

Chapter 1 Introduction

1.1 Introduction

The steel industry is the heart of the global economy. Despite the influence of the pandemic (in 2020 and 2021), through its different regional impacts, the global steel industry was fortunate to end 2021 with a reasonable rise in steel demand but steel consumption has not improved worldwide in 2022.[1–3] World steel production in 2022 was 1885.4 million tonnes (Mt), decreased 76.9 Mt (3.92 pct) with respect to 2021 (1962.3 Mt). By producing 125.3 Mt steel in 2022, India again occupied 2nd position in the world's steel production (as shown in Table 1.1), preceded by China. In 2022, India increased steel production by 7.1 Mt (6.01 pct) with respect to 118.2 Mt in 2021 and apparent steel consumption per capita was also increased from 75.5 kg (2021) to 81.1 kg (2022), which is about 36 pct of the average world steel consumption per capita (221.8 kg).[2,3]

Steel is one of the most important products of the modern world and is of strategic importance to any industrial nation. As a raw material and an intermediate product, the production and consumption of steel are widely regarded as indicators of economic progress and industrial development. Steel has contributed immensely to India's economic growth. This is evident from the similar growth patterns of India's steel production and Gross Domestic Product (GDP) which also highlights the economy's dependence on steel. The Indian steel industry has advantages that the nation possesses in terms of growing demand, availability of key raw materials i.e. iron ore, and skilled manpower among others. The Indian steel industry contributes slightly more than 2 pct to the GDP of the country. This percentage accounts for direct contribution to the economy. In 2005, India became one of the top 10 steel producers in the world; while in 2018, India became the world's second-largest producer of crude steel.[4]

Table 1.1: Six major steel producing countries in world (Mt)[1]

Ranking in world	2016	2017	2018	2019	2020	2021	2022
1 st	China (808.4)	China (831.7)	China (920.0)	China (995.4)	China (1064.8)	China (1032.8)	China (1018)
2 nd	Japan (104.8)	Japan (104.7)	India (109.3)	India (111.4)	India (100.3)	India (118.1)	India (125.3)
3 rd	India (95.5)	India (101.4)	Japan (104.3)	Japan (99.3)	Japan (83.2)	Japan (96.3)	Japan (89.3)
4 th	USA (78.5)	USA (81.6)	USA (86.6)	USA (87.8)	USA (72.7)	USA (86.0)	USA (80.5)
5 th	Russia (70.5)	Russia (71.3)	South Korea (72.5)	Russia (71.7)	Russia (71.6)	Russia (76.0)	Russia (71.5)
6 th	South Korea (68.6)	South Korea (71.0)	Russia (72.1)	South Korea (71.4)	South Korea (67.1)	South Korea (70.6)	South Korea (65.8)
World Total	1,629.6	1,689.4	1,813.6	1,874.4	1,880.40	1,950.50	1,885.40

The Government of India released National Steel Policy (NSP) 2017 which framed the roadmap for the Indian steel industry by 2030-31, to set up a technologically advanced and globally competitive Indian steel industry that stimulates economic growth. As per NSP - 2017, an estimated domestic crude steel production of 300 Mt will be achieved by 2030–31 while per capita finished steel consumption target will be 158 kg.[5] For producing 300 Mt crude steel, India will be required about 513 Mt of processed iron ore and 639 Mt run of mine ore. Although India is fortunate regarding good reserves of high-grade iron ores. But with time, these reserves of high-grade iron ores are bound to be diluted. The fast depletion of high-grade iron ores and their increasing demand in the steel industry put pressure on assessing the exploitation of lean ores (i.e. low-grade ore, ore fines, etc.). Towards the future availability of iron ore for the domestic iron and steel industries and global business; attention to the potential use of low-grade iron ores, especially fines is gaining momentum.[6]

The total reserve of iron ore is about 33.27 billion tonnes (Bt), out of which about 22.48 Bt of hematite and 10.79 Bt of magnetite ore according to an estimate by Indian Bureau of Mines (IBM), Nagpur as on 1st April, 2015. About 8.06 Bt (35.85 pct) of the total reserves of low-grade hematite iron ore is available to meet the demand of Indian iron and steel industries (as shown in Table 1.1 and Table 1.2). From 2010 to 2015, there was a noticeable 25.7 pct (4.60 Bt) increase of iron ore resource while 59.1 pct of ore (2.72 Bt) was identified as low-grade iron ore.[7]:[8]

