Study the reduction of mill scale with lean grade coal through RI-RDI

Deepika Shekhawat¹, Vikas Kukshal², M K Banerjee³, Amar Patnaik¹

¹Mechanical Engineering Department, MNIT Jaipur, 302017, Rajasthan, India
²Mechanical Engineering Department, NIT Uttarakhand, 246174, Uttarakhand, India
³Mechanical Engineering Department, SKIT, Jaipur, 302017, Rajasthan, India

Email: apatnaik.mech@mnit.ac.in

Abstract. In the present study, efforts have been made to assess and study the reduction of mill scale in the presence of single gaseous reductant (i.e. CO gas) in RI-RDI (reducibility index (RI) and reduction degradation index) equipment. While conducting this study optimal process parameters like reduction temperature, mill scale size, reduction time and mill scale to coal ratio were analysed. An exceptional experimental profile is maintained inside the furnace to attain the optimum metallization. The mill scales are reduced inside the furnace and the extent of reduction is evaluated from the weight loss. Post conducting reduction in the RI-RDI test apparatus, the reduced mill scale is characterized for the microstructural and morphological studies using SEM, EDS, XRD. The most optimum results of the reduction were attained in RI-RDI apparatus giving iron content of (metallization) 89.15 % at the reduction temperature of 1050°C for 240 mins holding time. During the entire study on RI-RDI apparatus, flow rate of CO is maintained at 4.5 LPM (litres per minute) and N₂ at 10.5 LPM. Finally, the degree of metallisation in the sample as well as the product material is calculated by using the chemical analysis process (dichromate and ferric chloride method). The characterization of produced iron powder was done by chemical analysis, XRD, and FE-SEM. The FE-SEM results confirm the presence of resultant pore characteristics. It is observed that mill scale can be significantly reduced to metallic iron by utilizing lean grade coal.

1. Introduction

The by-products of steel and ironmaking industries are rich in iron (~72 % Fe). These by-products are dusts and mill scale which are produced in vast quantities and can be recycled by practicing some metallurgical procedures (e.g. blast furnace or direct reduction reactors) in the presence of coal (reducing agent) to yield pre-reduced pellets for the purpose of re-melting in electric steel plant [1]. Mixture of various oxides particularly hematite (Fe₂O₃), magnetite (Fe₃O₄), wustite (FeO) and other elementary oxides forms a by-product called as “mill scale” which is considered as a waste product of steel and iron industries [2]. Iron is extracted from this mill scale by the means of reduction process involving certain kinetics of reaction depending upon process parameters like temperature, time, gas flow, etc.

In recent decades, ample work has been carried out in the production of iron from direct reduction process thus calling need for improvement in the existing direct reduction methods in order to overlook the limitations of blast furnace. The RDI (reduction degradation index) of sinter is an index of great importance aiding in assessing the quality of sinter occurring in low temperature zone [3]. The process of aggregation wherein combustion of fuels generates heat inside the moving bed incorporating loosely stuffed iron ore, and other feed particles, in order to agglomerate these raw materials into a compact porous mass is called as sintering [4]. For obtaining increased output with the existing raw materials it is very important to ensure that premises are not affecting the quality and yield of sinter for which RDI is reduced to the greater extent [5].

The production of iron by direct reduction of mill scale using lean grade coal via RI-RDI will efficaciously help in opening up a novel approach for producing iron from easily available industrial waste or “by-product”. Numerous researchers focus on enhancing the RDI whereas a very little work have been conducted on RI (reduction index) and related mechanism concerning the production of iron from mill scale. So, this work mainly emphasizes on attaining optimum results of the reduction under
selected parameters (temperature and reduction time) and finally evaluating the percentage of metallization attained. The robustness of sinter in the process of reduction (RDI) and reducibility of sinter (RI) are of great importance. As RDI and RI are the leading and responsible indices contributing in deciding the overall furnace performance, this area has significantly drawn remarkable attention of the researchers as well as metallurgist in upbringging more information and data in this domain [5–8].

