Comparative review on the technologies of briquetting, sintering, pelletizing and direct use of fines in processing of ore and technogenic materials

***Yu. E. Kapelyushin**, PhD, Head of the Scientific and Research Laboratory "Physical-Chemistry and Gas Dynamics Problems", Senior Researcher of the Scientific and Research Laboratory "Hydrogen Technologies in Metallurgy"[1], e-mail: kapelyushinye@susu.ru*

[1] South Ural State University (Chelyabinsk, Russia)

A critical comparative analysis of technologies for preparation of ore and technogenic materials before metallurgical processing was conducted in this research. Briquetting, sintering, pelletizing and direct use of fines (processing without agglomeration) were conditionally emphasized among these technologies. The roller-press briquetting, vibropressing briquetting and stiff vacuum extrusion constitute the basis of the briquetting technology, advantages and disadvantages of these methods were analyzed that accompany briquetting. A few modern briquetting plants in CIS countries were commissioned. The main features were provided for agglomeration via pelletizing method. The sintering technology was reviewed, as well as data on new sintering plants in Russia. The technologies of direct processing of fines, which are conditionally divided into "fluidized bed" and direct processing of the fines in the melt, were briefly considered. The restrictions for processing in a "fluidized bed" were described as well as reduction characteristics of pellets and briquettes, which are often accompanied by swelling (variation of linear dimensions). The main causes of swelling of iron ore materials during reduction were described. The political and ecological factors of production and the problems of hydrogen power engineering were examined. The characteristics of total carbon dioxide emissions were provided for different production. It was shown that smelting of briquettes and pellets in arc furnaces, which are preliminary metalized by the gaseous reducing agents, are characterized by the lowest amount of emissions among the existing technologies. At the same time, the maximal carbon dioxide emissions are observed when using the alternative technologies, which utilize lump coal as a reducing agent.

Key words: roller-press briquetting, vibropressing briquetting, stiff vacuum extrusion, pelletizing, sintering, direct reduction, swelling of materials, hydrogen, carbon dioxide emissions.

DOI: 10.17580/cisisr.2023.02.01

1. Introduction

At present time, four main groups of technologies, which are applied for processing of ore and technogenic materials, can be conditionally emphasized: *briquetting, sintering, pelletizing* [1] and *direct use of fines* (technologies of "fluidized bed" or introduction of fines into the melt) [2]. Development of the technologies for processing of iron ore materials has a certain history, that effected methods of preparation before metallurgical processing. Based on objective reasons, most of the charge materials are subjected to agglomeration procedures. Agglomeration of fines, which are forming during ore mining and processing, was used for the first time in the XIX century with fabrication of briquettes [3]. Success of the briquetting technology was finalized in starting of operation of such production lines in Sweden, UK and USA until 1913. However, the patents for agglomeration methods of iron ore via sintering and for the conveyor sintering machine [4] were obtained in Germany in 1902 and in USA in 1907-1909. Owing to insufficient strength of briquettes and low productivity of briquetting machines, the sintering method was widely applied in the iron and steel industry and non-ferrous metallurgy, pushing out the briquetting technology. Afterwards, involvement of depleted iron ore in processing technologies and development of beneficiation technologies with obtaining of fine-dispersed concentrate led to development of another technology (pelletizing). The first patent for production of pellets was obtained in Sweden in 1916. This agglomeration method was not applied then widely, and commercial production of pellets started only in the second part of the XX century [5]. Subsequently, strengthening of ecological requirements arose the interest to the briquetting technology again. More wide application of the briquetting technique started during development of the processing methods of fine materials and metallurgical wastes [6] as well as in several direct iron reduction technologies, including those in the ferroalloys industry [7].

The fine materials are characterized by the most developed surface from kinetic point of view [8]. Thereby, the following technologies for processing of the fine charge materials without preliminary treatment and with direct processing in a "fluidized bed" or with introduction of particles into the melt, have been developed: FIOR, CIRCORED, FINMET, IRON CARBIDE, FINEX ("fluidized bed" technologies) and HISMELT, HISARNA [9] (direct iron smelting technologies). It should be noted that several such technologies were not developed to the stage of commercial application and were idled, due to certain difficulties [10, 11].

Issues in choosing the technology for preparation and processing of ore and technogenic materials can appear at the enterprises during putting into practice the new production facilities as well as during scientific and research work. Thereby, the present study was aimed to provide generalization and critical comparative analysis of the technologies of briquetting, sintering, pelletizing and direct processing of fines without agglomeration, in order to reveal their advantages and disadvantages.

2. Briquetting technology

Briquetting is one of the first agglomeration technologies for iron ore fines. There are three main briquetting methods – *roller press briquetting, vibropressing briquetting and stiff vacuum extrusion* [12].

2.1. Roller press briquetting

The roller press briquetting technology is realized in roll presses, which include housing with one or two pairs of rolls with steel sleeves mounted on this housing. The cells in the form of semi-form of briquettes are located on the sleeves in chess order. The prepared charge is subjected to pressing in the gap between the rolls which are rotated towards each other. Productivity of up-to-date roller press briquetting machines can achieve 50 tons per hour.

At present time, roller press briquetting is used in India, where it occupies one of the leading places worldwide in direct reduced iron (DRI) production. Based on this technology, DRI is reduced by coal in rotary kilns from ore, sinter and briquettes (annual production of DRI and hot-briquetted iron (HBI) in India exceeds 22 mln. tons [10]). The new roller press briquetting production line for manufacture of briquettes from oily mill scale and converter dust was put into practice at Vijayanagar plant in India in 2016; its productivity constitutes 30 tons per hour, or about 150,000 tons per year [13].

