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(54) Title: JOULE HEATING METHOD FOR IRON ORE REDUCTION WITH PLASTICS

(57) **Abstract:** The inventions disclosed herein relate to methods and systems for efficient iron oxide reduction by flash Joule heating of feedstock comprising iron oxide, plastic, and conductive carbon, wherein the plastic is thermally decomposed to hydrogen and solid carbon which act as reducing agents to the iron oxide. Embodiments of the invention further disclose Joule heated iron oxide reduction wherein the hydrogen and solid carbon reducing agents may be replenished by adding more plastic to the feedstock. Embodiments of the invention further disclose Joule heated iron oxide reduction wherein some of the reduced iron and/or some of the solid carbon may be removed and new iron oxide and/or new plastic are added to the feedstock to make the process continuous. Embodiments of the invention further disclose iron oxide reduction by flash Joule heating of feedstock comprising of iron oxide and conductive carbon, wherein the carbon acts as reducing agents to the iron oxide.

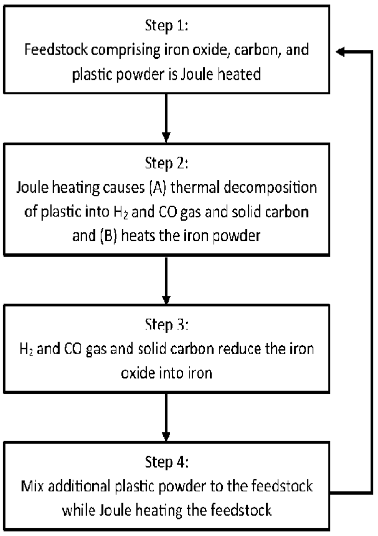

FIG. 2 – Continuous iron oxide reduction with plastic by flash Joule heating

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Joule Heating Method for Iron Ore Reduction with Plastics

Technical Field

[0001] The invention disclosed herein relates to methods and systems for efficient hydrogen-based Joule heating reduction of iron oxide to reduced iron with plastic feedstock, and, in particular, to the reduction of iron ore fines into iron.

Background of the Invention

[0002] The current state of the art is a Direct Reduced Iron (DRI) process that utilizes hydrogen as the reducing gas, and is the currently most promising decarbonization approach in the ironmaking industry. The reactors of choice for the H_2-based DRI processes are the shaft furnace and fluidized bed reactors. Known limitations of the H_2-based shaft furnace reactor include the requirement for high Fe content ore (67% or more), and dependence on pelletized iron ore, which is in short supply globally. The main advantages of the H_2-based fluidized bed reactor processes, such as HyREX, FINEX, and Circored, are the ability to use iron fines without pelletization and iron ores below 65% Fe content, but known limitations of the fluidized bed reactor include the low levels of reduction and metallization.

[0003] Most H_2-DRI processes require pre-heating of the reduction gases (H_2 and CO) and/or the ore. A major shortcoming of the DRI and the H_2-DRI processes is the reliance on secondary heat transfer, from a gas to the ore, to enable the ore reduction. In addition, the H_2-DRI processes do not melt the iron ore, and as result, the % of gangue remaining with the ore is higher than the optimal steelmaking processes need. An additional shortcoming of the existing H_2-DRI technologies is their dependence on green Hydrogen availability at quantities and prices suitable for the ironmaking and steel industries. The existing water electrolysis H_2 synthesis is not near the needed rate or cost of production.

[0004] A promising and CO_2 friendly approach to iron ore reduction is the use of waste plastics as the source for both hydrogen and carbon. *Matsuda et al.* demonstrated the feasibility of this approach, but the time-temperature synchronization of the plastics heating with the ore heating in conventional ovens means H_2 and CO gases may be consumed before the ore is properly heated, leading to a major limitation for practical solution.

[0005] Other ironmaking solutions that have been proposed include use of H_2 plasma and "flash ironmaking", which refers to ore particles suspended in flame. Both rely on an indirect heat transfer from plasma/gas to solids that lacks the thermal efficiency that the direct resistive Joule heating of this invention offers.

[0006] Flash Joule heating synthesis based methods and systems are described in Provisional Patent Application US 18/484,446, HYDROCARBON PYROLYSIS VIA JOULE HEATING OF POWDER, by *Mancevski*, having an application date of October 11, 2023, which is herein incorporated by reference in its entirety, and in Provisional Patent Application US 18/488,562, INDIRECT HYDROCARBON PYROLYSIS WITH JOULE HEATING OF POWDER, by *Mancevski*, having an application date of October 17, 2023, which is herein incorporated by reference in its entirety, and in Provisional Patent Application US 63/554,802, GRAPHITE SYNTHESIS VIA JOULE HEATING OF POWDERS, by *Mancevski*, having an application date of February 16, 2024, which is herein incorporated by reference in its entirety.

Summary Of The Invention

[0007] The present invention addresses many of the problems described above and also provides additional advantages. For example, the present invention resolves the problem of expensive H_2 by making inexpensive H_2 from plastic feedstock in situ in a reduction reactor. The current innovation also resolves the gas and solids timing problems described above by implementing rapid decomposition of the plastic into carbon and at least hydrogen gas at the same time as iron oxide ore reaches the temperature needed for its reduction to iron.

