INTRODUCTION

The extraction and refining of most metals takes place at temperatures ranging from 1273 to 1773 K because of their elevated melting points and the thermodynamic criteria for the decomposition of ores. When these temperatures are in excess of 1673 to 1873 K, the use of electrical energy in the form of arcs, submerged arcs, or submerged resistance heating, rather than the direct employment of fossil fuel, is generally the most efficient way to carry out the extraction process.

Reactors using thermal plasma as the energy source, however, may be logical candidates for replacing some of these technologies. The main attraction of plasma reactors in smelting, melting, or refining operations is their ability to supply a concentrated high-temperature heat source, which allows for a high processing rate per unit reactor volume.

With few exceptions, the application of high temperature plasma reactors to extractive metallurgy is still under laboratory or pilot-plant development. Relatively large-scale plasma equipment did not become available for metallurgical applications until NASA found it necessary to develop efficient torches for the investigation of reentry materials. At that time, there was a great rush to apply plasma technology to the development of new products and processes, using hardware already developed. This bypassed the fundamental studies that could have led to efficient design. In the past 10 years however, bench and pilot scale experiments have made possible the application of plasma technology to bulk metal heating and melting and as a heat source for fluidized beds and rotary kilns. Plasma technology has also been used as a supplement for blast furnaces and in a few instances for high temperature chemical reactions.

ENERGY CONSERVATION

Energy and capital costs cannot be easily separated in the extractive metallurgical industry because one is frequently traded for the other, particularly where the use of lower cost energy requires expensive environmental controls. Ultimately, the primary available energy will be electricity, which may well be an abundant and cheap fuel by the standards of the future economy. By the year 2000, world deficits of such metals as germanium, indium, mercury, silver, and zinc—all predicted by the U.S. Bureau of Mines—will require greater amounts of energy to process the remaining small mineral deposits and low grade ores. Obviously, this necessity will mandate the development of reduced energy and capital processes for metal production.

Although current fuel-burning extractive metallurgical processes frequently operate at lower efficiencies than 30 percent, it is possible to bring them to the 40 to 80 percent efficiency range through careful design and additional capital investment. Therefore, electricity should be selected for basic processing only when there are certain specific requirements:

- Temperatures are necessary which exceed those possible with fossil fuels (greater than 1873 K where, with fossil fuels, less than 30 percent of the energy is available for processing).
- No process other than one requiring electrical energy is known.
- Electrical energy permits the use of an integrated process that yields a variety of products and shows total energy conservation and capital reduction offsetting increased energy cost.

There are many opportunities for plasma processing that meet these criteria. Economics, however, dictate using as much fossil energy as possible to either reduce electrical input or produce such useful gaseous by-products as carbon oxides and hydrogen. Introducing carbon as a reductant in high-temperature plasma processing permits the sale of carbon monoxide as a by-product, increasing energy efficiency and decreasing cost.

PROCESSING LOW-GRADE ORE

The rapid increase in hazardous waste products will be aggravated by future needs to process leaner ores. This procedure will yield greater quantities of waste materials per pound of metal produced. The most cost- and energy-efficient way to solve these problems would be to totally enclose the system and use the gaseous and solid wastes as feed for other processing systems that produce valuable products.

Such integrated industrial complexes would also result in energy conservation and reduced capital requirements. Plasma processing techniques lend themselves most readily to the development of metal-separating processes as well as to a system where, through a series of high-temperature treatments under properly controlled atmospheres, the volatile oxides would first be removed. Then, via carbon reduction, the remaining materials would become two separate phases, one metallic and the other an oxide mixture which could be processed to produce the remaining metals. If the ore is also a hazardous waste product (such
as fly ash), the economics become particularly attractive.

More than 700 million tons of coal are used in the United States each year, primarily for electric power production. Some 10 to 15 percent of the bituminous coal is ash, 85 percent of which is blown out of the stack as fly ash (spherical particles ranging from 0.5 to 100 microns in diameter). One hundred million tons per year are available for processing. Within this context, one large generating station could annually produce 350,000 tons of aluminum oxide from 1.2 million tons of ash. Overall, if only 70 percent of the fly ash was recovered, 125,000 tons of aluminum could be recovered annually. A modern plasma processing system using fly ash might be modified to effect better separation of constituents and could produce product carbon monoxide for organic synthesis. One hundred million tons of fly ash per year could, in principle, provide a substitute source for all of the aluminum consumed in the United States, 40 percent of imported iron ore, and all imported ferrosilicon.