Briquetting works of Harsco Metals company are located in Europe, Asia and USA; they are intended for blast furnaces with total production volume 1.5 mln. tons per year. Such briquettes are added to the blast furnace charge (10-15 kg per ton of cast iron).

Roller press briquetting is also used in non-ferrous metallurgy for agglomeration of copper-nickel concentrates. In 2011 "Norilsk Nickel" mining and metallurgical company constructed the concentrate briquetting section at Zapolyarnyi production site of Kola mining and metallurgical company; it operates instead of the pellets production line. Annual production of this section is about 400,000 tons of briquettes. Transition to the roller press briquetting technology was caused by ecological load, connected with large amount of SO2 emission in the atmosphere during firing of pellets from copper-nickel concentrate [14].

High productivity, management simplicity, process continuity, relatively low wear of working surfaces, low energy consumption, wide range of sizes of initial fraction of pressing material are considered as advantages of the roller press briquetting technology. It allows pressing of fine and coarse particles, whereas large operating pressure (up to 150 MPa) provides high strength of green briquettes with permanent linear sizes.

The disadvantages include the use of essential proportion of binder in briquettes, short-term of the process (which can lead to air ingress), and there is a large output of recycled wastes from the mixture which was not charged in a forming cell (up to 30 % mass.).

Thus, roller press briquetting technology is operated worldwide in general, however its technical and economical parameters in the iron and steel industry can't be compared with sintering and pelletizing technologies.

2.2. Vibropressing briquetting

Vibropressing briquetting technology was firstly used in 1970-ies for agglomeration of natural and technogenic materials in the iron and steel industry. This method is based on the physical principle, when mixture viscosity decreases under vibrations with frequency >50 Hz in compacting material; it allows achieving higher compaction degree at lower pressure in comparison with compression [15, 16]. The first industrial vibropressing briquetting line was put into operation at the SSAB plant in Sweden for manufacture of briquettes as blast furnace charge components. Later vibropressing briquetting plants were built in Russia and Finland. Such a production line for manufacture of briquettes as blast furnace charge was inaugurated at the SSAB plant in Finland in 2012 after sintering plant closure in 2011. Vibropressing briquetting plant with annual productivity 120,000 tons was also operated at Kosaya Gora iron works in 2010-2015 [17].

There is information about negative operating experience of the vibropressing briquetting plant of Xstrata company (South Africa), which manufactured briquettes from chromium ore [18]. Another South African company Assmang had operated during several years the vibropressing briquetting plant for manufacture of briquettes from technogenic wastes of ferroalloy (ferromanganese) production, but in 2016 this line was reconstructed for the technology of stiff vacuum extrusion [19].

Successful project in the field of vibropressing briquetting of fine chromium ore on the base of "Gevit-Blok 2.6" vibropress was realized by the Russian company "Gevit" in Leningrad region in 2019; the roller-press briquetting briquetting line was replaced [20]. The company YuGPK also put into practice in Novotroitsk (Orenburg region) the vibropressing briquetting line for processing of metallurgical slags for their subsequent use in steel making [21].

Productivity of this technology substantially depends on size of obtained briquettes. The maximal productivity of a vibropressing briquetting line usually does not exceed 30 tons of green briquettes per hour. Such green briquettes obtained via vibropressing briquetting are not suitable for direct conveyor transportation to a storehouse just after manufacture. At first pallets with briquettes should be laid at a collecting stand, afterwards they are transferred in steaming chambers. Cement is usually used as a binder, its content in briquette mass can achieve 15 %.

Thus, in general, the experience of operation of vibropressing briquetting lines in the world shows the possibility of their application and, in some cases, with achievement of the required level of metallurgical properties of the briquettes produced.

2.3. Stiff vacuum extrusion

The term "BREX" was officially registered for briquettes manufactured via stiff vacuum extrusion in 2012 [22]. The stiff vacuum extrusion technology is realized as follows. The charge materials of the required granulometric composition are dosed and directed to mixer for homogenization of their composition. Then materials are forwarded into extruder through a feeder, which is equipped by the vacuum lock; green ductile briquettes with diameter 5-35 mm and with different length (depending on fracture features) are obtained at extruder exit. Cement is usually used as a binder during brex manufacture.

This technology was successfully used in metallurgy for the first time for agglomeration of materials in Serro Matoso (Columbia) at ferronickel production works in 1993. Absence of binders in briquetting process is the feature of the brex manufacture in Columbia [1, 23, 24]. In 2006, three stiff vacuum extrusion lines for agglomeration of nickel ore fines with capacity of 700,000 tons per year were constructed in Brazil by VALE company. In 2016, the brex production line was put into practice at Chelyabinsk ferroalloy plant of Chelyabinsk electrometallurgical works for briquetting of manganese ore concentrate with planned capacity of 260,000 tons per year [25]. In 2017, transnational company "Kazchrome" (Kazakhstan) started manufacture of brex from ferroalloy fines at its plant with annual capacity 80,000 tons [26]. In 2019, NLMK built three stiff vacuum extrusion lines with capacity of 700,000 tons per year [27].

Strict requirements for initial material are the features of the stiff vacuum extrusion technology; possibility of achievement of material plasticity state to provide efficient pressing through the die holes is considered as one of the main criteria of material suitability. To achieve this plasticity state, material moisture level and granulometric composition should correspond the preset requirements. Adjusting the particle size distribution to meet the requirements of stiff extrusion may require additional grinding of the briquetting mixture. Such briquettes are especially characterized by different linear size (various length) and high moisture level > 8 %, which leads to plasticity of green briquettes until the completion of strengthening process (curing) in the air. Information about service life of dies is absent in the open sources; economical expenses and equipment service life are mainly stipulated by parameters of initial material, abrasive properties of the material's particles and the level of conformity of the feed material to the requirements. Based on unconfirmed reports, increased wear of equipment can be observed during briquetting of fines containing carbides (carbides have high hardness).