[0008] The current invention includes embodiments relating to methods comprising Joule heating a powder feedstock in a reactor, wherein the feedstock comprises of iron oxide, carbon, and plastic powder; and reduction of at least some of the iron oxide into iron. The method may further include iron reduction enabled by hydrogen from the plastic. The method may further include iron reduction enabled by carbon from the plastic.

[0009] Further embodiments include a method comprising Joule heating a powder feedstock in a reactor, wherein the feedstock comprises of iron oxide and carbon; and reduction of at least some of the iron oxide into iron.

[0010] Further embodiments include a method comprising Joule heating a powder feedstock material in a reactor, wherein the feedstock comprises iron oxide, carbon, and plastic, at least some of the plastic is converted into carbon and hydrogen gas, at least some of the hydrogen gas reduces some of the iron oxide into iron, and adding more plastic feedstock during the Joule heating to produce additional hydrogen.

[0011] Further embodiments include a a method comprising converting plastic feedstock into at least heated hydrogen gas and carbon, by Joule heating the plastic in a hydrogen reactor, injecting the heated hydrogen gas into an iron processing reactor. This method may further include the iron processing reactor being a direct reduced iron furnace, and at least some of the hydrogen reducing at least some of the iron oxide ore into sponge iron. This method may further include the iron processing reactor being an electrical arc furnace for steelmaking, and the reduction of iron ore and the melting of iron occurring at substantially the same time, thus allowing for the production of liquid iron in a single step.

Brief Description of the Drawings

[0012] The drawings included herewith are for illustrating various examples of articles, methods, and systems of the present specification. In the drawings:

[0013] FIG. 1 – process diagram for flash Joule heating reduction of iron oxide with plastics.

[0014] FIG. 2 – continuous iron oxide reduction with plastics by flash Joule heating.

[0015] FIG. 3 – exemplary process of iron oxide reduction with plastics enabled by flash Joule heating.

Detailed Description

[0016] Various systems and processes are described below to provide examples of the exemplary embodiments. These are not intended to limits any claims, which may cover similar processes and systems that differ from the examples described in detail below. The exemplary embodiments are not limited to systems or processes having all of the features of any one exemplary system or process described below, or to features common to multiple or all of the exemplary systems described below.

[0017] The innovation discloses a novel, simple, rapid, and effective electrical flash Joule heating process for the reduction of iron ore, specifically, reduction accomplished by hydrogen and carbon monoxide from thermal decomposition of new or waste plastic material, wherein the Joule heating provides the heat for both the plastics thermal decomposition and the iron ore reduction.

[0018] The principle of the flash Joule heating process is to resistively heat (Joule heat) an electrically conductive material with electrical power to induce rapid and efficient self-heating that converts the composition and crystallinity of a material to a different state. The Joule heating process requires that the feedstock comprises an electrically conductive material that can conduct electrical current. One measure of electrical conductivity used in these exemplary embodiments is the material resistivity (Ω×cm), which is the bulk material resistance (Ω) normalized over the geometry (length and cross sectional area) of the measured volume of the material. It is preferred that the feedstock has electrical resistivity of less than 1000 Ω×cm. Higher material resistivities are possible but the applied voltages may have to be higher than 480 V. Different embodiments of this process may include more or fewer of these steps, and each exemplary embodiment may comprise different steps.

[0019] An exemplary process diagram of the disclosed technology is shown in Figure 1. In this method, the feedstock mix includes iron oxide 101, electrically conductive carbon (new or waste) powder 102, and hydrogen rich plastics (new or waste) powder 103.

[0020] The iron oxide 101 of this invention may, for example, include wustite (FeO), hematite ($Fe2O3$) and magnetite ($Fe3O4$) or any combination thereof. The iron oxide in the feedstock mix may be any iron oxide, including iron ore fines as well as pelletized iron ore. It is typically more economical if the iron ore does not have to be pelletized before it is reduced to iron. Pelletized iron ore is typically produced from fine iron ore combined with a binder (like bentonite clay) and flux (like limestone) and fired at high temperatures to harden them. Typical iron ore pellets are 1 cm in diameter.

[0021] Plastic is a synthetic or semi-synthetic material made from polymers and can comprise carbon, hydrogen, and, depending on the plastics, oxygen, nitrogen, and other molecules. The plastics 103 that may be used for this innovation include raw and waste plastic materials such as PP, PE, HDPE, LDPE, PET, PS, PVC, PC, ABS, and mixed waste, but are not limited to these examples. When plastic or polymer undergoes a thermal decomposition, whether by conventional heating or by Joule heating, the volatile components like hydrogen, CO, and oxygen can be released as gases, leaving behind the carbon.