Table 1.2: Reserves/Resources of iron ore (hematite) as on 01.04.2010 and 01.04.2015[7]:[8]

Sr. No.	Grades	Total resources of iron ore (hematite) - 17.88 Bt (as on 01.04.2010)			Total resources of iron ore (hematite) - 22.48 Bt (as on 01.04.2015)		
		Amount of resources (Bt)	Low-grade resources (Bt)	pct Low-grade resources (w.r.t. total resource)	Amount of resources (Bt)	Low-grade resources (Bt)	pct Low-grade resources (w.r.t. total resource)
1	Lumps	9.93	1.62	9.06	12.46	2.28	10.14
2	Fines	3.82	1.19	6.66	3.66	1.42	6.32
3	Lumps & Fines	2.33	0.73	4.08	3.92	1.92	8.54
4	Unclassified	1.8	1.8	10.07	2.44	2.44	10.85
	Total	17.88	5.34	29.87	22.48	8.06	35.85

A wide variety of iron ore deposits have been found worldwide. The total 350 billion tonnes (Bt) of iron ore has an iron (Fe) content on average of 47 pct. A minor fraction of these deposits are commercially mined as iron ore with Fe content ranging from 30 to 65 pct. World consumption of iron ore grows on an average of 10 pct per annum with the main consumers China, Japan, India, Korea, USA and the European Union.[9]

There has been a tremendous increase in demand for iron and steel with the rise in industrial applications in the global scenario for industrial development. The fast depletion of high-grade iron ores and the increased demands of the industry put a strong focus on assessing the exploitation of low-grade to lean iron ores. Low-grade iron ore is

being beneficiated to enhance its iron content up to the desired level of industrial specification required for different industrial uses.[6]

As per current data on steel production and NSP – 2017, iron ore mine life is estimated (as shown in About 19.92 Bt (88.57 pct) of the Indian iron ore reserve needs processing before being used in the iron and steel plants. Out of 19.92 Bt, 8.06 Bt (40.46 pct) is categorized as a low-grade iron ore.[8] If low-grade iron ore is not utilized then this will adversely affect the Indian steel production. Due to this, iron and steel industries have to majorly depend on imported high-to-medium grade iron ore and a highly fluctuating commodity – steel scrap.[5], [10] These conditions have a serious impact on the economy of the nation and the steel industries. Therefore, the utilization of low-grade iron ore resources is advantageous to lessening the dependence on imported iron ore resources, which also has importance for the utilization of low-grade iron ore globally. An economical upgradation of low-grade iron ore is a globally undesirable technical difficulty due to the low iron content, complex mineral composition and fine dissemination of minerals.

Table 1.3). Based on these data and the limited reserve of iron ore, an iron ore mine life is going to increase by the *use of low-grade iron ore only*. [5], [8] Detail calculations of estimated iron ore mine life are shown in Appendix 1.

About 19.92 Bt (88.57 pct) of the Indian iron ore reserve needs processing before being used in the iron and steel plants. Out of 19.92 Bt, 8.06 Bt (40.46 pct) is categorized as a low-grade iron ore.[8] If low-grade iron ore is not utilized then this will adversely affect the Indian steel production. Due to this, iron and steel industries have to majorly depend on imported high-to-medium grade iron ore and a highly fluctuating commodity – steel scrap.[5], [10] These conditions have a serious impact on the economy of the nation and the steel industries. Therefore, the utilization of low-grade iron ore resources is advantageous to lessening the dependence on imported iron ore resources, which also has importance for the utilization of low-grade iron ore globally. An economical upgradation of low-grade iron ore is a globally undesirable technical difficulty due to the low iron content, complex mineral composition and fine dissemination of minerals.

Table 1.3: Estimated iron ore mine life

Year	Crude steel production (Mt)	Iron ore required (Mt)	Mine life (yrs.) (= <i>reserve of iron ore / iron ore required</i>)	
			on the basis of high-to-medium iron ore reserve	on the basis of total reserve of iron ore
2022	125	266	54.2	84.5
2030	300	639	22.6	35.2
<i>Estimated ratio = Iron ore required / Crude steel = 2.13</i>	<ul style="list-style-type: none"> • <i>Reserve of high-to-medium iron ore = Total ore – low grade ore = 22.48 - 8.06 = 14.42 Bt</i> • <i>Total reserve of iron ore = 22.48 Bt (high + medium + low grade)</i> 			

