PATENT SPECIFICATION

Australia

Tesla Group Holdings Pty Limited

Plasma Reduction Processing of Materials

Provisional Application

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Spruson & Ferguson Ref: 504307

Inventors: Jeffrey Tanner-Jones

PLASMA REDUCTION PROCESSING OF MATERIALS

Field of the Invention

The present invention relates to the chemical processing of materials in a plasma environment, and in particular relates to pyrometallurgical reduction processes in a plasma environment.

Background of the Invention

The pyrometallurgical reduction of metalliferous ores and concentrates typically involves the heating of the ore or concentrate in a smelting furnace with a reductant to a temperature which generally melts the ore and at which chemical reaction of the ore/concentrate with the reductant reduces the ore/concentrate into metallic product or higher end-value product with a lower oxidation state. Large amounts of energy are required to initiate and sustain reduction processes in such smelting furnaces, and the recovery rate of metallic product often renders such operations commercially unviable. The non-reduced components of the ore/concentrate form a slag, which often contains valuable metallic content. Recovery of the metallic content from such slags is, however, again often commercially unfeasible by conventional methods.

Microwave radiation has been utilised in various industrial applications for the application of energy to heat materials, including the microwave heating of chemical reactants to kinetically and thermodynamically stimulate the same for the initiation of chemical reactions. Microwave treatment of metalliferous ores and other comparable materials has been utilised as an augmentative precursor treatment, applying energy to the ore to thermodynamically stimulate the same and prepare it for conventional recovery techniques such as conventional pyrometallurgical reduction, leaching or hydrometallurgical recovery processes.

Object of the Invention

It is the object of the present invention to provide an improved pyrometallurgical reduction process.

Summary of the Invention

In a broad form the present invention provides a process for the reduction of a metalliferous ore or concentrate comprising the steps of:

preparing said ore or concentrate into a particulate form;

charging a reaction chamber with said ore or concentrate, a reductant and an input gas;

irradiating said reaction chamber with electromagnetic radiation within a frequency range of 30 MHz to 300GHz until a non-equilibrium plasma is initiated, and

sustaining and controlling said non-equilibrium plasma with said radiation until said ore or concentrate is reduced to form reduction product.

Typically, said plasma is a non-equilibrium plasma.

Typically, pressure within said reaction chamber is maintained below 300kPa during irradiation thereof.

Typically, said pressure is also maintained above 40kPa.

In several embodiments, said pressure is maintained at about atmospheric pressure.

Said plasma may be initiated in said input gas.

Alternatively or additionally, at least part of said input gas may be decomposed during said irradiation, said plasma being initiated at least in part in the decomposed product of said input gas.

The reductant will typically comprise a carbonaceous material.

The reductant may include a particulate carbonaceous material blended with said ore or concentrate.

The reductant may include carbon monoxide gas, said input gas including said carbon monoxide gas, said plasma being initiated at least in part in said carbon monoxide gas.

The reductant may comprise carbon monoxide gas and a particulate carbonaceous material.

Alternatively, the reductant may comprise a reactive metal.

The input gas may include an inert gas.

The inert gas may comprise argon or nitrogen.

The input gas may comprise air.

The input gas may include methane.

Preferably, said radiation is microwave radiation.

The ore or concentrate may be a concentrate derived directly from mined ore.

Alternatively the ore or concentrate may be a non-ore derived concentrate. Said non-ore concentrate may be a residue derived, waste derived or mining derived concentrate, such as from mine tailings or concentrator residue.

The ore or concentrate may be a concentrate in the form of a residue, such as a slag, slurry or slime, derived from metallurgical processing operations. Such residue may be derived from pyrometallurgical, hydrometallurgical, chemometallurgocal or electrometallurigcal processing stages during primary, secondary and/or tertiary stages of metallurgical processing operations.

The reaction chamber may be in the form of a fluidised bed reactor.

The reaction chamber may alternatively be in the form of an oven, said ore or concentrate being charged into a crucible placed within said oven.

The reaction chamber may be in the form of a rotary kiln reactor.

The reaction chamber may be in the form of a cyclone reactor.

