consolidation and 5 tons for slab ingots production.

Plasma casting in a slag envelope is accomplished using systems as shown schematically in Fig. 1. The materials processed in such furnaces include high temperature alloys, high melting and reactive metal alloys. These furnaces are also useful for melting ceramic materials and glass.



1 - plasma torch
2 - materials feed hopper
3 - molten metal pool
4 - slag lining
5 - crucible
6 - furnace chamber rollers

Fig. 1 Plasma melting in slag lined or skull melting crucible and casting production system

PLASMA TREATMENT OF METAL SURFACE

Plasma technology has been developed and applied for metal surface treatment in order to accomplish the following specific purposes: (a) surface cleaning and etching, (b) plasma mechanical treatment, (c) plasma arc cleaning and (d) plasma arc refining of the surface layer.

Surface cleaning with low current discharge is used for strips and wire replacing mechanical cleaning or pickling.

Plasma mechanical treatment is used for rough stripping of surface from ingots of high alloy steels and alloys of high-hardness.

Plasma arc cleaning is used for removal of defect layer from ingots and is intended to replace hot scarfing.

Plasma arc remelting surface layer is used to eliminate surface defects, improve surface purity, reduce oxides and to prevent cuts, splits and similar surface blemishes from spreading during hot working of the ingot or billet. This also helps reduce loss of metal in the form of machined chips or grinding dust, both of which are not easy to recycle.

Plasma torches required for surface treatment should meet certain special requirements of heat concentration, gas flow rate and soft laminar flow characteristics together with arc stability.

Argon and mixtures of argon and gases, such as, hydrogen, nitrogen, ammonia are used as plasma forming gas. The addition of helium to argon is also required to reduce heat loss in the plasma through radiation.

High productivity in surface dressing of ingots is attained through the use of multiple plasma torches, each of which melts a part of the ingot surface in an assigned zone.

Continuous surface cleaning systems through plasma heat application machines have been built and are in industrial use in the USSR. These machines are designed to clean both cylindrical and slab type ingots of stainless steels, precision alloys and super alloys. Surface layer melting to a depth of 6 to 8 mm develops higher quality in tubes made from such starting alloy material.

Remelted layer is noted to be dense in precision alloys even though the prior surface contained large number of defects, such as, cracks, pores, oxide flows, scale. The quality of hot rolled sheets produced with plasma remelted surface was in no way inferior to sheets produced from surface machined or ground ingots. Moreover, the yield of metal from plasma surface melted ingots was at least 15% higher compared to that from conventionally surfaced dressed ingots.

Recirculation of plasma torch gas and ingot dressing chamber gases contributed toward reduction of gas costs.

Efforts are underway in the U. S. to construct and operate such plasma surface treatment systems in the specialty metals industries.

CONCLUSIONS

Plasma heat sources and pilot scale plasma processing systems have shown considerable promise in meeting the requirements of several industrial systems for the production of primary materials. Plasma heat applications are gaining industrial recognition and acceptance in several overseas countries, including the USSR and the German Democratic Republic. In North America, plasma technology applications have not yet overcome the normal application barriers.

Main barrier problems include, lack of a reliable technology base, scarcity of information on design characterization of various types of plasma heat sources; paucity and uncertain credibility of information on heat transfer, energy balance extrapolated from bench scale studies using transferred arc, nontransferred arc, various gases and gas mixtures, A.C. and D.C. power operated plasma heat sources.

Plasma melting raises the quality level of metal to that produced by vacuum melting. Plasma melting provides a more economical and environmentally cleaner processing method for the production of alloys having narrow range of expensive alloying elements.

Plasma arc remelting is very promising for the production of alloys of platinum, palladium, and osmium, which must have very low inclusion content, ultra-low gas impurities and exceptionally high density.

Plasma arc melting in slag lined crucibles is an interesting development which can be adapted for recycling low level nuclear wastes, and wastes from reactive metals processing.

Fundamental studies of plasma heat generation and application in the following areas are recommended for further stimulation of progress in plasma metallurgy: (a) investigation of physical problems of plasma arc in the power range 1 MW to 10 MW; (b) pilot scale investigations of kinetics, thermodynamics of gas exchange processes, evaporation processes, deoxidation, decarburization, during plasma heating; (c) investigations of electrode erosion, process and methods of extending electrode life or improving its thermal stability in industrial scale systems; (d) reduction of cooling requirements of the bottom electrode in transferred arc plasma melting systems for overall improvement of electrical efficiency and maintenance requirements; (e) development of methods for the intensification of energy-mass exchange between the plasma arc and the heated body; (f) design, development of high response plasma power sources for plasma torch operations in a wider voltage range, different gas atmospheres and pressure conditions within the melting chambers; and (g) economic studies of plasma processing of materials through pilot scale and computer simulation studies.

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