Iron ore deposits are a finite, non-renewable, unique, and irreplaceable natural resource, and with the fast depletion of high-grade ores; the conservation of iron ore becomes a prime focus area to increase mine's life. Due to the increase in demand for high-grade iron ore for its limited reserve, beneficiation of low-to-medium grade iron ore is much needed task for iron and steel makers.[11] This must be necessitated to meet a supply of ore to its demands. To find out effective beneficiation, detailed mineralogical studies of ore are required to find out the relationship between mineralogical particularities of ores with a beneficiation technique as well as upgraded ore (i.e. final product of beneficiation).[10] Mineralogical characterization is having a crucial role in the design of process flow sheets for the beneficiation of low-grade iron ore.[11]

Mineralogical studies employ several characterization techniques for fundamental investigation in mineral separation (or processing). The significance of the studies is obtained from the quote by Prof. Arun Kumar Biswas: *The basic dictum of scientific research is reproducibility or falsifiability, and how can a claim regarding experimental results on an incompletely characterised system be verified or refuted... Yet in the area of processing of low grade ores, the standard of characterisation is indeed mediocre to put it mildly.*[12] The characterisation of solid is most important since the process selection is closely linked to nature of the minerals / ores resulting from the geological formation. The mineralogical characterisation may involve the identification of minerals, an association of minerals, quantification of phases, elemental associations, and occurrence

of minor / trace minerals / elements. The need for characterization techniques arises due to one or more of the following reasons:[13]

- Nature of sample employed for characterisation,
- Fingerprint matching character of the techniques,
- Specific character of techniques,
- Spatial resolution of the techniques and
- Process and materials specific needs.

Thorough knowledge of the ore and gangue minerals present in iron ore is significant to understanding its beneficiation and downstream processing characteristics. Research is being conducted on an ongoing basis on mineral identification and phase analysis using a range of optical microscopy, electron microscopy, electron microprobe, x-ray diffraction (XRD), and image analysis techniques to classify iron ores into broad ore types (with distinct ore and gangue mineralogy, ore texture and porosity) for predicting downstream processing performance.[14]

Mineral engineering/processing/dressing involves physical as well as chemical beneficiation or purification of low-grade mineral deposits. Gaudin[15] defined *mineral dressing* as the processing by means that do not destroy the physical and chemical identity of the minerals. This operation normally follows comminution and precedes agglomeration. Further processing of the upgraded ores necessitates for production of commodities for industrial use.[16]

In mineral processing, mined ores in large pieces are crushed and ground to sizes where ore minerals are liberated from gangue minerals so that they may be separated by making use of the mineralogical properties listed below:[17]

Size	Optical
Shape	Thermal
Surface	Magnetic
Hardness or brittleness	Electrical
Specific gravity	Radioactive

The choice of separation methods depends strongly on *particle size*. Ores available in the past could be liberated at relatively coarse sizes, allowing separation methods based on gravity. However, ore utilized in recent years is more finely disseminated requiring a finer mesh-of-grind for liberation.[17] Research on powder morphology and surface chemistry has been emphasized in mineral processing for the basic understating of ore mineral liberation. So, detailed mineralogical studies are helpful for low-grade ore or complex structured ore.