[0022] The electrically conductive carbon additive 102 of this invention may, for example, be carbon black, calcinated petroleum coke, metallurgical coke, activated carbon, char, graphene, flash graphene, carbon nanotubes, carbon nanofibers, carbon fiber, graphitized carbon fiber, or any combination thereof. The electrically conductive carbon of this invention may also include: anthracite coal, green petroleum coke, asphaltenes, recycled-tire carbon black, bio char, wood char, plant char, paralyzed cellulose, conductive polymer, conductive plastic, plastic char, or plastic ash. One convenient carbon additive may be the carbon residue from a Joule heating decomposition of plastic that may have been collected from a previous batch of Joule heating iron ore reduction. A residual reduced iron may also be acceptable as the conductive additive. A combination of residual carbon and iron from a previous process batch may also be used as the conductive additive.

[0023] In the disclosed exemplary processes, the electrical current passes through the feedstock mix, self-heating it. The flash Joule heating 104 can accomplish multiple simultaneous processes such as: (i) thermal decomposition of the plastic material into solid carbon 106 and hot hydrogen and carbon monoxide gases 105 at feedstock ranges from 400 to 1000 C, (ii) heating of the iron oxide powder 107 to the high temperatures needed for its reduction to iron at feedstock ranges from 800 to 1600 C, and (iii) reaction 108 between the hot H2 and CO gases and the hot iron oxide powder to reduce the iron oxide 107 into metallic iron 110. The heating referenced in these exemplary embodiments may take from a few seconds to 10s of minutes, and its dependent on the heated mass and the thermal losses of the reactor in which the feedstock is heated.

[0024] The thermal decomposition of plastic typically happens in the range of 400 to 1000 C and can produce at least hydrogen and CO gases, and solid carbon. The reaction between iron oxide and carbon at high temperatures (800-1600 C) can produce reduced iron and CO gas, wherein the iron oxide and the CO gas react to form metallic iron and CO2 gas. On the other hand, the reaction between iron oxide and hydrogen at high temperatures (800-1600 C) can produce reduced iron and water. The efficiency and the yield of the reduction process can depend on the C/O ratio of the feedstock mix and the reduction temperatures. For efficient iron reduction, it is possible to have C/O ratios from 0.5 to 10, wherein the C can come from the plastic or from the electrically conductive carbon additive. Possible reduction temperatures are from 800 to 1600 C, although temperatures above 1600 C are also possible. At temperatures higher than 1600 C, the reduced iron can melt and then solidify during the cooling as more pure form of iron nuggets in the size from 0.1 mm to a few millimeters.

[0025] Due to the rapid speed with which the plastic reaches the decomposition temperature, it can release H2 and CO reduction gases 105 at the same time as the iron oxide particle 107 reaches its process temperature, so that the reduction gases can reduce the iron oxide to iron 110 at high efficiencies. Because the plastic powder is embedded with the iron oxide powder, the spatial distribution of the H2 and CO gases may enable a more uniform iron reduction process.

[0026] In one exemplary embodiment of this invention, in addition to the reduction 108 of iron oxide into iron 110 with hydrogen and CO 105, the residual carbon 106 from the plastic decomposition and the carbon from the conductive carbon 102 can also reduce (process step 108) the iron oxide into iron 110.

[0027] In another exemplary embodiment of this invention, the iron oxide 101 can be reduced to metallic iron 110, and has separated from the residual carbon. One exemplary method of the flash Joule heating reaction can be configured to be rapid such that iron molecules do not have time to form new bonds with the carbon, but instead iron and carbon recrystallize into pure iron metal particles and carbon powder that is free from the iron particles. Another exemplary method of the flash Joule heating reaction can be configured to that the reduced iron with presence of carbon that have been created by Joule heating the feedstock comprising iron oxide, carbon, and plastic, is further heated to temperatures above 1600 C to melt the iron, and, upon cooling, form metallic iron particles free from carbon, and carbon powder free from iron. In one exemplary embodiment, the metallic iron can be separated from the free unattached carbon with magnetic sieving. In one exemplary embodiment, some of the iron particles may form iron carbides whose presence is acceptable during the subsequent steelmaking process. In another exemplary embodiment, the flash Joule heating reaction can be configured to allow the reduction of iron ore and the melting of reduced iron to occur at substantially the same time, or sequentially one after another, to produce liquid iron in a single step inside a flash Joule reactor. Exemplary forms of carbon possible with some embodiments of the disclosed invention include sponge iron and pig iron. Sponge iron (also known as direct reduced iron) is a porous form of iron produced by reducing iron ore with a reducing gas (like hydrogen or carbon monoxide) at temperatures below the melting point of iron. Pig iron is a form of iron previously obtained by prior art methods of smelting iron ore in a blast furnace, and is characterized by its high carbon content. Embodiments of this invention enable the production of various forms of iron, including for example sponge iron and pig iron in a novel way.

[0028] Exemplary feedstock can comprise iron oxide, carbon additive, and plastic will result in iron oxide reduction by the hydrogen, CO, and by the carbon (from the carbon additive or from the plastic). It typically only takes 5-10 wt.% of carbon additive to cause the non-conductive iron ore and non-conductive plastic powder to become sufficiently electrically conductive to start the flash Joule reaction. Typical plastics have about 86 wt.% of carbon to about 14 wt.% of Hydrogen. Therefore, in one exemplary feedstock, there is 10% C, 10% plastic, and 80% of iron oxide, wherein after the thermal plastic decomposition there may be 18.6% of carbon, 1.4% of hydrogen, and 56% iron, and 24% oxygen. The C/O molar ratio for this example is 1. Therefore, if there is a shortage of hydrogen for full iron oxide reduction, then additional hydrogen may be needed without restarting the reduction process in the reactor. One way to achieve this goal is to add more plastic to the reaction.