Lean grade coal from Rajasthan contains very low levels of ash, sulphur, presenting itself as a potential reductant for the reduction of mill scale through Direct Reduction of Iron (DRI). On the other hand, mill scale is a by-product of iron and steel industries rich in iron content in the form of oxides. Experiments were carried out by mixing equal proportion of mill scale and coal and charging into the RI-RDI apparatus. Coal is procured from Matasukh Coal Mines, Nagaur, Rajasthan through RSMML, Rajasthan. The entire study is completed in three steps; materials used, reduction process and the testing.

2. Materials and Method

The lean grade coal of Rajasthan comprises lower levels of sulphur, ash, introducing itself as a promising reductant while carrying out the mill scale reduction through Direct Reduction of Iron (DRI). On the contrary procured mill scale is entitled as a by-product of rolling mill, iron and steel industries comprising of higher iron content in oxides form. The materials procured for current study are illustrated in Table 1.

Table 1. Materials procured for studying

| 1. Mill Scale | 2. Lean Grade Coal |
|---------------|--------------------|
| **Procured:** | **Procured:** |
| Sarda Industrial Enterprises Ltd., Jaipur, Rajasthan | Rajasthan State Mine and Minerals Ltd. (RSMML), Matasukh Coal Mines, Nagaur, Rajasthan India |

Fig. 1 As-recived mill scale

Fig. 2 As-recived lean grade coal

The chemical analysis of the mill scale procured from Sarda Industrial Enterprises Ltd., Jaipur, Rajasthan is illustrated in Table 2. This as-received mill scale is washed with demineralized water followed by compression air drying. Thereafter this mill scale was in bigger size and could not be used directly in the experiment, so these were crushed in roll crusher followed by meshing in rod mill [9]. Thereafter mill scale were initially hand sieved for visible foreign material separation. As this mill scale contains material fines of different size the homogeneity of the sample selection cannot be maintained if the as received material is put to the experiment. Therefore, sieving machine was used for 1 hour to collect different fraction of mill scale particles (i.e. 825, 600, 425 and 300 microns). Though oxygen and carbon percentage present in the mill scale is not indicated by this analysis but it does imply that Fe-oxides are about 71.99 % and rest is metallic iron which is entitled as the main constituent. The phases of hematite (Fe₂O₃), magnetite (Fe₃O₄), and wustite (FeO) are confirmed in
the XRD graph of unreduced mill scale (Fig. 3). Apart from this, presence of some other elements is also observed as these mill scales come from iron and steel plants.

**Table 2. Chemical analysis (by XRF) of procured mill scale**

| Fe-oxides & Metallic iron | Al₂O₃ | CaO | SiO₂ | S     | MnO | Ni | Cr | MnO | MgO |
|--------------------------|------|-----|------|-------|-----|----|----|-----|-----|
| 71.99 %                  | 0.94%| 1.26%| 4.82%| 3447.86 ppm | 0.59%| 0.05%| 0.04%| 0.59%| 1.31%|

Acquired coal was in bigger size so manual crushing was done to make them into suitable size. Whereas for the analysis of fixed carbon content, moisture, volatile-matter, ash in the procured low-grade coal, proximity analysis was carried out and results revealed that coal possessed fixed carbon content of 24.51 % (Table 3).

**Table 3. Proximity analysis results of coal**

| Material | Moisture % | Volatile % | Ash % | Fixed Carbon % |
|----------|------------|------------|-------|----------------|
| Coal     | 19.71      | 46.31      | 9.47  | 24.51          |