3. Sintering technology

The sintering technology in a sintering machine has replaced briquetting technology in the beginning of the XX century and became at present time the main and most widely spread technique for agglomeration of charge materials before blast furnace smelting in the iron and steel industry. This technology is also applied in non-ferrous metallurgy [28-31] – in aluminium, nickel and lead production [32].

High productivity and very wide range of charge materials, which can be subjected to sintering in a sintering machine after agglomeration, are considered as the main advantages of this technology.

Complication in organization of sintering plant operation as well as ecological load on the environment are essential disadvantages of the sintering technology. Sintering plant, being incorporated in an integrated steel works, is a source of more than 50 % of all gas and dust emissions. Chemical, mineralogical and granulometric compositions of ore and concentrates are not permanent, thereby homogenization is carried out in order to obtain sinter with minimal deviations in chemical composition. Sintering process is characterized by definite requirements to charge loading. During sintering it is necessary to load sufficient charge amount to provide permanent and uniform height and width of the sintered layer in a sintering machine. Productivity of this machine, strength of the sinter and fuel consumption depend on correct support of external heating and ignition process. Layer strength in the upper part of sinter can differ from layer strength in the medium part of the sinter charge, what can be accompanied by difference in physical and chemical properties of final sinter.

Additional crushing and screening operations in order to classify sinter by size before subsequent metallurgical processing should be considered as disadvantage, it leads to additional economical and energy expenses as well as to return of the low-grade sinter to charge at sinter plant. Building of a sintering plant requires capital investments for auxiliary equipment (car dumpers for materials unloading, pallet stackers, equipment for pelletizing of dust-containing materials with manufacture of pellets, crushers and screens for classification of final sinter). Sintering technology has certain restrictions regarding metallurgical wastes. E.g. oily mill scale is added to sinter in a very small amount due to the oil evaporation, that leads to sticking of fine materials to exhauster blades. It should be mentioned that sinter is not characterized by sufficient mechanical strength for long-distance transportation.

In Russia, the new sintering plant with annual capacity of up to 6.5 mln. tons was commissioned in 2005 at Chelyabinsk metallurgical plant [33]. In 2019 the new sintering plant with annual capacity of up to 5.5 mln. tons and with 19 environment protection units was built at Magnitogorsk iron and steel works [34].

Despite all the disadvantages, today the sintering technology is the most widely spread and it is applied for large production volumes at integrated steel works with blast furnace production cycle.

4. Pelletizing technology

The first industrial equipment for pellets' manufacture in the world was built and put into operation in the USA in 1951; wide global development of this technology has started worldwide just after this event. In 1958 global production of pellets was about 15 mln. tons, in 1967 it increased up to 84 mln. tons [35-38].

At present time, the pelletizing technology is widely spread in the iron and steel industry and in non-ferrous metallurgy as well as in the ferroalloys industry and for utilization of metallurgical wastes [39].

In the iron and steel industry, pelletizing technology is widely used for involvement of magnetite ores in processing. Manufacture of pellets with subsequent metallization using the Midrex technology is realized in Russia at Oskol electrometallurgical plant with annual capacity of 3.3 mln. tons [40]. In non-ferrous metallurgy, pelletizing technology was used at "Norilsk Nickel" mining and metallurgical company in 1960-ies for processing of copper-nickel ores. It was in practice until the department for pelletizing and induration (belonging to Kola mining and metallurgical company) was closed and replaced by roller-press briquetting technology [14].

Pelletizing is also used for agglomeration of zinc-containing dust from dust cleaning facilities of electric arc steelmaking furnaces [41]. As a rule, reducing agent is presented in composition of such pellets. High strength of final pellets and possibility of their long-distance transportation (what can't be provided by the sintering technology) are considered as important advantages of the pelletizing technology. Thereby it is widely spread at the mining and metallurgical works. Pelletizing is also used as one of the stages of charge preparation during sintering [30]. Low strength of green pellets, which require drying and special induration at high temperatures, is considered as disadvantage of this technology. These processes are accompanied by power and economical expenses in comparison with briquetting technologies, which don't need high-temperature firing.

Addition of a reducing agent can make essential influence on material's properties during pelletizing; it can also lead to decrease in strength of green pellets and has the effect on selection of parameters for induration conductions. As soon as the firing temperature rises, strength of pellets increases and the strengthening process develops more intensively. However, the firing temperature can't be too high, and the temperature of pellets' sintering is the upper limit. When the sintering processes are developing, pellets stick into grapes and conglomerates; cooling, withdrawal and transportation of such pellets become either difficult, or impossible. But it is possible to manufacture pellets without induration, i.e. unfired pellets. However, in technical literature there are no information about industrial scale of manufacture of the unfired pellets.

One more disadvantage of the pelletizing technology is possibility of swelling (volume change) during subsequent reduction under certain ranges of temperature and gas compositions; it might effect on gas permeability and operating conditions of unts.

5. Direct utilization of fines

The methods of direct utilization of fines without agglomeration can be conditionally divided into the technologies of material processing in "fluidized bed" and the technologies of direct charge of fines in the melt.