[0029] In another exemplary embodiment of this invention, illustrated in Figure 2, after most of the plastic has been decomposed to hydrogen (and CO) gas and solid carbon (Step 2), and the hydrogen (and CO) has been consumed to reduce the iron oxide into iron (Step 3), additional plastic powder may be added to the reactor during the process (Step 4). The process may then return to Step 1 to form additional hydrogen (and CO) gas (in Step 2) that can enable further iron oxide reduction. The plastic addition and the iron oxide reduction can continue until most of the iron oxide is reduced or the desired reduced iron to carbon ratio in the reactor is achieved.

[0030] Since the iron oxide reduction can be achieved with both carbon and hydrogen (requiring plastic in the feedstock), the additional plastic may be added at any time without stopping the reduction process. The additional plastic may be added when the Joule heating is ongoing, or the Joule heating may be paused to add the plastic and then restarted. Once the Joule heating reduction process commences, there may no longer be a need to add a conductive carbon additive, since the carbon residue from the plastic may act as a conductive carbon additive, making the feedstock electrically conductive. Additionally, the reduced iron may be electrically conductive and may make the feedstock electrically conductive. The amount of additional plastic may be controlled to maintain the electrical conductivity of the feedstock in the reactor.

[0031] In one embodiment, the reduction process can be a batch reaction, wherein the reduced iron may be removed from the reactor and new feedstock mix may be added into the reactor for a new batch processing. In another exemplary embodiment, the reduction process may be continuous, wherein reduced iron and excess carbon may be removed from the reactor and additional plastic may be added to the feedstock in the desired carbon to iron oxide ratios to enable continuous iron oxide reduction operation. In another embodiment, additional iron oxide may be added to the reactor after some reduced iron or excess carbon or both are removed from the reactor.

[0032] Figure 3 shows exemplary data from an exemplary process of iron oxide reduction with plastics enabled by flash Joule heating. The exemplary feedstock for this process included 82.6% iron oxide, 8.3% carbon black, and 9.1% of polyethylene plastic powder. Figure 3a shows an optical image of the iron oxide powder. Figure 3b shows an optical image of the resulting reduced iron material. Figure 3c shows an SEM image of the resulting reduced iron material. Figure 3d shows an EDX analysis of the resulting reduced iron material.

[0033] In one example of the disclosed innovation, the method may include feedstock comprising iron ore fines in the range from 1 μm to 16 mm. The iron ore fines are typically more abundant and do not require pelletization of the iron ore prior to its reduction. The feedstock of this invention may also include feedstock comprising low quality iron ores with iron content between 25 to 67 wt.% Fe. The disclosed exemplary iron reduction process is not impeded by the presence of impurities in the feedstock, such as, for example, SiO2, Al2O3, MgO, Cu, etc. at percentages common in low grade iron ores. In one example of the disclosed exemplary iron reduction process, the energy for ore reduction is in the range of 2 to 20 GJ/t Fe. In one example of the disclosed exemplary iron reduction process, the resulting CO2e emissions due to the benefits of the disclosed technology may be in the range 10 to 360 kg CO2e/mt of Fe & gangue. In one example of the disclosed exemplary iron reduction process, the ore reduction degree of up to 95% may be achieved.

[0034] The disclosed electrically based flash Joule iron ore reduction with hydrogen from waste plastics process resolves the shortcomings described in the prior art. In the disclosed process, non-pelletized fine iron ore powder with less than 65% iron content is premixed with electrically conductive carbon powder and hydrogen rich waste plastics powder to make an electrically conductive iron ore mixture. The mixture is fed through a flash Joule heating reactor, as described for example in *Mancevski* 18/484,446, where electrical current is passed through the mixture, self-heating it. The joule heat substantially instantaneously and substantially simultaneously heats the iron ore and the plastic, wherein the plastic substantially instantaneously pyrolyzes into mainly hydrogen and CO gases which react with the hot iron ore to reduce it to iron, typically within seconds after the reaction temperature is reached. It typically only takes 5-10 wt.% of carbon to make the non-conductive iron ore and plastic powder become sufficiently conductive to start the flash Joule reaction. In one embodiment of the invention, the reactor may include a system for mixing the feedstock powder, as described in Mancevski 63/554,802, to improve the uniformity of the feedstock constituents, the iron oxide powder, the additive carbon powder, and the plastic powder. Improved powder mixing may enable a more uniform reduction process. The electrical conductivity is controlled by the carbon, not the iron content, and therefore, the % Fe or % impurities in the ore are not a significant factor for this proposed process. There is typically no need for separate hydrogen generation units as the process itself generates the hydrogen gas. The 100% reliance on electricity for heating, hydrogen generation, and reduction results in significantly low CO2e emissions.