**Fig. 3 X-ray diffraction of unreduced mill scale**

### 3. Experimental Processes

#### 3.1 The Reduction in RI-RDI apparatus

The reduction of mill scale was carried out in RI-RDI test apparatus (Salvin Instruments Pvt Ltd. Bangalore), in the Advanced Research Lab for Tribology, MNIT Jaipur. Before feeding mill scale into the RI-RDI apparatus, mill scale was heated at 150°C for 2 hr in order to eliminate the residual moisture. Reduction of mill scale is carried out inside the retort which also acts as a fixed bed in which samples are placed along with the alumina (Al₂O₃) balls inside the furnace. The temperature is set for the split type furnace and burner is switched on. Thereafter N₂ (nitrogen) gas is released with a fixed amount of flow i.e. 10 LPM for the stabilization of temperature at 900°C. When the temperature of the furnace reaches its set value then the flow of the N₂ is raised to 15 LPM and it is maintained for 30 minutes.
After 30 minutes, the \( \text{N}_2 \) flow rate is adjusted to 10.5 LPM and the CO (carbon monoxide) flow rate is maintained at 4.5 LPM. This process is continued for set time i.e. 1 hr. After 1 hr of reduction, the heater is switched off, the CO gas flow is stopped and \( \text{N}_2 \) is passed at 5 LPM. In burner blue flame is generated during reduction. It shows that CO is converted into \( \text{CO}_2 \) (carbon dioxide) gas. After the experiment, the furnace is opened and the retort is transferred inside the chiller for cooling. As soon as it reaches the room temperature, the reduced samples are removed from the reduction tube followed by magnetic separation and final testing for the analysis of metallic iron.

### 3.1.1 Procedure for evaluating RDI index

Online weighing balance is utilized for recording the weight loss and record the reading by attaching it to retort the assembly. The stability is observed for the reading on the balance by holding it for 10 minutes. After pre-heating the mill scale samples, 500 gm of it is placed inside the vessel. The furnace temperature is set. \( \text{N}_2 \) gas is flowed (5 LPM) till the temperature reaches its defined value. As soon as temperature desired temperature is reached, the flow rate of \( \text{N}_2 \) is raised to 10.5 LPM and of CO gas at 4.5 LPM. Reading in the weighing balance is recorded for every 3 minutes. The supply of CO is stopped at the end and only \( \text{N}_2 \) is allowed to pass at 5 LPM. Furnace is opened and retort assembly is placed inside the cooling chamber. The initial weight (say \( W_i \)) is observed followed by transferring it into tumbler rotating drum (300 revolution at 10 rev./min). The sample is collected from the drum and sieving is carried out with 3.15 mm sieve. Again, the weight (say \( W_f \)) of the samples is measured and RDI is evaluated using following formula;

\[
\frac{W_1 - W_2}{W_1} \times 100
\]  

(1)

![Fig. 4 Gas flow diagram for RI-RDI apparatus](image)

### 3.1.2 Procedure for evaluating RI index

Evaluating RI index follows similar procedure till recording the reading in the weighing balance for every 3 minutes as in RDI index evaluation (in section 3.1.1). The process of recording the balance (weighing balance) reading is continued till 60 % of the RI value that can be evaluated using following formula;

\[
\% \text{RI} = \frac{m_1 - m_2}{m_0(0.42W_{\text{Fe}} - W_{\text{FeO}})} \times 10^4
\]

(2)
Where $W_{Fe}$ is % of Fe, $W_{FeO}$ is % of FeO, and $\Delta m^{1/2}$ is the weight at the time of reduction.

As soon as the above experiment is over all the gas valves are closed and only $N_2$ is allowed to flow at the rate of 5 LPM till the furnace temperature is reduced to 500°C. Blue flame is observed during the $N_2$ flow indicating the conversion of CO to CO$_2$ and the entire gas flow is illustrated in Fig. 4. The split type furnace is opened and the retort carrying mill scale is place inside the cooling chamber followed by collecting the mill scale samples.

### 3.1.3 Procedure for CO generation

The generation of CO gas involves a few sets of procedures that are elaborated in this section. The desired quantity of low-grade coal (2 kg) is preheated (at 100°C, 6 hr) in order to eradicate the existing moisture. The coal is filled up to 3/4th of the CO retort in furnace 1 (Fig. 5) followed by covering it with gasket and hardware to prevent any leakage of the gas. The CO generating furnace (Furnace 1, Fig. 5) is paired with a water tank which absorbs the heat generating from the furnace. Further CO storage tank accompanies two filters (a) KOH tank and (b) water tank. The connection of the retort with KOH filter and gas panel for CO$_2$ gas into the retort is checked for the leakages. Progressing towards the end of the experiment the outlet valve of the tank is opened, burner is switched off, and the temperature is set at 1050°C. As soon as the CO furnace temperature reaches 700°C, the CO$_2$ flow is fixed at 1 LPM, when reaches 1050°C the CO$_2$ flow rate is set at 2 LPM.