The reaction chamber may be in the form of a conveyor fed reactor.

In such a conveyor fed reactor, said ore or concetrate is preferably prepared into a pelletised particulate form.

Preferably, said reduction product is of metallic form.

Said metallic reaction product may be in the form of a fume, said fume being extracted from said reaction chamber and separated from gases produced during said reduction.

Alternatively, said reduction product is a compound of reduced oxidation state.

The reduction product may be formed by reduction of said ore or concentrate through a series of subsequent reduction reactions.

The process may include the step of generating carbon monoxide, said plasma being initiated and sustained at least in part in said carbon monoxide.

When said input gas includes air and said reductant includes particulate carbonaceous material, said carbon monoxide may be generated from reaction of oxygen within said air with said particulate carbonaceous material.

Alternatively or additionally, when said gas includes particulate carbonaceous material, said carbon monoxide may be generated from reaction of carbon dioxide produced during said reduction with said particulate carbonaceous material.

Alternatively or additionally, particulate carbonaceous material may be introduced into said reaction chamber after initiation of said plasma, said carbon monoxide being generated from reaction of carbon dioxide produced during said reduction, and / or oxygen within said air when said input gas includes air, with said introduced particulate carbonaceous material.

Preferably, said ore or concentrate is enveloped in a non-oxidising or inert gas ment during said reduction and during cooling of said reduction product following ion of said reaction chamber.

Preferably, said non-oxidising or inert gas is introduced to said reaction chamber said cooling.

In one embodiment, said input gas is passed through said ore or concentrate said irradiating step.

Preferably, said input gas is blasted upwardly through said ore or concentrate.

Preferably, said input gas is preheated prior to charging into said reaction r.

It has been a commonly held view that the generation of plasmas during the ave chemical processing of materials, and in particular during the tallurgical reduction of metalliferous ores and concentrates, is detrimental to the system harware and monitoring and control diagnostics equipment, and ngly it is typical for such processes to be controlled in a manner to explicitly avoid eration of a plasma.

Reaction rates, however, can increase by one or more orders of magnitude under processing. A plasma is a mixture of excited molecules, atoms, ions, electrons combined particles in a ground state host gas. With the high particle energies are characteristic of such plasma components, the physical and chemical behaviour e component particles differs markedly from equivalent particles in the "ground

In pyrometallurgical processes conducted in a plasma environment, there is a minance of reaction chemistry occurring at the plasma-solid or plasma-liquid ce. Whilst this feature is characteristic of pyrometallurgical processes in general, on rates across these interfaces are greatly enhanced by plasma chemistry, with an ance of highly energised reactive species.

Plasmas initiated and sustained at high pressures exhibit an approximate ience of temperature between electrons and heavy particles (ions, atoms, excited cles). Accordingly these plasmas are termed equilibrium plasmas, as there is al equilibrium between particles. This is exhibited particularly at higher pressures as igh density of particles provides an increased frequency of collision between les distributing energy relatively evenly between particles, providing a consistent temperature throughout the particles of the plasma. Because of the high-energy ties (thermal mass), equilibrium plasmas have commonly been utilised as precursor

methods in material processing for their capability to heat, sinter, melt or vaporise solid materials. These are all essentially physical processes merely taking advantage of the physical thermal properties of the equilibrium plasma.

Non-equilibrium plasmas, which are more characteristic of low pressure environments, are characterised by particle temperature non-equivalence, with the "temperature" of electrons far exceeding that of the temperatures of the heavier particles. Figure 1 depicts the separation of electron and heavy particle temperatures at low pressures, both with conventional plasmas and plasmas stimulated by microwave (or RF) radiation. It can be seen that at higher pressures, the electron and heavy particle temperatures merge. In a non-equilibrium plasma, the physical and chemical behaviour of the component particles may be profoundly different from that in the equivalent ground state environment. In a non-equilibrium plasma, with the various particle species moving with different energies, the measure of such energy, typically in the form of a "temperature" will vary greatly between species and between particles in each species population. This is evident when "temperature", a measure of thermal energy, is obtained by a mean readinfg by averaging-out the electron voltages (temperature equivalents) of particles having no adjustment for "thermal mass". Accordingly, the temperature of the plasma itself becomes meaningless as particle "temperatures" vary by perhaps four orders of magnitude, and "bulk" temperature measurements of plasma by different methods can disagree by an order of magnitude.