5.1. Reduction of materials in "fluidized bed".

From the point of view of reaction kinetics, the technologies of direct processing of fines in a "fluidized bed" seem to be the most logical [8]. However, a row of physical restrictions are overlapped on these technologies. E.g. maximal temperature in the lower reactor of FINEX unit achieves 800-850 °C, what is caused by the beginning of intensive sintering process of iron ore particles. These processes deteriorate gas dynamics of the unit, increase complication of the complete reduction control and lead to subsequent material smelting [42]. Variations of the linear sizes of particles during reduction also have influence on gas dynamic processes. It is necessary to underline the following conditions, which should be balanced during realization of the reduction processes in a "fluidized bed" [43]:

1. Size of particles of initial material. From one side, minimal size of the particles is the most preferable in order to avoid kinetic restrictions. From another side, the particles should have maximal size, to provide high rate of the gas flow.

2. Height of layer. To minimize heat losses, height of the layer (height of a reactor) should be minimal. But height of the layer should be maximal, to avoid kinetic restrictions.

3. Reduction temperature. It should be as low as possible (to avoid sintering), but at the same time it should be as high as possible (to avoid kinetic restrictions and increase ratio of the gas use).

4. Gas flow rate. It should be as low as possible (to minimize the particles' ejection from the reactor), but at the same time it should be as high as possible (to provide maximal material charge and heat transfer rate, as well as to avoid sintering).

It can be seen from the a.m. conditions that control of these units is characterized by definite restrictions to initial materials and requires rather serious recruitment of the high-skilled staff to conduct technological operations.

5.2. Technologies of direct charge of fines into the melt

Such technologies (e.g. HIsmelt) are characterized by reduction and smelting of fines in the same unit, in a liquid metal bath [44]. Development of this technology is implemented in Australia and China. Thermal characteristics of the units are lower in comparison with the blast furnaces.

The advantage of the technology is its versatility, which makes it possible to process many types of iron-containing materials and titanomagnetites that are not suitable for blast furnace smelting due to the high content of impurities (such as phosphorus [45] or titanium [46]), as well as due to the fine particle size (dust and sludge from steel mills). Non-coking coals and other kinds of solid carbon-bearing reducing agents (including biomass) can be used for reduction. Very high wear of refractories is considered as disadvantage of the early version of this technology (at Kwinana plant in Australia). Afterwards this problem was partially solved via mounting of the water-cooled panels above tuyeres. This technology is also characterized by low productivity of units. At present time the problem of use of biomass instead of coal (in the case of introduction of high taxes for carbon footprint) is also discussed [47].

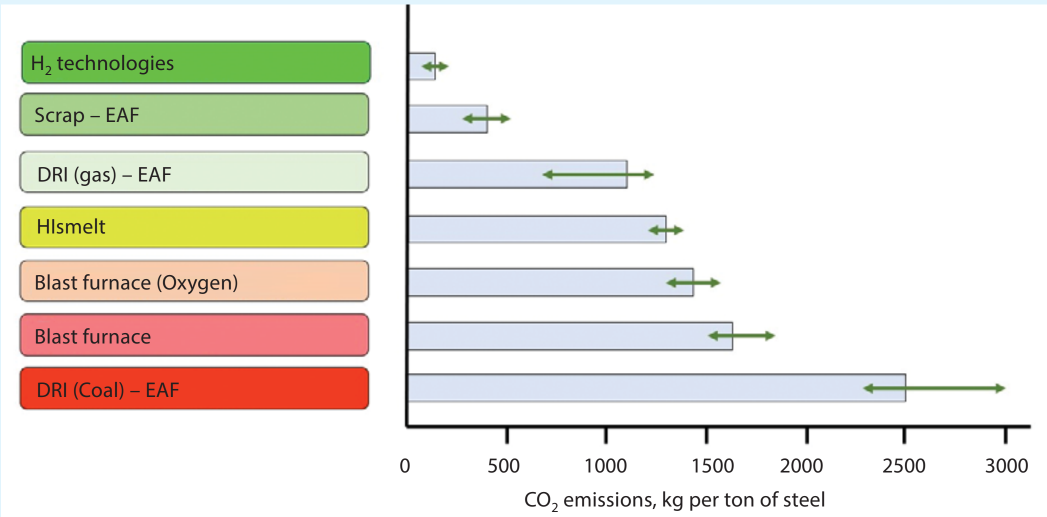
6. Features of reduction of pellets and briquettes

It has been noted that the peculiarity of reduction of some pellets and briquettes is their tendency to swell (change in size) during the reduction process at certain temperatures. This process is not usually observed in sinter processing. It should be noted that there are several causes of swelling. Swelling might occur due to definite conditions of heat treatment (firing of pellets) [48, 49], reduction temperature and composition of reducing gas [50, 51], growth of iron whiskers on reduced metal [52-57], metal crust burst due to increase in CO/CO_2 or H_2/H_2O pressure at interphase boundary between oxide phase and reduced metal (forming of gas bubbles) [58, 59], destruction stresses during Fe_2O_3 in Fe_3O_4 transformation [60, 61], influence of impurities (silica, lime, alkali, dolomite, sulfur etc. [48]), and structural effects (such as crystallographic transformations) [62]. Swelling of pelletized material can influence on operating parameters of metallurgical units, in some cases it can achieve catastrophic values of increase in material's sizes (up to 290 %) [51]. An ore type also has the kinetic type features. E.g., two tasks are solved in the process of firing of magnetite pellets: strengthening of the pellets takes place and transformation of cubic Fe_3O_4 lattice into hexagonal Fe_2O_3 lattice occurs; during the following reduction operation in metallurgical units the reverse transformation of hexagonal Fe_2O_3 lattice in cubic Fe_3O_4 lattice increases porosity [63]. The degree of Fe reduction does not usually exceed 60-70 % without preliminary oxidizing firing of magnetite ore [64].