![Fig. 5 RI-RDI test apparatus in The Advanced Research Lab for Tribology, MNIT Jaipur](image)

### 4. Results and Discussions

#### 4.1 SEM micrographs of as-received mill scale and reduce iron powder

The morphological examination of unreduced (as-received) mill scale at lower magnification is presented in Fig. 6, at higher magnification is presented in Fig. 7, and that of final iron powder is presented in Fig. 8. The morphological results conducted for as-received mill scale demonstrates non-uniform size and irregular shaped structure Fig. 6 and Fig. 7; under higher resolution. Along with this, micro sized pinholes and small pores are detected on the mill scale surface (Fig. 7); formed due to release of entrapped gases within the iron oxide layer during reheating. The Fig. 8 depicts the SEM micrograph of sponge iron (iron powder after mill scale reduction) at the most optimal temperature producing higher % of metallization i.e. 1050°C. The bright phases in Fig. 8 implies metallic constituents primarily Fe, whereas the darker phases imply unreduced non-metallic constituents; obtained observation confirms
with the past published literature [9–11]. The EDS analysis plot of the produced iron powder is depicted in Fig. 9 that demonstrates the iron yield at 1050°C for 240 minutes. The procured metallic iron powder was further observed via chemical analysis; the results revealed the percentage of metallic iron to be approximately ~62.11% which was in agreement with the results obtained from EDS analysis (63.13%).

**Fig. 6** SEM micrograph of unreduced mill scale

**Fig. 7** SEM micrograph of unreduced mill scale at higher magnification

**Fig. 8** SEM micrograph of iron powder reduced at 1050°C

**Fig. 9** EDS analysis of the reduced iron at 1050°C for 240 minutes

### 4.2 XRD analysis of reduced mill scale with respect to reduction temperature and time

#### 4.2.1 XRD analysis for temperature

The resultant structural analysis of reduced mill scale samples was carried out using XRD employing Cu-Kα (λ = 0.15406 nm) radiation. The behavior of the mill scale after reduction with respect to different temperatures has been illustrated in Fig. 10. At room temperature mill scale consists of iron and its oxides. It is perceived from Fig. 10 that the intensity of the highest peak is maximum at 1050°C due to presence of metallic iron (Fe). The highest fraction of metallic iron is attained at 1050°C (~66.43%), as compared to 1000°C (~65.01%) or 950°C (~57.11%), or 900°C (~46.77%) and this yield tends to decrease beyond 1050°C. The sequence of possible reduction (mill scale → iron powder) occurring at 1050°C could be Fe₂O₃ → Fe₃O₄ → FeO → Fe.
Fig. 10 XRD at different temperatures (A) reduced iron at 900°C, (B) reduced iron at 950°C, (C) reduced iron at 1000°C and (D) reduced iron at 1050°C

4.2.2 Analysis of metallic iron by chemical analysis after reduction

The reduced samples from the furnace are magnetically separated and extracted iron powder is chemically analyzed using dichromate and ferric chloride method [12,13]. To prepare potassium dichromate solution, 4.903 g of K₂Cr₂O₇ is mixed with 500 ml of distilled water and stirred (Fig. 11) till it completely dissolute in water. After this the normality of the solution is evaluated by calculating N/10 factor. Concentrated H₂SO₄ (5 to 7 ml) is added to 100 ml distilled water in a beaker. FeS is mixed in this solution until completely dissolved followed by mixing 10 ml of mixed acid along with 5 to 6 drops of BDS indicator into this solution. The previously prepared K₂Cr₂O₇ solution is filled in the burette and titration is carried out dropwise and continued till the colour of solution in the beaker turns into violet. As soon as the colour turns to violet the reading of the burette is noted.