The processing effectiveness of low pressure, non-equilibrium plasmas is imbued by the reactivity of the chemically active species present rather than by the total energy available in the plasma. This reactivity makes non-equilibrium plasmas more suited to chemical reactions, as per that of the present application, than the equilibrium plasmas which have been used primarily in physical processes as discussed above.

The form of the diagram of Figure 1 will be dependent upon various parameters, including the gas composition, ionising characteristics of the species present, and the form of energy applied to the system to generate the plasma. The pressure up to which a plasma will be of the non-equilibrium form will thus vary depending on these and other parameters.

Typical methods of producing plasmas are through ionisation by heating (thermal stimulation), ionisation by irradiation, and ionising by electrical discharge. Whilst most plasma production methods will result in an equilibrium plasma at pressures up to around atmospheric pressure, it is believed that the generation of a plasma by irradiation, particularly in the RF and microwave frequency ranges between 30MHz and 300GHz,

pushes the graph of Figure 1 to the right as depicted, such that non-equilibrium plasmas can be generated and sustained at operationally important pressures around atmospheric (101.4 kPa) and up to about three atmospheres (about 300 kPa) under sufficient applied energy, appropriate available species (chemistry) and at responsive radiation frequencies.

This is believed to be as a result of the microwave radiation applying energy to the dieletrically disparate particles of the plasma, in particular to the electrons. At frequencies within the RF and microwave frequencies, only the electrons in the ionised field can follow the oscillations of the electric field applied. As a result the electrons become more highly energised that the heavier particles of the plasma, such that the RF / microwave plasmas can generally be defined as non-equilibrium plasmas. Such RF/ microwave plasmas can be induced and operated over a large pressure range, from below 0.1 kPa (for operations outside the main interest of the present invention), to pressures in excess of 300 kPa.

When a microwave field is applied across a gas, charged particles in that gas are accelerated. Because the mass of electrons is much much less than that of the heavier ion, atom and molecule particles, the action of the field is primarily to give energy to the electron. Accordingly, electron temperatures can be in the extremely high range of tens of thousands of Kelvin whereas the apparent bulk temperature of the plasma (primarily determined by the heavier particles) is orders of magnitude lower.

Reaction rates are generally governed by the mass transport diffusion of reactants, which is greatly enhanced by dielectric heating mechanisms during RF / microwave processing, typically in the presence of an RF / microwave stimulated plasma which, by definition, will have a high population of reactive species.

Plasma processing utilising RF / microwave stimulation also enables a great degree of control over the process, with the microwave radiation able to be directed to the reactant charge, in such a way as to envelope the entire reactant charge within the reaction chamber or to occupy a zone discretely within the charge. In continuous processing systems, residence time and thermochemical parameters can effectively be controlled through control of the applied radiation, providing superior processing or reduction results.

Whilst lower pressures well below atmospheric pressures ensure generation of an unambiguously non-equilibrium plasma with a large disparity between the temperatures of the electron and heavier particles, if the pressure in the reaction chamber is too low, then the density of reactive species to carry out the chemical processing will be too low

for economically viable processing. Accordingly, it is preferred that the pressure of the reaction chamber in which the plasma is initiated and sustained is greater than 40 kPa.

The inherent advantage of the non-equilibrium plasma chemistry (ionisation chemistry) of non-equilibrium plasmas when utilised in chemical and meatallurgical applications is that these plasmas can provide particles with the high energy required to stimulate and complete chemical reactions at high kinetic rates. For the range of applications relevant to the present application, high rates of mass transfer are desired with the high kinetic rate. Therefore, commerically viable productivity levels are often not achievable at extremely low pressures whivch provide extremely low mass transfer rates.