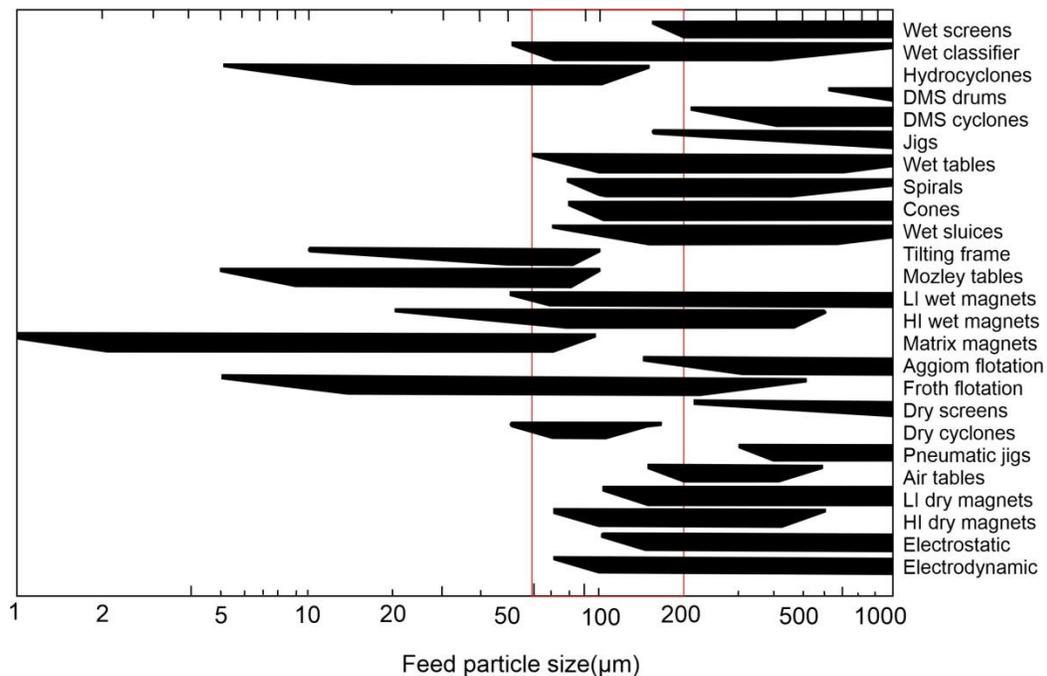


Figure 1.1: Effective separation range of mineral processing techniques[18]

The object of mineral processing is always the same regardless of the methods used, i.e. to separate the minerals into two or more products with the values in the concentrates, the gangue in the tailings, and the *locked* particles in the middling. Such separations are never perfect, so that much of the middling produced are misplaced particles, i.e. those particles which ideally should have reported to the concentrate or the tailing. This is often particularly serious when treating ultra-fine particles, where the efficiency of separation is usually low. In such cases, fine liberated valuable mineral particles often report in the middling and tailing. Figure 1.1 shows the general size range applicability of unit concentration processes. Most processes can be applied effectively on feed ore with the

particle size in the range of 75 to 200 μm . It should be pointed out that the unit operation / process is also limited by the mineralogical nature of the ore.[18]

Crushing and grinding generate very high contributions to the total processing costs. Hence the cost applied to the final product will be extremely important as a low-grade ore would yield a small ultimate product tonnage both due to the low content of the desired mineral(s) and the typical reduced recovery that is related to the low-grade compared to richer ores. Pre-concentration, i.e. removal of coarse size low-grade waste may become very important. Electronic machine sorting, heavy media separation, jigging, and coarse magnetic separation methods offer possibilities to minimize the volume of ore that must be finely grounded to adequately liberate the desired minerals. India is endowed with large reserves of high-grade hematite ore. However, steady consumption of these iron ores is now a concern forcing to develop beneficiation strategies to utilize low-grade iron ores. In India, iron ores are generally washed to remove the high alumina containing clayey matter. Conventionally, after washing, the lumps are directly fed to the blast furnace, and the fines are used after agglomerating them into sinter/pellet. The most commonly used beneficiation methods for iron ores are the gravity and magnetic separation methods. Recovery of valuables from natural ores by gravity concentration process is one of the oldest and most economical techniques.[19]

The quantities of fines and slimes are accumulated over the years. These are available in already ground form and assaying reasonably high iron content. If these are properly beneficiated, then these can be considered a national resource rather than a waste of nuisance value. The alumina content of these, if brought to <2 pct to maintain the $\text{Al}_2\text{O}_3/\text{SiO}_2$ ratio is one for agglomeration; and reduces coke rate in BF ironmaking. Al_2O_3 in the beneficiated product will: (a) lead to better utilization of national resources and (b) reduce environmental hazards associated with storage and disposal of slimes. Keeping the above facts in view, attempts must be made to process these to recover the iron values which will be a step forward for the conservation of natural resources and will provide an opportunity for sustainable growth for iron ore industries.[20]

The dominance of Blast Furnace Technology in ironmaking, however, has been subject to scrutiny owing to some inherent limitations in the process such as dependence on coking

coal, strict quality norms regarding raw materials, sinter plant, and coke oven plant, limited process flexibility and high investment cost for furnace and auxiliary equipment, sophisticated process control systems and facilities to arrest pollution and consequently huge investment. Continuous supply of good quality metallurgical coke at a competitive price is becoming difficult nowadays.[21], [22]

