A novel process of producing liquid iron using microwaves

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Abstract

The Steel industry is facing escalating pressure to reduce CO_2 emissions. In blast furnace (BF) process, iron ore lumps are crushed and turned into sinter or pellets. Separately, coal is carbonized and converted into coke. The sinter / pellets and coke are then charged into BF, where burning of coke and coal generate gases which reduce sinter / pellets to produce liquid iron. In BF, coal and coke are used which generate a large amount of greenhouse gases (GHG). To minimize these emissions, Industrial Microwave Research Centre of Pradeep Metals Limited, Navi-Mumbai has developed an iron-making process, where a novel route has been explored based on rapid interactions of iron ore and coal with microwaves. The process uses coal to fulfil chemical demand of carbon for direct reduction of iron oxides and microwaves to fulfil thermal demand for the same, thereby leading to a substantial decrease in GHG emissions. The process uses powdery iron ore which is not favoured in BF. The pig iron so produced is almost rust free and has low levels of Si, P and S, which are favourable for steelmaking. The tapping of liquids could be successfully tried, obtaining iron pieces weighing up to 8.15 kg. This paper presents the efforts made for establishing a prototype plant together with the results of some selected trials.

1. INTRODUCTION

Based on World Steel Association analysis, the steel industry is responsible for 5-8 % of global CO_2 emissions [1]. It is further stated that every ton of steel, produced in 2018, emitted an average of 1.85 tons of CO_2. The Paris Agreement of 2019 mandates carbon neutrality from steel production by 2050. Hence, a change in steelmaking technology is inevitable. But the pathway to facilitate this change is not easy because of long investment cycles of 10 to 15 years [2]. To address this problem, a plethora of processes are being developed around the world under the umbrella of the so called smelting-reduction processes such as HISMELT, AUSIRON, HISARNA, HYBRIT, etc. Some of these new processes are expected to start their large-scale pilot-plant production by 2030.

In India, Industrial Microwave Research Center (IMRC) of Pradeep Metals Limited (PML), Navi-Mumbai has adopted a new approach where microwave energy is used to make pig iron. This was done after realizing that iron ore and coal can interact rapidly with microwaves, thereby achieving high temperatures in a short time. IMRC had already developed a process for producing sponge iron with microwaves [3]. The same process was extended to make pig iron with few modifications. The prime aim was to preserve the environment by using iron ore fines and coal fines, and avoiding entirely the use of coke to make purer pig iron. For establishing a prototype plant, IMRC-PML collaborated with the Chubu University of Japan. IMRC-PML was fortunate to receive partial funding from Steel Development Fund (SDF), Ministry of Steel, Govt. of India, for this project.

2. LABORATORY SCALE DEVELOPMENTS

The behaviour of different iron ores on laboratory scale was studied using a 3-kW microwave system. Time temperature profile of hematite and magnetite is depicted in Fig. 1 which shows that iron ores like hematite and magnetite interact rapidly with microwaves and temperatures of 1200-1300^{0}C could be achieved in few minutes.

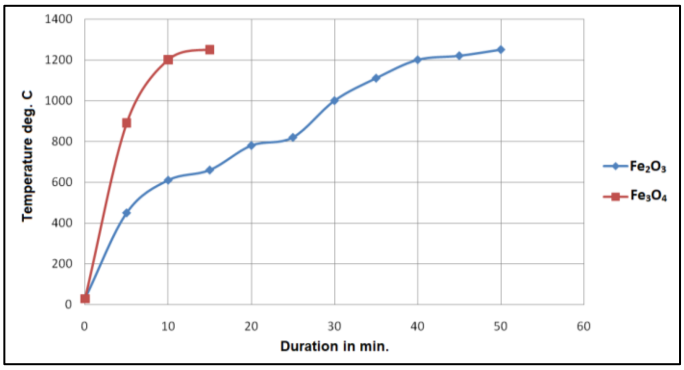
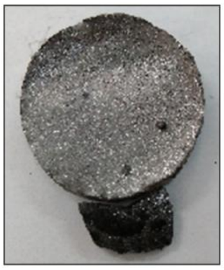


Fig. 1: Time temperature profile of hematite & magnetite under microwave exposure

After completing this study, few experiments were planned for making pig iron by direct reduction of green pellets which were prepared by mixing of iron ore, coal, and fluxes in fine form. Then they were subjected to microwaves under different experimental conditions. The results of two such experiments are presented in Fig. 2 (a & b) and were quite encouraging.