7. Political and ecological aspects

Taking into account the ecological agenda, policy regarding CO_2, as well as possibility of introduction of substantial carbon footprint and coke use credits, it should be noted that building of new sintering workshops together with blast furnaces can be very problematic in the nearest future due to political and ecological aspects. Parameters of emissions for each steelmaking technology are presented in the **Figure** based on the data [65-67].

Minimal amount of CO_2 emissions among the existing technologies is observed in the process of steel scrap processing in electric arc furnaces. When processing initial ore, minimal amount of CO_2 emissions is observed in the alternative technologies, which use gas as a reducing agent, with agglomeration of initial materials via pelletizing or briquetting technologies. In Russia, Fe reduction by natural gas from iron ore pellets is realized in Midrex shaft furnaces at Oskol electrometallurgical plant [40]. It is possible to further decrease CO_2 emissions via use of hydrogen technologies. Construction of the green metallurgy complex via HYL technology using natural gas as a reducing agent is planned in Vyksa by 2025; its annual production capacity will make up to 1.8 mln. tons. It is noted that in the future natural gas can be replaced by hydrogen [68].



Amount of CO_2 emissions per ton of steel depending on steelmaking technologies

Comparative analysis of the existing technologies

Technology	Advantages, features	Disadvantages
Roller-press briquetting	– technological simplicity and low cost of equipment; – possibility of transportation of some briquettes.	– large proportion of binders; – large amount of recycled mixture (up to 30 %); – possibility of swelling during subsequent reduction.
Briquetting via vibropressing	– low amount of binders in comparison with the roller-press briquetting. – possibility of swelling during subsequent reduction.	– green briquettes are not valid for direct transportation just after fabrication;
Stiff vacuum extrusion	– low amount of binders in comparison with other briquetting technologies (possibility of agglomeration of certain materials without binders); – drying (curing) in the air without high-temperature firing.	– special requirements to granulometric composition and moisture to achieve a plasticity state of the material, necessity of additional grinding; – increased abrasive wear of equipment caused by the use of the materials with high hardness of particles; – possibility of swelling during subsequent reduction.
Sintering	– large production capacity; – absence of sinter swelling during subsequent reduction.	- complication of organization of a sinter plant operation; – unsuitable for small production capacity; – ecological load, carbon footprint issues; – unsuitable for sinter transportation; – existence of certain technical limitations.
Pelletizing	– high strength of final pellets; – possibility of pellets transportation.	– low strength of green pellets; – requirement to perform induration; – possibility of swelling during subsequent reduction.
Fluidized bed	– absence of capital expenses for agglomeration; – the best kinetic conditions during reduction.	– complication of control of the gas dynamics process; – restriction of the temperature due to development of sintering processes and sticking of fines in a reactor.
Direct processing of fines in the melt	– absence of capital expenses for agglomeration; - the best kinetic conditions during reduction; – high process versatility and flexibility (in comparison with a blast furnace technology); – use of non-coking coal.	– low productivity of the units; – increased lining wear; – the problems connected with a solid state reducing agent and carbon footprint.

Hydrogen power engineering is developing in Russia, and the Government has approved the plan for development of technologies for production, storage, transportation and use of hydrogen as an efficient and renewable energy source [69, 70]. As a result of implementation of the planned measures, hydrogen should become an ecologically clean and competitively acceptable energy carrier for wide use, as well as a reducing agent in metallurgy. However, it has been noted in the high profile paper [71] that hydrogen use and production can be expedient only for the regions which use alternative energy sources (which are characterized by non-stable operation). In this case hydrogen allows us to transfer, to accumulate and save energy. At the same time expedience of the use of coal-containing energy sources is still valid for Russia. In addition, from the thermodynamic point of view, it is not completely correct to use green hydrogen in the iron and steel industry, because electric power is consumed for water separation into O_2 and H_2, and then to use hydrogen to get water during Fe reduction from its oxides. This illogicality causes development of the ULCOWIN technology for direct electrolysis of fine iron ore particles. It is important to note in advance that low productivity and anode materials are the large drawbacks of such technologies [72].

Maximal amount of emissions is provided by alternative technologies using lump coal. The conventional blast furnace cycle is characterized by smaller amount of CO_2 emissions in comparison with these technologies (owing to high thermal efficiency factor); however, it is larger than in the gas reduction technologies with subsequent electric arc smelting of metalized materials. The technology for direct processing of fines in liquid metal (HIsmelt technology) has lower efficiency factor in comparison with a blast furnace, but it does not require organization of the coke production facilities and sintering plant, while kinetic conditions are optimal.

8. Comparative analysis

The generalized comparative analysis of the existing technologies, which are used in processing of ore and technogenic materials, is presented in the following **table**.

9. Conclusions

When choosing a certain technology, each raw material requires an individual approach and detailed investigations. For example, oily mill scale can’t be utilized via sintering technology due to possibility of the exhauster breakdown. Use of stiff vacuum extrusion technology for processing of the high hardness of materials can lead to increased wear of the screw feeds and dies, which are the base of the equipment for the manufacture of brex.

For magnetite ore, it is often needed to take into account the operation of oxidizing firing in order to provide the transfer of Fe_3O_4 to Fe_2O_3, otherwise subsequent Fe reduction degree may not exceed 60-70 %. Materials, which were agglomerated with certain binders or reduced under specific conditions, can swell by more than 2 times to catastrophic values in a linear dimensions variation, that might significantly effect on the gas dynamics of a metallurgical unit.