An integrated system using plasma processing for the more difficult separations, where all process wastes are used as raw materials for other processes, would solve most of the problems besetting the extractive metallurgy industry today.

**ADVANTAGES OF PLASMA PROCESSING**

There are many advantages to plasma processing when applied to extractive metallurgy. In a plasma reactor, the atmosphere can be controlled because its construction makes it compatible with almost any gas—reducing, oxidizing, or inert. High reaction rates and heat transfer at plasma temperatures, coupled with high massless energy release, permit high feed rates of reactants and short residence times and allow reduced complexity, improved energy efficiency, and reduced capital costs. Using arc heated air at 4000 Btu/lb, 40 percent of the energy is available for plasma processing at 2480 K as compared with only 1530 K for a natural-gas flame at the same available energy efficiency. Heat fluxes as high as 16 kW/cm² are possible in a transferred dc arc as compared to 4.5 kW/cm² in an argon jet and only 0.3 kW/cm² in an oxygen fossil fuel flame. Heat transfer is enhanced by high velocities, high plasma gas thermal conductivities, and high temperatures.

**DISADVANTAGES**

Although high temperatures result in high reaction rates in plasma reactors, a number of inherent problems must be resolved to make plasma processing economically attractive. For example, after the reaction is complete, the products contain a high potential energy level in the form of latent heat. If a large fraction of this heat is not recovered as electrical energy or preheat for future reactants, the resultant thermal inefficiency makes the process economically unattractive.

Longer electrode life depends on continuous operation, which yields high productivity and low labor, maintenance, and capital costs. Electrode life in some plasma heaters is purported to be as high as 300 to 400 days under ideal conditions, but this life probably cannot be maintained at the high temperatures and severe conditions required for plasma reactors. Since some electrode melting and vaporization is inevitable, development of lower cost, longer life materials will be essential in developing economically viable processes.

Despite the high reaction rates at the temperatures envisioned, it is unlikely that high yields can be obtained with conventional processes. Some means of swirling, baffling, or extended reaction chambers are necessary to give the reacting solids sufficient time at appropriate temperatures and pressures to result in high yields. Much work has been done in this area, but plasma reactors are process-sensitive, requiring specific reaction chamber designs for each use.

Many dissociation reactions envisioned for plasma processing have high activation energies and the production of products could be 2000-3000 kWh per ton, considerably more than conventional technology. Additional problems are posed by the unavailability of the plasma torches needed for such an application (in the 40 to 100-MW range).

These considerations will not apply to scrap melting with plasma guns, a technology practiced by Voest Alpine in Austria, or for some special situations, such as in Sweden, where local circumstances encourage the development of such operations.

Manganese and chromium, at 26 and 10 million tons per year of world production, respectively, ranked second and fourth as the world's most needed and used metals. A significant fraction of each of them is produced electrolytically. They are found in large quantities in fine electrostatically collected dusts from other processes, and 98 percent of the manganese and 91 percent of the chromium used in the United States is imported. Therefore, these metals meet the criterion of high consumption rates, require electrical energy for their production, and appear as fine dust in the scrap recycle loop. Since they also have a relatively high value between the ore and the usable metal, they are strong candidates to economically support the development.

**POSSIBLE APPLICATIONS**

Iron oxide reduction in a single step using hydrogen or methane as the reductant would have many advantages. In this process, electricity would be used for heat, process energy, and the production of the hydrogen reductant from natural gas or coal. Production of costly metallurgical coke would be avoided, and carbon- and oxygen-free iron would be produced in a totally enclosed system, reducing pollution control measures and yielding a product from which steel could be made in simplified processing steps. Such a process has been demonstrated technically at a 1 MW-pilot scale.

It is rather unlikely, however, that plasma technology will be used for the smelting of iron ores on a tonnage scale, except for special applications. This is because the overall energy requirements of producing steel in plasma reactors are estimated to be 2000-3000 kWh per ton, considerably more than conventional technology. Additional problems are posed by the unavailability of the plasma torches needed for such an application (in the 40 to 100-MW range).

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