![Magnetic stirring](image)

Fig. 11 Magnetic stirring

The following formula is used for calculation of N/10 factor-

\[
\text{Normality} = \frac{\text{Given weight}}{\text{Equivalent weight} \times \text{Burette reading}}
\]
4.3 Influence of process parameters on the reduction

In RI-RDI apparatus, mill scale is reduced by the CO gas only. Here mill scale is heated in the furnace and CO gas is produced in the other furnace. This CO is allowed to react with the heated sample for sufficient period of time, and reduction condition is observed.

4.3.1 Effect of mill scale size

Fig. 12 illustrates the % of metallic iron procured in response to the mill scale size (300 to 825 µm) at the reduction temperature of 900°C. Results revealed that lower the particle size (in between 425 to 300 µm) resulted in higher degree of metallization. Significant results were attained at the reduction temperature of 900°C and with the reduction in particle size (> 300 µm) the extent of metallization exhibits an increasing trend; it can be perceived from Table 4 that metallic yield increased from 26.89% for the particles size of 825 µm to 64.62% for the particles size of 300 µm. The reason behind this increasing trend of metallization is the increasing reaction rate which takes place owing to increased diffusion of reductant resulting in increased reaction area on the smaller particle size [14–17]. Attributable to the fact that bigger iron ore size will inhibit the diffusion of gases, and will lessen the tenancy of gas-solid contact region, that decelerates the rate of reduction. This provides an evidence that the size of the particles is one of the significant decisive factors in controlling the mill scale reduction to metallic iron.

Table 4. Results of chemical analysis of reduced mill scale with respect to various process parameters

| Process parameter | Mill scale size (µm) | CO (LPM) | N₂ (LPM) | Time (min) | Temperature (°C) | Metallic Iron (wt.%) | Metallization (%) |
|-------------------|---------------------|----------|----------|------------|------------------|---------------------|------------------|
| Effect of Mill Scale Size | 825 | 4.5 | 10.5 | 180 | 900 | 26.89 | 38.42 |
| | 600 | 4.5 | 10.5 | 180 | 900 | 28.78 | 42.32 |
| | 425 | 4.5 | 10.5 | 180 | 900 | 32.89 | 45.39 |
| | 300 | 4.5 | 10.5 | 180 | 900 | 64.62 | 50.48 |
| Effect of Temp. (°C) | 300 | 4.5 | 10.5 | 180 | 900 | 46.77 | 64.31 |
| | 300 | 4.5 | 10.5 | 180 | 950 | 57.11 | 66.08 |
| | 300 | 4.5 | 10.5 | 180 | 1000 | 65.01 | 69.12 |
| | 300 | 4.5 | 10.5 | 180 | 1050 | 66.43 | 72.48 |
| Effect of Time (min) | 300 | 4.5 | 10.5 | 90 | 1050 | 15.51 | 38.70 |
| | 300 | 4.5 | 10.5 | 120 | 1050 | 23.01 | 56.08 |
| | 300 | 4.5 | 10.5 | 180 | 1050 | 61.04 | 64.36 |
| | 300 | 4.5 | 10.5 | 240 | 1050 | 70.29 | 89.15 |
4.3.2 Effect of reduction temperature

The obtained results revealed that with the increase in temperature in the furnace, the metallization degree increases as a greater number of oxides are removed. This trend was observed till rise of temperature from 900°C to 1050°C and metallic iron percentage increased from 46.77 to 66.43% respectively (Table 4). Beyond temperature of 1050°C the weight fraction of metallic iron tends to decrease (Fig. 13); as a consequence of chemical reactions occurring at the time of reduction process stating significance of temperature during reduction process. It can be clearly perceived that the increase in the rate of Boudouard reaction is the chief reason for this increased metallic yield and maximum was observed at 1050°C (66.43%) [18,19]. The other parameters affecting the impact of temperature upon the degree of metallization is influenced by the quality of coal taken for conducting the reduction process, depending on the reactivity of coal. It can be concluded that by increasing the temperature, the consecutive reduction rate could be enhanced considerably thereby resulting in higher degree of metallization. Approximately 72.48% (Table 4) of metallization was achieved at the temperature of 1050°C.