Thereby, at present time there is no universal technology for agglomeration of iron ore materials. When choosing the agglomeration technology and the technology for subsequent processing, the whole complex of factors should be considered. Among them the following factors should be emphasized: chemical composition and morphology of charge materials, use of a binder and type of a reducing agent, productivity of metallurgical units at the subsequent processing stage, operating temperature, gas dynamics and especially political and ecological factors, which are connected with the carbon footprint issues and can terminate construction of new blast furnace plants in the future.

The research was funded by the Russian Science Foundation grant No. 21-79-00081 of the Russian scientific fund, https://rscf.ru/project/21-79-00081/.

REFERENCES

1. Bizhanov A., Chizhikova V. Agglomeration in Metallurgy. Springer International Publishing. 2020. 454 p.
2. Yang, W.-C. Handbook of Fluidization and Fluid-Particle Systems. 2003. Vol. 1. 850 p.
3. Bizhanov A. Briquetting in Metallurgy. CRC Press. 2022. 326 p.
4. Holowaty M. O. History of Iron Ore Sintering Recalls Variety of Experimentation. *JOM, The Journal of The Minerals, Metals & Materials Society (TMS)*. 1955. No. 7. pp. 19–23. DOI: 10.1007/BF03377448.
5. de Moraes S. L., de Lima J. R. B., Ribeiro T. R. Iron ore pelletizing process: An Overview. *Iron Ores and Iron Oxide Materials*. 2018. 280 p. Ch. 3.
6. Mousa E., Ahmed H., Söderström D. Potential of Alternative Organic Binders in Briquetting and Enhancing Residue Recycling in the Steel Industry. *Recycling*. 2022. No. 7. pp. 21. DOI: 10.3390/recycling7020021.
7. Ravich B. M. Briquetting in Ferrous and Nonferrous Metallurgy. Moscow. Metallurgy. 1975. 232 p.
8. Pavlov V. V. Inconsistencies in metallurgy. Their elimination. UGGU. 2013. 211 p.
9. Morris A. E. Iron Resources and Direct Iron Production. Encyclopedia of Materials: Science and Technology. 2001. pp. 4302–4310.
10. World DRI Statistics 2021. URL: https://www.midrex.com/wp-content/uploads/MidrexSTATSBook2021.pdf
11. Seetharaman S., McLean A., Guthrie R., Sridhar S. Treatise on Process Metallurgy. Publisher Elsevier Ltd. 2013. Vol. 1. 952 p.
12. Kurunov I., Bizhanov A. Stiff Extrusion Briquetting in Metallurgy. Springer. 2018. 170 p.
13. Kumar D. S., Sah R., Sekhar V. R., Vishwanath S. C. Development and Use of Mill Scale Briquettes in BOF. *Ironmaking & Steelmaking*. 2017. Vol. 44. pp. 134–139. DOI: 10.1080/03019233.2016.1165499.
14. Kola mining and metallurgical company continues reducing sulfur dioxide emissions. 31-07-2018. URL: https://www.nornickel.ru/news-and-media/press-releases-and-news/kolskaya-gmk-prodolzhaet-snizhat-vybrosy-dioksida-sery/ (access date: 05.08.2023).
15. Bizhanov A. M, Kurunov I. F. Extrusion briquettes (brexes) – the new stage in agglomeration of raw materials in the iron and steel industry. M. Metallurgizdat. 2017. 234 p.
16. Guzman I. Ya. Chemical technology of ceramics. Moscow. RIF “Stroimaterialy” JSC. 2003. 406 p.
17. BF No. 1: Continuation of technological researches. 28-07-2010. URL: http://www.kmz-tula.ru/articles-20100728.html (access date: 05.08.2023).
18. Naiker O., Riley T. Xstrata Alloys in Profile. *Proceedings of the South African Pyrometallurgy*. 2006. pp 297–305.
19. Davey K. P. The Development of an Agglomerate through the Use of FeMn Waste. *Proceedings of the tenth international ferroalloy congress (INFACON X)*. 2004. Vol. 27. pp. 272–280.
20. The Russian briquetting line is put into practice at the metallurgical works in Leningrad region. 10-11-2019. URL: https://sdelanounas.ru/blogs/126816/ (access date: 05.08.2023).
21. Balashova L. The new briquetting line AKKERMANN METAL was put into operation at YuUGPK JSC. 25-07-2019. URL: https://www.ural56.ru/news/628602/ (access date: 05.08.2023).
22. Kurunov I. F., Bizhanov A. M. Brexes as the new stage in agglomeration of raw materials for blast furnaces. *Metallurg*. 2014. No. 3. pp. 49–53.
23. Bizhanov A. M. Substantiation of choosing the production technology and examination of metallurgical properties of briquettes in order to rise efficiency of their use in extraction processes of the iron and steel industry. Moscow. MISiS. 2016. 152 p.
24. Bizhanov A. M., Steele R. B., Podgorodetskiy G. S., Kurunov I. F., Dashevskiy V. Y., Korovushkin V. V. Extruded Briquettes (Bricks) for Ferroalloy Production. *Metallurgist*. 2013. Vol. 56. pp. 925–932.
25. Chelyabinsk electrometallurgical plant mastered production of manganese brexes. 13-08-2018. URL: https://briket-brex.ru/news/chemk-osvoil-vypusk-vypusk-margantsevykh-breksov/ (access date: 05.08.2023).
26. Kazchrome started building of the USD 2.5 mln. shop for brexes production. 06-10-2016. URL: https://www.erg.kz/ru/news/585 (access date: 05.08.2023).
27. NLMK Group puts into practice new production facilities based on secondary resources. URL: https://lipetsk.nlmk.com/ru/media-center/press-releases/nlmk-group-launches-new-by-product-fuelled-facility/?from=en (access date: 05.08.2023).
28. Sigov A. A., Shurkhal V. A. Sintering process. Kiev. Tekhnika. 1969. 232 p.
29. Gubanov V. I., Tseitlin A. I. Reference book of a sintering plant worker. Chelyabinsk. Metallurgiya. 1987. 207 p.
30. Korotich V. I., Frolov Yu. A., Bezdezhskiy G. N. Sintering of raw materials. Ekaterinburg. UGTU-UPI. 2003. 400 p.
31. Zhilkin V. P., Doronin D. N. Sinter production. Technology, equipment, automation. Ekaterinburg. Uralskiy tsentr PR i reklamy. 2004. 292 p.
32. Marchenko N. V., Vershinina E. P., Gildebrandt E. M., Blednova B. P. Metallurgy of heavy non-ferrous metals. 2009. 394 p.
33. Chelyabinsk metallurgical plant delivered 150 mln. t of sinter. 28-02-2019. URL: https://mechel.ru/press/news/chmk-otgruzil-150-millionov-tonn-aglomerata/ (access date: 05.08.2023).
34. New MMK sintering plant: the most modern and green in Russia. 12-12-2019. URL: https://www.vnedra.ru/glavnaya-tema/novaya-aglofabrika-mmk-samaya-sovremennaya-i-zelenaya-v-rossii-9299/#:~:text= (access date: 05.08.2023).
35. Yusfin Yu. S., Bazilevich T. N. Burning of iron ore pellets. Moscow. Metallurgiya. 1973. 272 p.
36. Maerchak Sh. Manufacture of pellets. Moscow. Metallurgiya. 1982. 232 p.
37. Zhuravlev F. M., Malysheva T. Ya. Pellets from concentrates of ferriferous quartzite. Moscow. Metallurgiya. 1991. 127 p.