One of the critical feed materials for the blast furnace is a lump iron ore. As compared to fines, a lump of iron ore does not require any sort of processing / treatment before feeding to the Indian's blast furnace. That's why, it has better price in competitive market. Over time, the quality of lump ore decreases due to limited reserve. While ore fines must be agglomerated before charging into blast furnace or any other ironmaking reactors. For an efficient blast furnace process, there must be a balanced feed charge of *lump ore and fines*. Operation of blast furnace has become more difficult over the two decades due to a shortage of good quality lump ore and coke, as well as several characteristics of agglomerated feed material.[23]

The Conventional route of iron and steel making needs several energy intensive unit operations with stringent physical, chemical, and mineralogical specifications for feed materials. The complexity of the route is not viable for the exploitation of low-grade iron ore. Modification of existing routes or development of a tailor-made route is essential for the low-grade iron ore on the basis of its nature – *characteristics, mineral complexity, and behaviour*.[24]

Mining and processing of Indian iron ore generate huge amounts of fines. Besides, there are huge deposits of naturally occurring iron ore fines (blue dust) with 60–65 pct total iron content. These fines need to be agglomerated for use as burden material.[25] The option is to convert the iron ore and carbonaceous fines into cold bonded composite pellets / briquettes. By producing cold bonded iron ore-coal / coke composite pellets / briquettes, a viable utilization of these fines takes place and also controls the pollution.[21] The *composite pellet* means a pellet containing a mixture of fines of iron bearing oxide and carbonaceous material (coke / coal / charcoal) prepared by cold-bonding technique. The pellet should have sufficient strength to withstand high temperature and stresses when charged in a furnace.[25] Taking into consideration the

optimum use of the raw materials use in steelmaking; valuable raw materials can be conserved and last longer. This can be feasible only by utilizing low-grade ore lumps / fines, recycling of wastes as well as conversion of these into value-added products (i.e. iron ore-coal/coke composite pellets / briquettes).

Cold bonded iron ore-coal pellets / briquettes with adequate mechanical strength and other characteristics are emerging as a potential burden material for the extraction of iron in different furnaces.[26] Recent studies have demonstrated that cold-bonded composite pellets / briquettes can be successfully used as a burden material in several ironmaking and steelmaking reactors. Reduction is much faster in the case of composite pellets / briquettes than the indurated iron ore pellets or lumps. This lowers residence time in a rotary kiln by a factor of 6 to 8, thus improving productivity. Reduction of oxide has been achieved satisfactorily in a reactor as well.[27], [28], [29], [30], [31], [32], [33]

Iron is produced worldwide through two major routes:

- (a) Conventional route i.e. blast furnace (BF) and
- (b) Alternative route i.e. direct reduction (DR) and smelting reduction (SR).

The BF is the dominant means for making iron, after which comes DR. Currently, smelting reduction shares a relatively small portion of global iron production; however, increasing attention is being paid to this process as a challenger to the BF process. The BF technology is well established and dominates the commercial ironmaking industry. However, few DR and SR processes have already been adopted in ironmaking plants.[34]

The alternative ironmaking processes are required to fulfil the criteria such as the make use of non-coking coals, basic feed material preparation, hot metal with the least impurities, autonomous process steps, closed energy system, efficient pollution control system, and minimal waste generation. Such processes should have a higher productivity than BF and the capital cost seems to be appreciably lower than BF.[35]

In SR processes, iron ore and coal are added directly to a metal-slag phase where the ore is reduced. The SR process combines the gasification of coal with the smelting reduction of iron ore. Energy consumption of smelting reduction is lower than that of blast furnace,

as a coking step is avoided and the need for ore preparation is reduced.[22] A few of examples of these processes are Finex and Hismelt. Although SR process reduces greenhouse gas (GHG) emissions, the process demands higher energy for the ironmaking step (18.7 GJ/t of crude steel) that exceeds the total energy required for the entire steelmaking process through the BF-BOF route (15.8 GJ/t).[34]

SR or direct smelting has been the *Holy Grail* of the iron and steel making for a long time. The purpose of SR process is to produce liquid hot metal similar to the blast furnace hot metal but without any dependency on coke. It requires a minute preparation of iron oxide feed and uses coal, oxygen, and/or electric energy. The basic principle of SR process is to melt the iron ore/sinter/pellets with the non-coking coal and oxygen or hot blast in a reactor. In recent years, about twenty SR processes have been under development throughout the world. All SR processes aim: (i) to produce hot metal, without using either coke or high grade iron ore as the feedstock; (ii) to consume the least amount of coal and oxygen to make a *fuel efficient* process.[36]

SR processes of liquid ironmaking are drawing considerable attention. SR processes are currently being developed as an alternative route to BF ironmaking with the following objectives:[22]

- To utilize low-grade solid fuels and ore fines,
- To produce hot metal at a lower cost and by low capital investment,
- To reduce pollutant emissions,
- To achieve flexibility regarding input of raw materials and selection of operating parameters and
- To install small hot metal production units to meet fluctuating market demand and increase production in small steps of capital investment.