163 gm green pellets of high grade iron ore (Fe-65.0%) mixed with coal and binder, heated to 1380^{0}C under N_2 atmosphere. Metal recovered weighed 95 gm (91%) and slag 10 gm (9%)

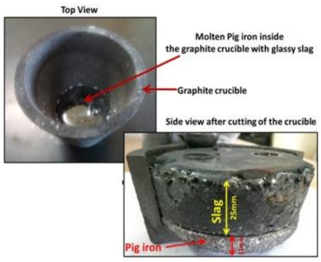


Chemical analysis of the pig iron and slag

Pig iron	Slag analysis
C – 3.77%	Total Fe - 5.54 %
S – 0.015%	SiO_2 – 45.68 %
P – 0.015 %	Al_2O_3 – 15.17%
Mn – 0.085%	MnO_2 - NIL
Si – 0.10%	CaO – 27.15 %
Fe – 97.78 %	

2a

700 gm green pellets made from low grade Goa iron ore (Fe-46.0%)mixed with flux and coal powder with binder, heated to 1315^{0}C under N_2 atmosphere Metal recovered weighed 250 gm (78%) and slag 260 gm



Pig iron analysis	Slag analysis
C – 4.33%	Total Fe 2.01 %
S – 0.05%	SiO_2 – 37.07%
P – 0.19 %	Al_2O_3 – 25.72 %
Mn – NIL	MnO_2 – 1.74%
Si – 0.05%	CaO – 32.06%
Fe – 95.04 %	

2b

Fig. 2: Lab-scale experiment results: (2a) with high grade iron ore, and (2b) with low grade iron ore

3. DESIGN AND INSTALLATION OF PROTOTYPE PLANT

The above results confirmed that better quality pig iron could be made using microwave technology and any grade of iron ore. Based on success of these laboratory experiments, Dr. Sato, a faculty of Chubu University, Japan, helped us to design a prototype plant for scaling up the process. The plant had a provision of installing 1 to 4 nos. of water-cooled magnetrons, each with 6 kW microwave output capacity working at 2450 MHz. There was also a provision for installing klystrons, each of 30 kW, in place of magnetrons. Other safety components such as circulators, tuners and quartz windows and microwave leakage detectors were also provided with the plant, and all gadgets were procured from Japan.

On receiving the prototype plant from Japan, complete assembling, commissioning, and testing of the plant was done in 3 weeks and a first trial was conducted. This trial failed and after doing failure analysis, three main reasons could be listed: a) rapid increase in the temperature of exhaust blower, b) oxidizing atmosphere in the reduction zone (14-18% O_2), and c) insufficient microwave energy reaching the reduction zone (reaching only 10-20%). The first two problems were overcome relatively quickly as alternatives were available locally.

For enabling more microwave field to reach the reduction zone, help from Society for Applied Microwave Electronics Engineering and Research (SAMEER), Mumbai was taken for checking antenna design using their simulation program. Based on the simulation results, new designs of waveguide were worked out and their fabrication done by a local fabricator. Next challenge was to find the proper location of the sample in the cavity of a volume of 80 litres, where maximum microwave density would be available [4]. For this, a testing system was made (Fig. 3) and installed where a tiny antenna connected to a network analyser and microwave field at different locations was monitored. Area with maximum microwave intensity was marked and it was decided to place the samples within this area. After all modifications, the prototype plant (Fig. 4) was ready for next set of trials.

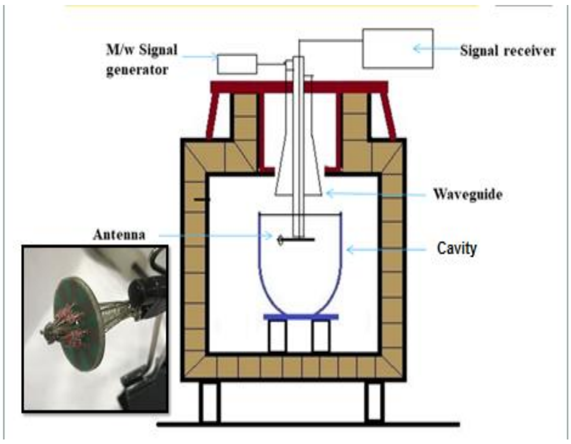


Fig. 3: Setup for location of maximum microwave field in the cavity

Fig. 4: Final reformed picture of microwave assisted prototype plant

4. PROTOTYPE PLANT OPERATION RESULTS

4.1 After completing all modifications of the prototype plant & cavity, a trial was conducted which was successful. In this trial, a 1.0 kg raw mix made by mixing iron ore (93% Fe_2O_3) & coal powder and flux were heated to around 1300^{0}C to achieve good separation of metal (400g) & slag (Fig. 5). The chemistry of products of this trial is summarised below in Table I.