Fig. 12 Variation of iron content (wt.%) vs mill scale size (µm)

4.3.3 Effect of reduction time

Fig. 13 Variation of iron content (wt.%) vs temperature (°C)

4.3.3 Effect of reduction time
The degree of metallization presents direct relationship with the reduction time (Fig. 14). In addition to this, the increment in temperature significantly reduces the dependency of reduction process (mill scale to iron powder) with respect to the time. The increment in residence time escalates the atomic movement during the chemical reaction; resulting in enhanced reaction kinetics \[14\]. The increment in efficiency and the metallic yield are attributable to the Boudouard reaction \[19,20\]. The success of reduction process entirely depends upon the Boudouard reaction that releases heat efficient enough to execute the reduction process efficaciously. It can be clearly perceived from Table 4; the metallic iron percentage increased from 15.51 to 70.29% upon increasing reduction time from 90 to 240 minutes. Approximately 89.15% of metallization was achieved at 240 minutes time.

![Fig. 14 Variation of iron content (wt.%) vs reduction time (min)](image)

5. Conclusion

Current experimental study emphasizes on attaining the optimum results of the mill scale reduction under selected parameters (temperature and reduction time) and finally evaluating the percentage of metallization attained after reduction. Successful optimization of process parameters for reducing mill scale with improved metallization was carried out by making use of lean-grade coal from Rajasthan. The process parameters considered for current study were size of mill scale, reduction time, and temperature respectively. The outcomes of the study demonstrated that with the increment in time and temperature, and reduced mill scale size, the percentage (%) of metallization improved exponentially. The results indicated the highest % of metallization achieved was 89.15 % at 1050°C temperature, holding time of 240 minutes, selecting mill scale size less than 300 µm with a fixed flow of CO (4.5 LPM) and N\(_2\) (10.5 LPM) gas for attaining optimal results during the reduction process. In present study there is no mill scale to coal ratio used as they both are fed into two different vessels (Furnace 1 and Furnace 2) so interaction of these two does not affect the reduction process. Other factor affecting the reduction kinetics reaction is the atmosphere. N\(_2\) is utilized throughout the process for reaction to occur. As there are lots of gases present in the burning chamber that may hinder the reduction process, in that case N\(_2\) helps in eliminating those unwanted gases and a constant temperature is maintained throughout the experiments.

Acknowledgements

The authors would like to give sincere thanks to the Ministry of Steel, Government of India (F. No 11(11)/GBS/2013-TW DATED 28.09.2015) for all the financial support. The authors also wish to acknowledge The Advanced Research Lab for Tribology, Department of Mechanical Engineering, Department of Metallurgical and Materials Engineering, MNIT, Jaipur for providing the rotary kiln
reduction facility, and other testing facilities and the Material Research Centre, MNIT Jaipur, for providing the characterization facility.