The Corex process is the most successful SR development. It differs from the conventional blast furnace route in that non-coking coal can be directly used for iron ore reduction and smelting process, eliminating the need for coke oven plants. The use of lump ore or pellets also eliminates the need for sintering units. The process combines pre-reduction of ore in a shaft furnace, to a level of about 80% with final reduction and

melting in a melter/gasifier.[22] The process is not completely independent of coking coal. The exact coke requirement is unclear. Another drawback of the Corex process is that it depends on efficient usage of the large amount of export gas for its economical viability.[37]

The relative share of the three major routes of steel production in India are:[10]

- about 45 pct by Blast Furnace / Corex – Basic Oxygen Furnace route,
- about 30 pct by Induction Furnace (IF) route and
- about 25 pct by Electric Arc Furnace(EAF) route.

The average overall scrap usage at present is about 22 pct. This level of scrap usage in India is quite low, considering that about 55 pct steel is produced by IF and EAF. Scrap usage in India is low because of the non-availability of quality scrap. Many steel producers using electric arc furnace (EAF), prefer hot metal over scrap due to high power tariffs. Import of good quality scrap is expensive and can meet only a small share of national requirements. Scrap arising within steel plant (known as home scrap) is not adequate to meet the full requirement. Therefore, it is requirement to increase part of iron bearing charge materials in steelmaking.[10]

Almost 2 billion tons of steel are produced each year, and half of that is produced from iron ore (*virgin material*). Steel production is responsible for about 7 to 9 pct of total global carbon emissions.[38] So, it is a prime need to develop sustainable steel technologies. Research works are going on alternative or path-breaking iron making technologies for: (i) minimizing greenhouse gas (GHG) emissions, (ii) lowering dependency on quality raw materials (iii) making more efficient current technologies than a recent time. Green technologies in iron and steel making are majorly working for decarbonisation.[39]

Kobe Steel developed a new technique for creating steel by hydrogen gas. By adding hot briquetted iron (HBI) as a fuel source, it has maintained the efficiency of the CO₂ reduction process and uses less coke as fuel. This process reduces CO₂ emissions associated with production by about 20 pct.[40], [41] In Europe, a project in collaboration with mining company LKAB and energy producer Vattenfall - HYBRIT on H₂ Green

steel — aim to replace fossil fuels with green hydrogen. In 2021, Swedish company - SSAB delivered the world's first batch of fossil-free steel to carmaker Volvo. This so-called green steel was delivered as part of HYBRIT. [40], [42] In the United States, Boston Metal, a company that emerged from the Massachusetts Institute of Technology (MIT), is developing direct electrolysis from iron ore, a process similar to that currently used for aluminium. In both cases, the electricity used would be from renewable sources, ensuring sustainability and no emissions during the process.[43], [44] Tata Steel commissioned a 5 tonnes per day carbon capture plant at its Jamshedpur Works, making it the India's first steel company to adopt such a carbon capture technology that extracts CO₂ directly from the blast furnace gas.[45]

1.2 Objective

Looking into the above aspect, the objective of the present study is twofold:

1. Mineralogical and beneficiation studies of low-grade iron ore by using several techniques and constructing an appropriate route for beneficiation with good recovery of iron and upgrading the iron content.
2. Utilization of composite briquettes in liquid metal bath for steel making. As well as auxiliary studies as backup investigation with emphasis on isothermal reduction kinetics.

1.3 Plan of work

Plan of work as follows:

1. Mineralogical studies of low-grade iron ore
2. Beneficiation studies of low-grade iron ore by using several techniques and developing an appropriate route for beneficiation with good recovery of iron and upgrading the iron content
3. Different size of composite briquettes making and testing of composite briquettes
4. Reduction studies (isothermal and non-isothermal) of composite briquettes and characterization of isothermal composite briquettes

5. Utilization of composite briquettes in liquid metallic bath for steel making. As well as auxiliary studies as backup investigation with emphasis on isothermal reduction kinetics.
6. Testing of produced steel samples