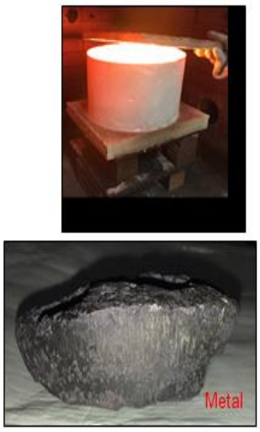


Fig. 5 : Successful trial from pilot plant

Table I: Chemical composition of molten metal and slag

Metal		Slag	
	%		%
C	1.29	SiO_2	34.30
Si	2.07	Al_2O_3	13.78
Mn	0.12	CaO	34.45
P	0.095	MgO	6.19
S	0.055	Fe_2O_3	11.31

Table II: Continuous raw mix feeding data

Temp. regaining time (min)	Qty (g)	Initial Temp (^{0}C)	Final Temp (^{0}C)	Power consu med (kW)
6	250	1430	1416	2
5	250	1416	1400	2
9	500	1400	1460	3
9	500	1460	1432	4
8	500	1432	1447	3
10	500	1447	1430	4
15	500	1430	1450	5
7	500	1450	1480	2
7	500	1480	1465	2
7	500	1465	1468	4
10	500	1468	1476	4

The yield of metal in this trial was > 90%. However, a small part of metal and slag was lost in refractory lining. The composition of metal is given in Table 1.

4.2 After completing batch trials, the next step was to drain molten mass from sample holder to the collection crucible. For this, trials were conducted where continuous feeding and collection of molten mass was attempted. In these experiments, two crucibles were placed within the microwave cavity, one above the other. The top crucible had a hole at the bottom side rim for draining the molten metal and slag, while the bottom crucible was for collection of molten products. During these trials initially about 500g to 2.0 kg raw-mix was placed in the top sample holder. Heating was done by gradually increasing the microwave input power to reach the desired temperature of >1450^{0}C. Complete melting of the raw mix pellets was ascertained by visual observations from the top sapphire window. Then, additions of raw-mix pellets were done from the top-feeding port. Before each addition, the completion of smelting-reduction reaction was ensured (Fig. 6) by visual observations through the top window.

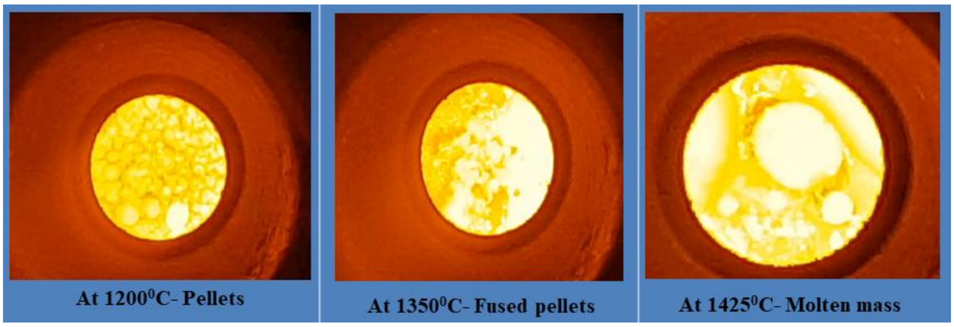


Fig. 6: Progress of smelting-reduction reaction

Details of one set of trial where such 11 additions of raw mix were made are given above in Table II. During addition of fresh raw-mix pellets in the molten mass, the temperature decreased rapidly but recovered equally fast due to high temperature of the active molten metal bath and microwave field around it. It was observed that depending on the quantity of fresh material, the regaining of temperature to >1450^{0}C varied, for 250g regaining time was 5-6 min., while for 500g it varied from 7 to15 min.