[0035] An exemplary system that enables a flash Joule heating process of iron oxide reduction with plastics may include a reactor, a feeder of iron ore powder, carbon additive powder, and plastic powder that may feed the powders into the reactor, a reactor lid to control the oxygen levels in the reactor, a pressure relieve valve to prevent reactor overpressure due to H2 or CO gas accumulation, a set of electrodes to apply electrical current for Joule heating to the electrically conductive feedstock, and a feedstock mixing arm to physically stir the powder. A continuous system for a flash Joule heating process of iron oxide reduction also may include a dispenser to remove reduced iron and/or residual carbon from the bottom of the reactor that can operate while the Joule heating is ongoing or while the Joule heating is paused.

[0036] Another exemplary method and system for efficient hydrogen based Joule heating reduction of iron oxide to reduced iron with plastic feedstock is also described. In this embodiment, a standalone flash Joule reactor that may convert plastic feedstock into at least hydrogen gas and solid carbon residue may be operated alongside a conventional H_2 based direct reduction iron (DRI) reactor/furnace and may feed it hydrogen. At least some of the hydrogen produced by Joule heating methods may be used to reduce at least some of the iron oxide ore inside the DRI furnace into, for example, sponge iron. At least some of the residual carbon produced by Joule heating of plastic to make hydrogen may also be used as carbon source in the operation of the DRI furnace. The standalone joule heating reactor, for example as described in *Mancevski* (US 18/484,446) and *Mancevski* (US 18/488,562) and *Mancevski* (US 63/554,802), may be capable of producing hydrogen, CO, syngas, and other hydrocarbons from plastic feedstock, as well as from methane gas and other hydrocarbon gases. An advantage of this exemplary embodiment may be that the resulting reduction gases, hydrogen and CO, may be configured to exit preheated, because they come from a high temperature Joule heating process, and may then be piped to the main DRI reactor/furnace without the need for additional gas preheating. This approach also eliminates the need to store the hydrogen gas. The hydrogen production may be controlled to match the DRI operation, and may also be paused if the hydrogen generation is no longer needed. The Joule heating production of hydrogen from plastics may be operated in batch mode or in a continuous mode.

[0037] In another exemplary embodiment of this configuration, the standalone Joule heated hydrogen production reactor may feed an electrical arc furnace/reactor for steelmaking. At least some of the hydrogen produced by Joule heating methods may reduce at least some of the non-reduced iron (for example FeO in the slug) inside the electric arc furnace as part of the steelmaking process. At least some of the residual carbon produced by Joule heating of plastic to make hydrogen may also be used as carbon source in the operation of the electric arc furnace. In one embodiment of the invention, the reduction of iron ore and the melting of iron may occur at substantially the same time, or sequentially one after another, to allowing for the production of liquid iron in a single step inside an electric arc furnace.

[0038] While the above description provides examples of various apparatuses, methods, and systems, other apparatuses, methods, or systems may be within the reasonable scope of the claims as interpreted by one of skill in the art.

Claims

1) A method comprising

    a) Joule heating a powder feedstock in a reactor, wherein the feedstock comprises of iron oxide, carbon, and plastic powder; and

    b) reduction of at least some of the iron oxide into iron.

2) The method of claim 1 wherein:

    a) the iron reduction is enabled by hydrogen from the plastic.

3) The method of claim 1 wherein:

    a) the iron reduction is enabled by carbon from the plastic.

4) A method comprising:

    a) Joule heating a powder feedstock in a reactor, wherein the feedstock comprises of iron oxide and carbon; and

    b) reduction of at least some of the iron oxide into iron.

5) A method comprising:

    a) Joule heating a powder feedstock material in a reactor, wherein

    b) the feedstock comprises iron oxide, carbon, and plastic,

    c) at least some of the plastic is converted into carbon and hydrogen gas,

    d) at least some of the hydrogen gas reduces some of the iron oxide into iron,

    e) adding more plastic feedstock during the Joule heating to produce additional hydrogen.

6) A method comprising:

    a) converting plastic feedstock into at least heated hydrogen gas and carbon, by Joule heating the plastic in a hydrogen reactor,

    b) injecting the heated hydrogen gas into an iron processing reactor.

7) The method of claim 6 wherein:

    a) the iron processing reactor is a direct reduced iron furnace, and

   b) at least some of the hydrogen reduces at least some of the iron oxide ore into sponge iron.

8) The method of claim 6 wherein:

   a) the iron processing reactor is an electrical arc furnace for steelmaking, and

   b) the reduction of iron ore and the melting of iron occur at substantially the same time, allowing for the production of liquid iron in a single step.

AMENDED CLAIMS
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1) A method comprising

   a) adding a powder feedstock into a reactor;

   b) Joule heating the powder feedstock in the reactor, wherein the feedstock comprises of iron oxide, carbon, and plastic powder; and

   c) reduction of at least some of the iron oxide into iron in the reactor;

   d) without the use or creation of a molten liquid slag.

2) The method of claim 1 wherein:

   a) the iron reduction is enabled by hydrogen from the plastic.

3) The method of claim 1 wherein:

   a) the iron reduction is enabled by carbon from the plastic.