References

[1] S. Mechachti, O. Benchiheub, S. Serrai, M.E.H. Shalabi, Preparation of iron Powders by Reduction of Rolling Mill Scale, Int. J. Sci. Eng. Res. 4 (2013).
[2] O. Benchiheub, S. Mechachti, S. Serrai, M.G. Khalifa, Elaboration of iron powder from mill scale, J. Mater. Environ. Sci. 1 (2010) 267–276.
[3] Z. Xu, Z. Jian-liang, H. Zheng-wen, H. Zuo, Effect of CaCl2 on RDI and RI of Sinter, J. Iron Steel Res. Int. 17 (2010) 7–12.
[4] S. Srivastava, Use of halide solution to improve the RDI and RI of sinter: A Case Study, Arch. Ind. Biotechnol. 2 (2018).
[5] N. Taguchi, T. Otomo, Y. Omori, Immersion Treatment of Sinter into Calcium Halide Solution, ISIJ Int. 30 (1990) 281–289.
[6] A.J.B. Muwanguzi, A. V Karasev, J.K. Byaruhanga, G. J, Characterisation of the Physical and Metallurgical Properties of Natural Iron Ore for Iron Production, Int. Sch. Res. Netw. (2012). https://doi.org/10.5402/2012/147420.
[7] T. Paananen, The Effect of Minor Oxide Components on Reduction of Iron Ore Agglomerates, 2013.
[8] A.I. Journal, M. Kumar, S. Jena, S.K. Patel, Characterization Of Properties And Reduction Behavior Of Iron Ores For Application In Sponge Ironmaking, Miner. Process. Extr. Metall. Rev. 29 (2007) 118–129. https://doi.org/10.1080/08827500701421896.
[9] R. Sen, U. Pandel, Closed crucible reduction of lump powdered mill scale or iron ore by coal: The sequential methodology and mechanism for optimization of process parameters, Adv. Powder Technol. (2020). https://doi.org/10.1016/j.powtec.2020.07.017.
[10] P. Ghods, O.B. Isgor, G.A. Mcrae, J. Li, G.P. Gu, Microscopic investigation of mill scale and its proposed effect on the variability of chloride-induced depassivation of carbon steel rebar, Corros. Sci. 53 (2011) 946–954. https://doi.org/10.1016/j.corsci.2010.11.025.
[11] Y. Man, J.X. Feng, F.J. Li, Q. Ge, Y.M. Chen, J.Z. Zhou, Influence of temperature and time on reduction behavior in iron ore–coal composite pellets, Powder Technol. 256 (2014) 361–366. https://doi.org/10.1016/j.powtec.2014.02.039.
[12] H.T. Materials, O. Yucel, A. Turan, M. Alkan, Determination of Direct Reduction Conditions of Mill Scale, High Temp. Mater. Process. 32 (2013) 405–412. https://doi.org/10.1515/htmp-2012-0167.
[13] N. Gade, G. Verma, R. Sen, Effect of Calcium Carbonate on the Reduction Behaviour of Mill Scale, Procedia Earth Planet. Sci. 11 (2015) 319–324. https://doi.org/10.1016/j.proeps.2015.06.067.
[14] A. Kumar, V.R. Kiragi, S. Kumar, A. Patnaik, Synthesis and Characterization of Metallic Iron Reduced from Low-grade Coal in Rajasthan, Mining, Metall. Explor. 37 (2020) 1741–1751.
[15] N.M. Gaballah, A.F. Zikry, M.G. Khalifa, A.B. Farag, M.E.H. Shalabi, Production of Iron from Mill Scale Industrial Waste via Hydrogen, Open J. Inorg. Non-Metallic Mater. 3 (2013) 23–28.
[16] M.I. Martin, F.A. López, J.M. Torralba, Production of sponge iron powder by reduction of rolling mill scale Production of sponge iron powder by reduction of rolling mill scale, Ironmak. Steelmak. 39 (2012) 155–162. https://doi.org/10.1179/1743281211Y.0000000078.
[17] N. Gidikova, V. Manolov, V. Petkov, Mill Scale Reduction, J. Mater. Sci. Technol. 25 (2017) 12–19.
[18] M.C. Bagatini, V. Zymla, E. Osório, A. Cezar, F. Vilela, Characterization and Reduction Behavior of Mill Scale, ISIJ Int. 51 (2011) 1072–1079.
[19] A. Ahmed, M. Eissa, S. Shahein, A. Ahmed, M. Eissa, S. Shahein, Direct chromium alloying by smelting reduction of mill scale and low grade chromite ore, Process. Prod. Appl. 42 (2015) 648–655. https://doi.org/10.1179/1743281215Y.0000000008.
[20] H.İ. Ünal, E. Turgut, Ş.H. Atapek, A. Alkan, Direct Reduction of Ferrous Oxides to form an Iron-Rich Alternative Charge Material, High Temp. Mater. Process. 34 (2015) 751–756. https://doi.org/10.1515(htmp-2014-0125).