4.3 The third and final stage of the project was tapping of the molten mass outside the cavity & furnace. During this step, the molten slag and metal were needed to be collected outside the main cavity & furnace through a tapping hole made in the crucible. This hole was initially sealed with patching mass. For taking out the molten products, a graphite tube was inserted in the tapping hole of the ceramic crucible. To prevent oxidation of graphite at high temperatures, this graphite tube was covered with alumina tube. For avoiding solidifications of the molten products, the ceramic tube was heated to 1300-1350°C with SiC heating elements. The molten mass was collected outside in another crucible half-filled with dried sand. During actual trial, as per SOP developed by us, raw-mix pellets were placed in the sample holder and heated to 1450^{0}C using microwaves. After confirming melt formation (Fig. 6), subsequent additions were made by adding 250/500g raw-mix pellets. After completion of melting, the tapping hole was gently broken and molten products were allowed to flow out in the product collector (Fig. 7).

Fig. 7: Tapping of molten iron and slag

Table III: Chemistry of molten metal and slag (range)

Metal Chemistry		Slag Chemistry	
C (%)	1.63-2.16	SiO_2 (%)	40.5 - 44.1
S (%)	0.016-0.12	CaO (%)	24.6 - 30.2
P (%)	0.012-0.08	Al_2O_3 (%)	11.5 - 18.9
Mn (%)	0.025-0.088	MgO (%)	4.8 - 8.02
Si (%)	0.08- 0.18	Fe_2O_3 (%)	2.5 - 3.01
		MnO (%)	1.5 - 1.8
		S (%)	0.15 - 0.17
		P (%)	0.06 - 0.08

5. DISCUSSION

It is well known that direct reduction of iron oxide is chemically very efficient but is highly endothermic, whereas indirect reduction is chemically not efficient but is slightly exothermic. It is evident that if availability of carbon for total direct reduction is met along with fulfilling the thermal requirements for the same by using microwaves, it will result in minimum carbon rate. This philosophy could be adopted with success to select coal/ore ratio and to regulate microwave energy in this novel process.

While designing the raw-mix, requisite amount of fine particulates of coal, ore and fluxing agents were mixed so as to fulfil chemical (reducer) demand of carbon. Exposing such raw-mix pellets to microwaves gave: a) Minimum possible carbon consumption, and thereby minimum GHG emission and b) Molten pig iron.

The present study had further indicated that microwave cavity and antenna design were critical in microwave processing to get maximum energy efficiency. Tuning of the big microwave cavity has been found very crucial. Depending on final temperature, the process can produce sponge iron or molten pig iron directly from green pellets consisting of iron oxide, coal, and fluxing agent. The viability of the technology depended on the fact that iron ore and carbon powders are excellent microwave absorbers, and the desired high temperatures can be reached in a short time. This process does not require coke and offers flexibility in selection of ore as it can process hematite, magnetite, or any other type of iron ore. Magnetite is hard to reduce, but with microwaves it interacts very rapidly (more than hematite) where temperature of 1000^0C can be reached in a few minutes (Fig. 1). Overall, the product chemistry obtained from this technology showed much less % of Si, S, and P in metal (Table III).

It emerges from these studies that the microwave assisted process is a green process that uses only fine coal (no coke) and fine ore, as against sized/agglomerated ore and coke with pulverized coal injection in the conventional BF. Another important feature is that the kinetics of reaction is quite favourable and is likely to be conducive for attainment of high production rates. Calculations indicate that the process consumes a low coal rate of about 300 kg/ tons of hot metal (tHM) as against about 600 kg (coke + coal)/tHM in a conventional BF. This will be quite beneficial for commercialisation of this process. This minimum carbon consumption/tHM, indicates that maximum direct reduction (>80%) is taking place in this process. The process offers a number of other benefits like; elimination of pelletisation, sintering, coking, and corresponding reduction in GHG emissions, production of purer pig iron (with less impurities), utilization of unused fine iron ore & coal, and above all has no requirement of coke. The process is already patented by PML in Russia, Ukraine, Japan and Australia [5].

6. CONCLUSION

The novel process has been established by PML-IMRC team from conceptual stage to a reality by getting molten metal and slag along with continuous tapping of the products outside the prototype furnace. While developing this process, careful studies were made to list all possible benefits of the process to steel industry, including production of iron without requiring pelletisation, sintering of iron ore, and avoiding the need for coke. This technology utilizes the advantages of microwave heating, viz. rapid volumetric heating, high energy efficiency and acceleration in the speed of chemical reactions. It is expected that this new and simplified process will require less capital cost, while getting higher productivity, purer product, and considerable reduction in environmental pollution, thus consisting of all the ingredients of a successful future technology.

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