Conversely, the advantage of processing certain reactions under non-equilibrium plasma conditions, despite low mass transfer rates, is that in the low density plasma environment, the high energy free electrons and ionised particles experience a greatly increased mean free path before collision and re-combination, imparting greatly increased energy to re-combination chemistry. This increased energy at possible reaction sites enables the activation energy requirement to be met for reactions which require extremely high energy input to proceed. Consequently, certain thermodynamically demanding metallurgical and chemical reactions can be carried out efficiently, if slowly, or if at all, by utilising the extremely high energy particles at low pressures.

Processes which require protection from re-oxidation reactions benefit from the protection implied by removal of potential oxidation sources by initial and continuing evacuation of oxidising agents, such as the common reduction reaction product carbon dioxide, from the reaction environment. This can be achieved by maintaining the process at low pressures, continually evacuating the reaction chamber. Alternatively, or additionally, such carbon dioxide can be converted to the reductant carbon monoxide with fine carbon in the reaction chamber at elevated temperatures.

Brief Description of the Drawings

Preferred forms of the present invention will now be described by way of example with reference to the accompanying drawings wherein:

Figure 1 is a diagram showing the separation of electron and heavy particle temperatures in a plasma at varying pressures.

Figure 2 is a partially cross sectioned view of a reaction chamber used in the process of Example 1.

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Tesla Group Holdings Pty Limited

Plasma Processing of Materials

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Inventors:	Jeffrey Tanner-Jones

PLASMA PROCESSING OF MATERIALS

Field of the Invention

The present invention relates to the chemical processing of materials in a plasma environment, and in particular relates to, but is not limited to, pyrometallurgical reduction processes in a plasma environment.

Background of the Invention

The pyrometallurgical reduction of metalliferous ores and concentrates typically involves the heating of the ore or concentrate in a smelting furnace with a reductant to a temperature which generally melts the ore and at which chemical reaction of the ore/concentrate with the reductant reduces the ore/concentrate into metallic product or higher end-value product with a lower oxidation state. Large amounts of energy are required to initiate and sustain reduction processes in such smelting furnaces, and the recovery rate of metallic product often renders such operations commercially unviable. The non-reduced components of the ore/concentrate form a slag, which often contains valuable metallic content. Recovery of the metallic content from such slags is, however, again often commercially unfeasible by conventional methods.

Microwave radiation has been utilised in various industrial applications for the application of energy to heat materials, including the microwave heating of chemical reactants to kinetically and thermodynamically stimulate the same for the initiation of chemical reactions. Microwave treatment of metalliferous ores and other comparable materials has been utilised as an augmentative precursor treatment, applying energy to the ore to thermodynamically stimulate the same and prepare it for conventional recovery techniques such as conventional pyrometallurgical reduction, leaching or hydrometallurgical recovery processes.

Object of the Invention

It is the object of the present invention to provide an improved method for chemically processing materials.

Summary of the Invention

In a broad form the present invention provides a method for chemical processing of reactant material comprising the steps of:

charging a reaction chamber with said reactant material and an input gas;

irradiating said reaction chamber with electromagnetic radiation within a frequency range of 30 MHz to 300GHz until a non-equilibrium plasma is initiated, and

sustaining and controlling said non-equilibrium plasma with said radiation until chemical conversion of said reactant material is achieved.

Typically, pressure within said reaction chamber is maintained below 300kPa during irradiation thereof.

Typically, said pressure is also maintained above 40kPa.

In several embodiments, said pressure is maintained at about atmospheric pressure.

Typically, said reactant material is solid, said method further comprising the step of preparing said solid reactant material into a particulate form prior to said charging.

The solid reactant may include a metalliferous ore or concentrate, said solid reactant and/or said input gas including a reductant, said chemical conversion comprising reduction of said metalliferous ore or concentrate.

Alternatively, said chemical conversion may comprise a disproportionation, dissociation or sublimation reaction.

Said chemical conversion may alternatively comprise a synthesis reaction.

In such a synthesis reaction, said reactant material may comprise two gaseous materiales.

Said chemical conversion may alternatively comprise a diffusion or materials processing reaction.

Said chemical conversion may alternatively comprise a destructive distillation reaction.