38. Kokorin L. K., Leleko S. N. Production of oxidized pellets. Ekaterinburg. Uralskiy tsentr PR i reklamy. 2004. 280 p.
39. Bondarenko I. V., Tastanov E. A. Obtaining Multi-Component Pellets from Finely Dispersed Chromium Concentrates, Refined Ferrochrome Slags and Diatomite Raw Materials of Kazakhstan. *Metallurgist*. 2019. Vol. 62. pp. 1213–1218. DOI: 10.1007/s11015-019-00776-0.
40. Oskol electrometallurgical plant produced 70th million ton of metalized pellets. 07-02-2019. URL: https://bel.ru/news/2019-02-07/oemk-proizvyol-70-millionnuyu-tonnu-metallizovannyh-okatyshey-330276 (access date: 05.08.2023).
41. Ferreira F. B., Flores B. D., Osório E., Vilela A. C. F. Evaluation of Zinc Removal and Compressive Strength of Self-Reducing Pellets Composed of Electric Arc Furnace Dust. *Rev. Esc. Minas*. 2019. Vol. 72. pp. 71–77. DOI: 10.1590/0370-44672017720190.
42. Hyun-Soo Kim, Minyoung Cho, Chang-Kuk Ko, Sunkwang Jeong and Sang-Ho Yi. Direct Use of Magnetite Concentrates in the Fluidized-Bed Reactors of FINEX®. *Proceedings of the AISTech Conference*. 2014. pp. 1-6.
43. Wolfinger T., Spreitzer D., Schenk J. Using Iron Ore Ultra-Fines for Hydrogen-Based Fluidized Bed Direct Reduction – A Mathematical Evaluation. *Materials (Basel)*. 2022. Vol. 15. 3943. DOI: 10.3390/ma15113943.
44. Burke P. D., Gul S. HIsmelt – the Alternative Ironmaking Technology. *Proceedings of the International Conference on Smelting Reduction for Ironmaking*. Jouhari A. K., Galgali R. K., Misra V. N. (Eds). 2002. pp. 61–71.
45. Li Y., Li H., Wang H., Qing S., Hu J., Hou Y., Li H., Li L. Smelting Potential of HIsmelt Technology for High-Phosphorus Iron Ore and Ilmenite. *Proceedings of the International Conference on Computer Distributed Control and Intelligent Environmental Monitoring*. CDCIEM 2011 (IEEE). 2011. pp. 1283–1286.
46. Zhang S., Hu P., Rao J., Wang Z., Zong Y., Zhang J. Effect of Smelting Time on Vanadium and Titanium Distribution Behavior and Slag Viscosity in HIsmelt. *Metals*. MDPI. 2022. 12. 1019. DOI: 10.3390/met12061019.
47. Goodman N. J. The HIsmelt Technology: From Australia to China... and Back Again? *Proceedings of the Iron Ore Conference 2019*. 2019. pp. 3–13.
48. Gupta R. C., Prakash B. Effect of Firing Condition and Ingredients on the Swelling Behaviour of Iron Ore Pellets. *Iron and Steel Institute of Japan International*. 1993. Vol. 3. pp. 446–453. DOI: 10.2355/isijinternational.33.446.
49. Gupta S. K., Lu W. K. Effect of Additives on the Strength, Reducibility and Swelling of Low Silica Iron Ore Pellets. *Canadian Metallurgical Quarterly*. 1987. Vol. 26. pp. 329–339. DOI: 10.1179/cmq.1987.26.4.329.
50. Gupta R. C., Prakash B. Swelling of Iron Ore Pellets by Statistical Design of Experiment. *Iron and Steel Institute of Japan International*. 1992. Vol. 32. pp. 1268–1275. DOI: 10.2355/isijinternational.32.1268.
51. Wang H., Sohn H. Y. Effects of Reducing Gas on Swelling and Iron Whisker Formation during the Reduction of Iron Oxide Compact. *Steel Research International*. 2012. Vol. 83. pp. 903–909. DOI: 10.1002/srin.201200054.
52. Nakiboglu F. Mechanism of Swelling of Iron Oxide Pellets. PhD Thesis. 1981. 198 p.
53. Sharma T., Gupta R. C., Prakash B. Effect of Gangue Content on the Swelling Behaviour of Iron Ore Pellets. *Minerals Engineering*. 1990. No. 3. pp. 509–516.
54. Chang M., De Jonghe L. C. Whisker Growth in Reduction of Oxides. *Metallurgical and Materials Transactions B*. 1984. Vol. 15. pp. 685–694. DOI: 10.1007/BF02657290.
55. Abdel Halim K. S., Bahgat M., El-Kelesh H. A., Nasr M. I. Metallic Iron Whisker Formation and Growth during Iron Oxide Reduction: Basicity Effect. *Ironmaking & Steelmaking*. 2009. Vol. 36. pp. 631–640. DOI: 10.1179/174328109X463020.