4) A method comprising:

   a) adding a powder feedstock into a reactor;

   b) Joule heating the powder feedstock in the reactor, wherein the feedstock comprises of iron oxide and carbon; and

   c) reduction of at least some of the iron oxide into iron in the reactor;

   d) without the use or creation of a molten liquid slag.

5) A method comprising:

   a) Joule heating a powder feedstock material in a reactor, wherein

   b) the feedstock comprises iron oxide, carbon, and plastic,

   c) at least some of the plastic is converted into carbon and hydrogen gas in the reactor,

   d) at least some of the hydrogen gas reduces some of the iron oxide into iron in the reactor,

   e) adding more plastic feedstock into the reactor during the Joule heating to produce additional hydrogen.

6) A method comprising:

a) converting plastic feedstock into at least heated hydrogen gas and carbon, by Joule heating the plastic in a hydrogen reactor

b) wherein the hydrogen reactor does not use or create molten liquid slag,

c) injecting the heated hydrogen gas into an iron processing reactor.

7) The method of claim 6 wherein:

a) the iron processing reactor is a direct reduced iron furnace, and

b) at least some of the hydrogen reduces at least some of the iron oxide ore into sponge iron.

8) The method of claim 6 wherein:

a) the iron processing reactor is an electrical arc furnace for steelmaking, and

b) the reduction of iron ore and the melting of iron occur at substantially the same time, allowing for the production of liquid iron in a single step.

STATEMENT UNDER ARTICLE 19(1)

In the Written Opinion herein the examiner found that claim 4 is anticipated by the cited prior art, and that the remaining claims are obvious in light of the cited prior art. In reaching these conclusions, the examiner relied primarily on cited reference WO 2023/066794 to Wurth ("*Wurth*"). Of the rejected claims, claims 1, 4, 5, and 6 are independent, and the remaining claims are dependent. The comments below focus on independent claims 1, 4, 5, and 6.

The Specification was amended by the typographical correction of the word "slug" to "slag", and the addition of the statement "Slag is known in the art, as referenced for example in WO 2023/066794." The purpose is to confirm that the term slag as used in the amended claims is known in the art.

Independent Claims 1, 4, and 5 were amended to limit the claimed invention to a single reactor, to distinguish it from the prior art which discloses only a multi-step process requiring multiple reactors. The amendment limits the invention to a single reactor by specifically claiming that the powder feedstock is added into a reactor, and that the remaining steps occur "in the reactor." The cited prior art, on the other hand, requires four steps including at least a "fluidized bed reactor" and a "submerged arc furnace reactor." *Wurth*, par. [0005]. It does not disclose facilitating the entire process in a single reactor. *Id.*

Independent Claims 1, 4, and 6 were amended to limit the invention to exclude the use or creation of molten liquid slag, to distinguish it from the prior art which requires slag to function. The amendments specifically exclude the use of slag in the process. The cited prior art, on the other hand, requires the use of a "top slag layer" to facilitate heating the hot molten iron metal below. *Wurth*, par. [0005]. It does not disclose a process that can operate in the absence of slag.

For the reasons stated, amended independent claims 1, 4, 5, and 6 are novel over the cited references.

The remaining dependent claims depend from amended independent claims 1, 4, 5, or 6, and were not amended. Accordingly, in light of the amendments, these dependent claims are also novel.

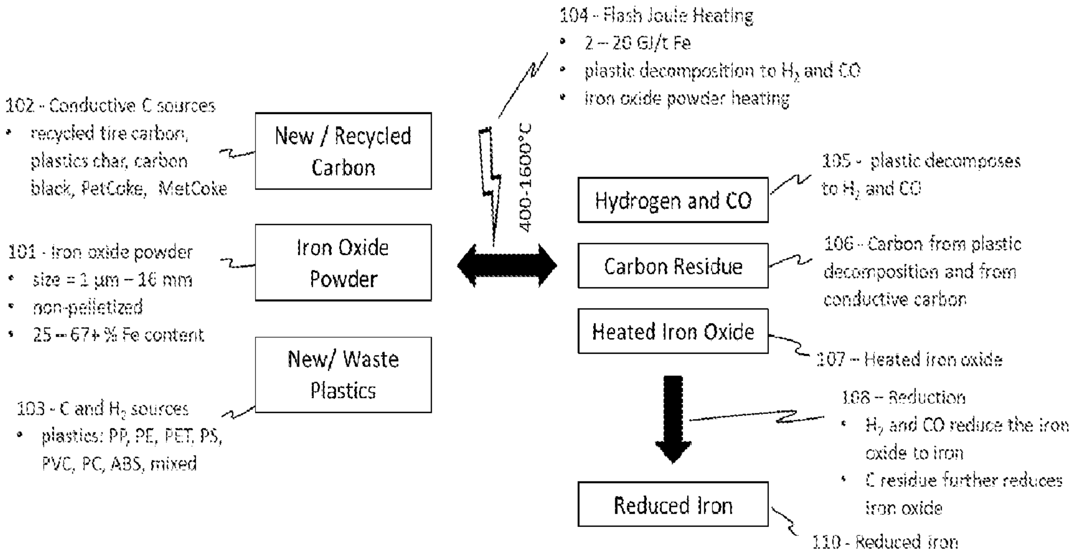


Figure 1: Process diagram of flash Joule heating reduction of iron oxide with plastics