Said chemical conversion may alternatively comprise a reactive process for materials regeneration (reactivation) or refurbishment (reclamation).

In another broad form the present invention provides a process for the reduction of a metalliferous ore or concentrate comprising the steps of:

preparing said ore or concentrate into a particulate form;

charging a reaction chamber with said ore or concentrate, a reductant and an input gas;

irradiating said reaction chamber with electromagnetic radiation within a frequency range of 30 MHz to 300GHz until a non-equilibrium plasma is initiated, and

sustaining and controlling said non-equilibrium plasma with said radiation until said ore or concentrate is reduced to form reduction product.

Typically, said plasma is a non-equilibrium plasma.

Typically, pressure within said reaction chamber is maintained below 300kPa during irradiation thereof.

Typically, said pressure is also maintained above 40kPa.

In several embodiments, said pressure is maintained at about atmospheric pressure.

Said plasma may be initiated in said input gas.

Alternatively or additionally, at least part of said input gas may be decomposed during said irradiation, said plasma being initiated at least in part in the decomposed product of said input gas.

The reductant will typically comprise a carbonaceous material.

The reductant may include a particulate carbonaceous material blended with said ore or concentrate.

The reductant may include carbon monoxide gas, said input gas including said carbon monoxide gas, said plasma being initiated at least in part in said carbon monoxide gas.

The reductant may comprise carbon monoxide gas and a particulate carbonaceous material

Alternatively, the reductant may comprise a reactive metal.

The input gas may include an inert gas.

The inert gas may comprise argon or nitrogen.

The input gas may comprise air.

The input gas may include methane.

Preferably, said radiation is microwave radiation.

The ore or concentrate may be a concentrate derived directly from mined ore.

Alternatively the ore or concentrate may be a non-ore derived concentrate. Said non-ore concentrate may be a residue derived, waste derived or mining derived concentrate, such as from mine tailings or concentrator residue.

The ore or concentrate may be a concentrate in the form of a residue, such as a slag, slurry or slime, derived from metallurgical processing operations. Such residue may be derived from pyrometallurgical, hydrometallurgical, chemometallurgocal or

electrometallurgical processing stages during primary, secondary and/or tertiary stages of metallurgical processing operations.

The reaction chamber may be in the form of a fluidised bed reactor.

The reaction chamber may alternatively be in the form of an oven, said ore or concentrate being charged into a crucible placed within said oven.

The reaction chamber may be in the form of a rotary kiln reactor.

The reaction chamber may be in the form of a cyclone reactor.

The reaction chamber may be in the form of a conveyor fed reactor.

In such a conveyor fed reactor, said ore or concetrate is preferably prepared into a pelletised particulate form.

Preferably, said reduction product is of metallic form.

Said metallic reaction product may be in the form of a fume, said fume being extracted from said reaction chamber and separated from gases produced during said reduction.

Alternatively, said reduction product is a compound of reduced oxidation state.

The reduction product may be formed by reduction of said ore or concentrate through a series of subsequent reduction reactions.

The process may include the step of generating carbon monoxide, said plasma being initiated and sustained at least in part in said carbon monoxide.

When said input gas includes air and said reductant includes particulate carbonaceous material, said carbon monoxide may be generated from reaction of oxygen within said air with said particulate carbonaceous material.

Alternatively or additionally, when said gas includes particulate carbonaceous material, said carbon monoxide may be generated from reaction of carbon dioxide produced during said reduction with said particulate carbonaceous material.

Alternatively or additionally, particulate carbonaceous material may be introduced into said reaction chamber after initiation of said plasma, said carbon monoxide being generated from reaction of carbon dioxide produced during said reduction, and / or oxygen within said air when said input gas includes air, with said introduced particulate carbonaceous material.

Preferably, said ore or concentrate is enveloped in a non-oxidising or inert gas environment during said reduction and during cooling of said reduction product following irradiation of said reaction chamber.

Preferably, said non-oxidising or inert gas is introduced to said reaction chamber during said cooling.

In one embodiment, said input gas is passed through said ore or concentrate during said irradiating step.

Preferably, said input gas is blasted upwardly through said ore or concentrate.