56. John D. H. S., Nakiboglu F., Hayes P. C. The Effect of Sulfur on the Gaseous Reduction of Solid Calciowustites. *Metallurgical and Materials Transactions B*. 1986. Vol. 17. pp. 383–393. DOI: 10.1007/BF02655086.
57. Li G. H., Tang Z. K., Zhang Y. B., Cui Z. X., Jiang T. Reduction Swelling Behaviour of Haematite/Magnetite Agglomerates with Addition of MgO and CaO. *Ironmaking & Steelmaking*. 2010. Vol. 37. pp. 393–397. DOI: 10.1179/030192310X12690127076352.
58. El-Geassy A. A., Nasr M. I., Hessien M. M. Effect of Reducing Gas on the Volume Change during Reduction of Iron Oxide Compacts. *Iron and Steel Institute of Japan International*. 1996. Vol. 36. pp. 640–649. DOI: 10.2355/isijinternational.36.640.
59. St. John D. H., Matthew S. P., Hayes P. C. The Breakdown of Dense Iron Layers on Wustite in CO/CO_2 and H_2/H_2O Systems. *Metallurgical and Materials Transactions B*. 1985. Vol. 16. p. 857. DOI: 10.1007/BF02667525.
60. Hayes P. C., Grieveson P. Microstructural Changes on the Reduction of Hematite to Maanetite. *Metallurgical and Materials Transactions B*. 1981. Vol. 12. pp. 579–587. DOI: 10.1007/BF02654330.
61. Hayes P. C., Grieveson P. The Effects of Nucleation and Growth on the Reduction of Fe_2O_3 to Fe_3O_4. *Metallurgical and Materials Transactions B*. 1981. No. 12. pp. 319–326. DOI: 10.1007/BF02654465.
62. Jallouli M., Ajersch F. Analytical Model for the Swelling of Sintered Iron Oxide Pellets during the Haematite-Magnetite Transformation. *Journal of Materials Science*. 1986. Vol. 21. pp. 3528–3538. DOI: 10.1007/BF02402999.
63. Edstrom J. O. The Mechanism of Reduction of Iron Oxides. *The Journal of the Iron and Steel Institute*. 1953. Vol. 175. pp. 289.
64. Kapelyushin Y., Sasaki Y., Zhang J., Jeong S., Ostrovski O. Effects of Temperature and Gas Composition on Reduction and Swelling of Magnetite Concentrates. *Metallurgical and Materials Transactions B. 2016. Vol. 47. pp. 2263–2278.*
65. Quader M. A., Ahmed S., Ghazilla R. A. R., Ahmed S., Dahari M. A. Comprehensive Review on Energy Efficient CO_2 Breakthrough Technologies for Sustainable Green Iron and Steel Manufacturing. *Renewable and Sustainable Energy Reviews*. 2015. Vol. 50. pp. 594–614. DOI: 10.1016/j.rser.2015.05.026.
66. Ma Y., Souza Filho I. R., Bai Y., Schenk J., Patisson F., Beck A., van Bokhoven J. A., Willinger M. G., Li K., Xie D. et al. Hierarchical Nature of Hydrogen-Based Direct Reduction of Iron Oxides. *Scripta Materialia*. 2022. Vol. 213. 114571. DOI: 10.1016/j.scriptamat.2022.114571.
67. Orth A., Anastasijevic N., Eichberger H. Low CO_2 Emission Technologies for Iron and Steelmaking as Well as Titania Slag Production. *Minerals Engineering*. 2007. Vol. 20. pp. 854–861. DOI: 10.1016/j.mineng.2007.02.007.
68. The first Russian green metallurgy project Ecolant obtained starting investment from domestic banks for Euro 33 mln. 30-06-2021. URL: https://omk.ru/press/news/32963/ (access date: 05.08.2023).
69. RF power engineering strategy until 2035. URL: https://minenergo.gov.ru/node/1026?ysclid=l9mmahyl3z906956639 (access date: 05.08.2023).
70. RF Government approved the plan with measures for development of hydrogen power engineering. URL: https://minenergo.gov.ru/node/19194?ysclid=l9mmch6gp0222207625 (access date: 05.08.2023).
71. Litvinenko V. S., Tsvetkov P. S., Dvoinikov M. V., Buslaev G. V. The barriers to realization of hydrogen initiatives within the context of sustainable development of global power engineering. *Zapiski Gornogo instituta*. 2020. Vol. 244. pp. 428–438.
72. Cavaliere P. Electrolysis of Iron Ores: Most Efficient Technologies for Greenhouse Emissions Abatement. *In Clean Ironmaking and Steelmaking Processes*. *Springer*. 2019. pp. 555–576. DOI: 10.1007/978-3-030-21209-4_10.