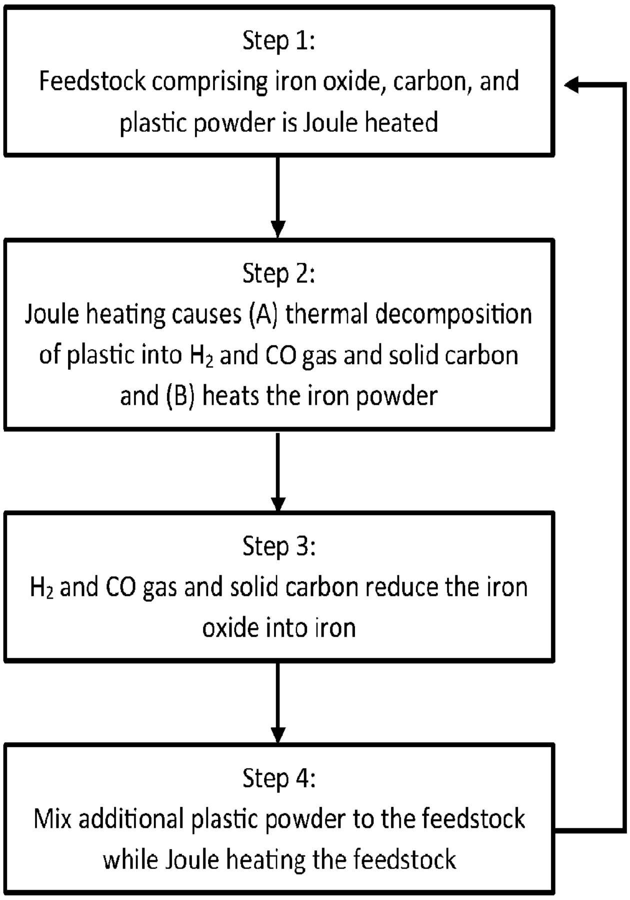


FIG. 2 – Continuous iron oxide reduction with plastic by flash Joule heating

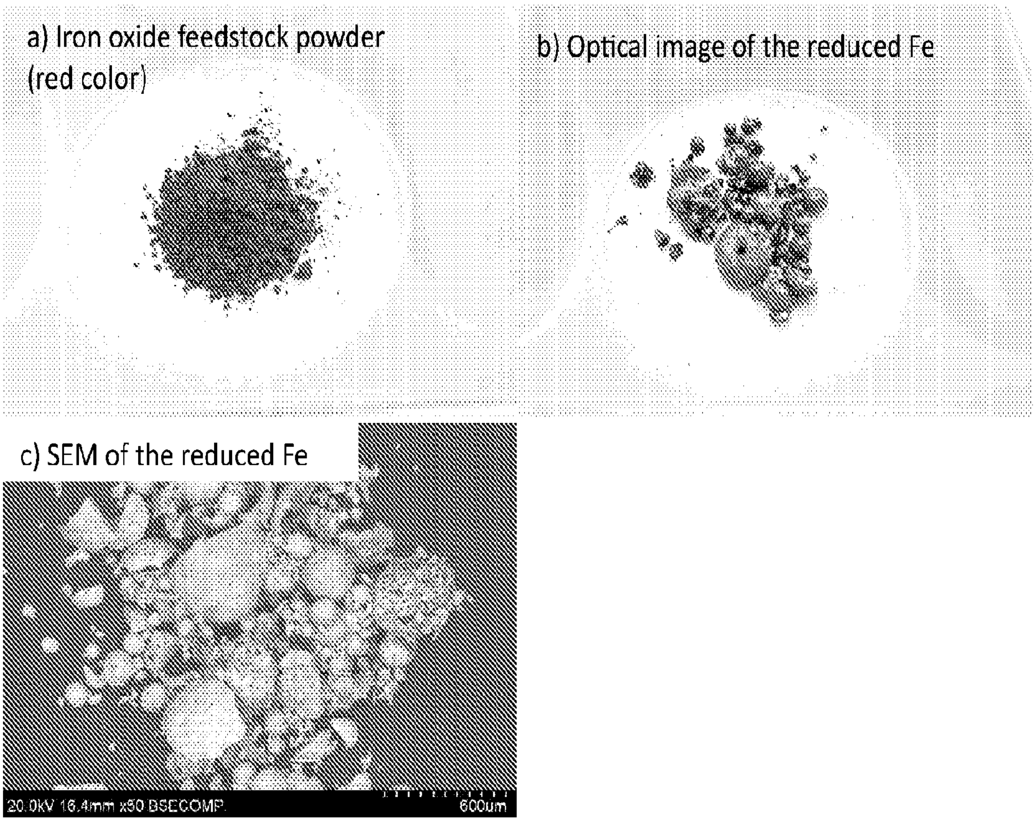
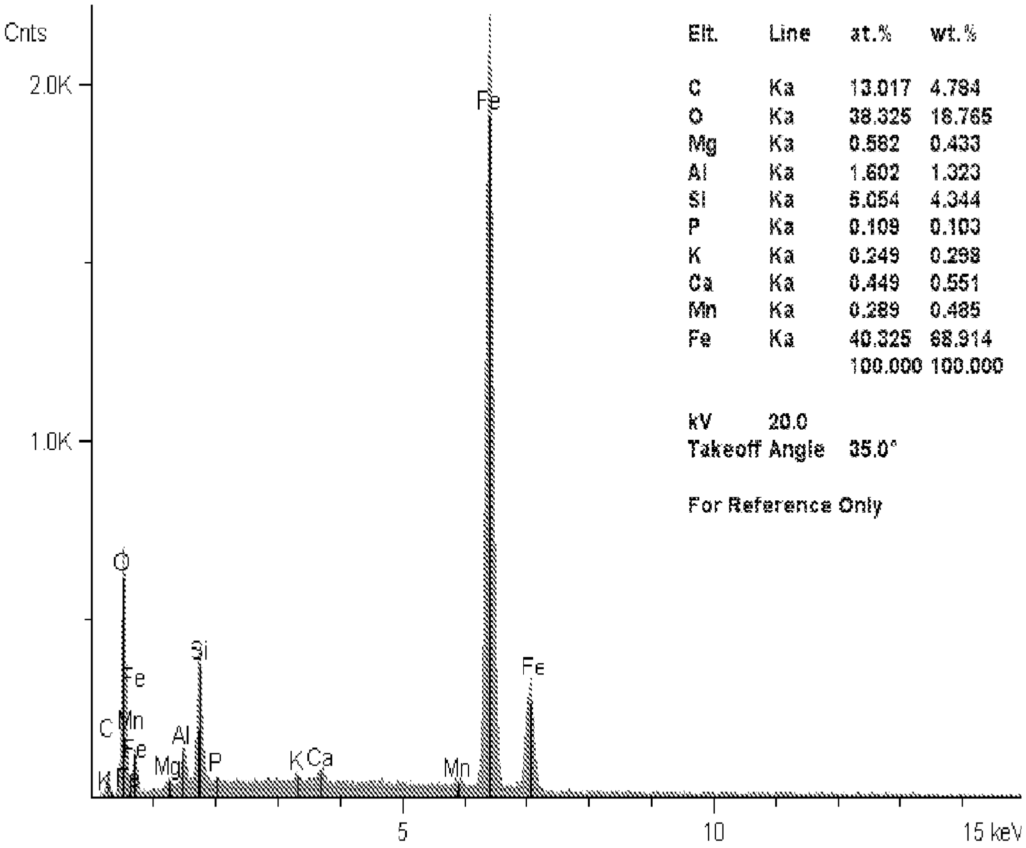