Preferably, said input gas is preheated prior to charging into said reaction chamber.

It has been a commonly held view that the generation of plasmas during the microwave chemical processing of materials, and in particular during the pyrometallurgical reduction of metalliferous ores and concentrates, is detrimental to the process system hardware and monitoring and control diagnostics equipment, and accordingly it is typical for such processes to be controlled in a manner to explicitly avoid the generation of a plasma.

Reaction rates, however, can increase by one or more orders of magnitude under plasma processing. A plasma is a mixture of excited molecules, atoms, ions, electrons and recombined particles in a ground state host gas. With the high particle energies which are characteristic of such plasma components, the physical and chemical behaviour of these component particles differs markedly from equivalent particles in the "ground state".

In pyrometallurgical processes conducted in a plasma environment, there is a predominance of reaction chemistry occurring at the plasma-solid or plasma-liquid interface. Whilst this feature is characteristic of pyrometallurgical processes in general, reaction rates across these interfaces are greatly enhanced by plasma chemistry, with an abundance of highly energised reactive species.

Plasmas initiated and sustained at high pressures exhibit an approximate equivalence of temperature between electrons and heavy particles (ions, atoms, excited molecules). Accordingly these plasmas are termed equilibrium plasmas, as there is thermal equilibrium between particles. This is exhibited particularly at higher pressures as the high density of particles provides an increased frequency of collision between particles distributing energy relatively evenly between particles, providing a consistent bulk temperature throughout the particles of the plasma. Because of the high-energy densities (thermal mass), equilibrium plasmas have commonly been utilised as precursor methods in material processing for their capability to heat, sinter, melt or vaporise solid materials. These are all essentially physical processes merely taking advantage of the physical thermal properties of the equilibrium plasma.

Non-equilibrium plasmas, which are more characteristic of low pressure environments, are characterised by particle temperature non-equivalence, with the

"temperature" of electrons far exceeding that of the temperatures of the heavier particles. Figure 1 depicts the separation of electron and heavy particle temperatures at low pressures, both with conventional plasmas and plasmas stimulated by microwave (or RF) radiation. It can be seen that at higher pressures, the electron and heavy particle temperatures merge. In a non-equilibrium plasma, the physical and chemical behaviour of the component particles may be profoundly different from that in the equivalent ground state environment. In a non-equilibrium plasma, with the various particle species moving with different energies, the measure of such energy, typically in the form of a "temperature" will vary greatly between species and between particles in each species population. This is evident when "temperature", a measure of thermal energy, is obtained by a mean readinfg by averaging-out the electron voltages (temperature equivalents) of particles having no adjustment for "thermal mass". Accordingly, the temperature of the plasma itself becomes meaningless as particle "temperatures" vary by perhaps four orders of magnitude, and "bulk" temperature measurements of plasma by different methods can disagree by an order of magnitude.

The processing effectiveness of low pressure, non-equilibrium plasmas is imbued by the reactivity of the chemically active species present rather than by the total energy available in the plasma. This reactivity makes non-equilibrium plasmas more suited to chemical reactions, as per that of the present application, than the equilibrium plasmas which have been used primarily in physical processes as discussed above.

The form of the diagram of Figure 1 will be dependent upon various parameters, including the gas composition, ionising characteristics of the species present, and the form of energy applied to the system to generate the plasma. The pressure up to which a plasma will be of the non-equilibrium form will thus vary depending on these and other parameters.

Typical methods of producing plasmas are through ionisation by heating (thermal stimulation), ionisation by irradiation, and ionising by electrical discharge. Whilst most plasma production methods will result in an equilibrium plasma at pressures up to around atmospheric pressure, it is believed that the generation of a plasma by irradiation, particularly in the RF and microwave frequency ranges between 30MHz and 300GHz, pushes the graph of Figure 1 to the right as depicted, such that non-equilibrium plasmas can be generated and sustained at operationally important pressures around atmospheric (101.4 kPa) and up to about three atmospheres (about 300 kPa) under sufficient applied energy, appropriate available species (chemistry) and at responsive radiation frequencies.

This is believed to be as a result of the microwave radiation applying energy to the dieletrically disparate particles of the plasma, in particular to the electrons. At frequencies within the RF and microwave frequencies, only the electrons in the ionised field can follow the oscillations of the electric field applied. As a result the electrons become more highly energised that the heavier particles of the plasma, such that the RF / microwave plasmas can generally be defined as non-equilibrium plasmas. Such RF/ microwave plasmas can be induced and operated over a large pressure range, from below 0.1 kPa (for operations outside the main interest of the present invention), to pressures in excess of 300 kPa.

When a microwave field is applied across a gas, charged particles in that gas are accelerated. Because the mass of electrons is much much less than that of the heavier ion, atom and molecule particles, the action of the field is primarily to give energy to the electron. Accordingly, electron temperatures can be in the extremely high range of tens of thousands of Kelvin whereas the apparent bulk temperature of the plasma (primarily determined by the heavier particles) is orders of magnitude lower.

Reaction rates are generally governed by the mass transport diffusion of reactants, which is greatly enhanced by dielectric heating mechanisms during RF / microwave processing, typically in the presence of an RF / microwave stimulated plasma which, by definition, will have a high population of reactive species.

Plasma processing utilising RF / microwave stimulation also enables a great degree of control over the process, with the microwave radiation able to be directed to the reactant charge, in such a way as to envelope the entire reactant charge within the reaction chamber or to occupy a zone discretely within the charge. In continuous processing systems, residence time and thermochemical parameters can effectively be controlled through control of the applied radiation, providing superior processing or reduction results.

Whilst lower pressures well below atmospheric pressures ensure generation of an unambiguously non-equilibrium plasma with a large disparity between the temperatures of the electron and heavier particles, if the pressure in the reaction chamber is too low, then the density of reactive species to carry out the chemical processing will be too low for economically viable processing. Accordingly, it is preferred that the pressure of the reaction chamber in which the plasma is initiated and sustained is greater than 40 kPa.

The inherent advantage of the non-equilibrium plasma chemistry (ionisation chemistry) of non-equilibrium plasmas when utilised in chemical and meatallurgical applications is that these plasmas can provide particles with the high energy required to

stimulate and complete chemical reactions at high kinetic rates. For the range of applications relevant to the present application, high rates of mass transfer are desired with the high kinetic rate. Therefore, commerically viable productivity levels are often not achievable at extremely low pressures whivch provide extremely low mass transfer rates.

Conversely, the advantage of processing certain reactions under non-equilibrium plasma conditions, despite low mass transfer rates, is that in the low density plasma environment, the high energy free electrons and ionised particles experience a greatly increased mean free path before collision and re-combination, imparting greatly increased energy to re-combination chemistry. This increased energy at possible reaction sites enables the activation energy requirement to be met for reactions which require extremely high energy input to proceed. Consequently, certain thermodynamically demanding metallurgical and chemical reactions can be carried out efficiently, if slowly, or if at all, by utilising the extremely high energy particles at low pressures.

Processes which require protection from re-oxidation reactions benefit from the protection implied by removal of potential oxidation sources by initial and continuing evacuation of oxidising agents, such as the common reduction reaction product carbon dioxide, from the reaction environment. This can be achieved by maintaining the process at low pressures, continually evacuating the reaction chamber. Alternatively, or additionally, such carbon dioxide can be converted to the reductant carbon monoxide with fine carbon in the reaction chamber at elevated temperatures.

Whilst the present invention particularly relates to pyrometallurgical reduction of metalliferrous ores and concentrates, chemical processing an electromagnetic radiation induced plasma is also applicable to various other forms of chemical reactions. Such other forms of reactions include:

disproportionation, dissociation and sublimation reactions;

synthesis reactions (including combustion synthesis and synthesis of intermetallic materials, hard materials and cermets and gas phase synthesis reactions for the synthesis of commodities of value , including fertilizers, from waste and industrial emmission gases);

diffusion and materials processing reactions;

carbonisation and other destructive distillation reactions; and

reactive processes for materials regeneration (reactivation) or refurbishment (reclamation).