Figure 3: Exemplary process of iron oxide reduction with plastics enabled by flash Joule heating. (a) iron oxide feedstock powder, (b) optical image of the reduced iron, (c) SEM image of the reduced iron



Elt.	Line	at.%	wt.%
C	Ka	13.017	4.784
O	Ka	38.325	18.765
Mg	Ka	0.582	0.433
Al	Ka	1.602	1.323
Si	Ka	5.054	4.344
P	Ka	0.109	0.103
K	Ka	0.249	0.298
Ca	Ka	0.449	0.551
Mn	Ka	0.289	0.485
Fe	Ka	40.325	68.914
		100.000	100.000

kV 20.0
Takeoff Angle 35.0°

For Reference Only

Figure 3D: Exemplary process of iron oxide reduction with plastics enabled by flash Joule heating. EDX analysis of the reduced iron.

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2025/020548

A. CLASSIFICATION OF SUBJECT MATTER

IPC: ***C21B 13/02*** (2025.01); ***C21B 13/12*** (2025.01)

CPC: ***C21B 13/02; C21B 13/023; C21B 13/12;*** *C21B 13/026*

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

See Search History Document

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

See Search History Document

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

See Search History Document

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 2023/066794 A1 (PAUL WURTH S.A.) 27 April 2023 (27.04.2023) entire document especially para [0005], [0012], [0038], [0033], [0017], [0009], and abstract	1-8
A	US 2020/0384727 A1 (IMPOSSIBLE OBJECTS LLC) 10 December 2020 (10.12.2020) entire document	1-8
A	US 2012/0022311 A1 (MARRILLET et al.) 26 January 2012 (26.01.2012) entire document	1-8
A	US 2014/0227548 A1 (MYRICK) 14 August 2014 (14.08.2014) entire document	1-8

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
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"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search **20 May 2025 (20.05.2025)**	Date of mailing of the international search report **30 May 2025 (30.05.2025)**
Name and mailing address of the ISA/US **COMMISSIONER FOR PATENTS** **MAIL STOP PCT, ATTN: ISA/US** **P.O. Box 1450** **Alexandria, VA 22313-1450** **UNITED STATES OF AMERICA** Facsimile No. **571-273-8300**	Authorized officer **KARI RODRIQUEZ** Telephone No. **PCT Help Desk: 571-272-4300**