# Innovative approaches to producing sponge iron from Dashkesan ore and its use in electric steel production

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This paper examines innovative processes for the direct reduction of sponge iron (DRI) and its use in electric steelmaking production. The primary raw material for iron reduction is iron ore from the Dashkesan deposit in the Republic of Azerbaijan. The chemical composition of Dashkesan iron ore is presented, along with the degree of metallization of this raw material. Data are provided on the extent of carbon, phosphorus, sulphur, and non-ferrous metal removal from the ore. It was found that in the process using a gaseous reductant, "sooty" carbon is deposited from the gas phase onto the developed surface of the DRI. The removal of phosphorus during direct reduction is not feasible; therefore, before this operation, deep beneficiation of ores intended for direct reduction is necessary. The main source of sulphur in DRI is the reductant. When using a solid reductant, the sulphur content is high, so in this case, flux (limestone, dolomite) must be added to the charge. When using a gaseous reductant, the sulphur content in the product is low. The content of non-ferrous metals, nitrogen, and hydrogen in metallized pellets is low. A relationship between the apparent density and porosity of briquettes, ores, and pellets has been established. High porosity is observed in pellets, which is related to the porosity of the initial iron ore and the reduction in oxide volume during reduction. The quality of the steel produced is greatly affected by the secondary oxidation of DRI. Due to its highly developed surface and high porosity, DRI is prone to secondary oxidation during transportation and storage. Therefore, studies were conducted to reduce the level of secondary oxidation, and a passivation technology was developed to protect the iron from further oxidation.

***Key words:*** iron ore, electric steelmaking, sponge iron, reduction, secondary oxidation, converted gas.
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## Introduction

In the structure of global steelmaking capacity, the share of electrometallurgy is rapidly increasing, with the main charge materials for this process being metal scrap and metallized iron pellets. Steel production in electric furnaces reduces $CO_2$ emissions into the environment by almost six times. The growing demand for steel products requires the expansion of sponge iron production using direct reduction methods.

It is known that Azerbaijan has a large iron ore deposit [1], the conversion of which into metallized iron could give a significant boost to the development of the domestic metallurgical industry. Therefore, the research and implementation of innovative technologies for the direct reduction method of iron production in our country is of great scientific and technical interest.

A review of the method for producing sponge iron (DRI) shows that the most advanced and widely used process for DRI production is the Midrex process, developed in 1966 by Midland–Ross Corporation. By 2002, this process was being used in 18 countries worldwide, operating 49 units.

The evolution of the Midrex process has focused on increasing productivity and reducing production costs. A new development in Midrex technology is the Midrex Hotlink system, aimed at saving energy in the "DRI production – electric steelmaking from DRI" process chain. This technology makes it possible to load the metallized pellets produced in the Midrex reactor into the electric furnace at a temperature of about 700 °C, without cooling them. With a DRI metallization degree of 95 %, this allows for a reduction in electric steelmaking power consumption by 120–140 kWt·h per ton of steel [2].

However, the rise in natural gas prices in highly developed countries of North America, and especially in European countries, has led to a sharp deterioration in the economic performance of the Midrex and HYL technologies. In countries such as the Republic of Azerbaijan, natural gas is still relatively inexpensive [3].

Based on the conducted literature review, it can be concluded that the well-known Midrex, HYL, and ITmk3 technologies are successfully used worldwide. Depending on energy resources, each country adopts the technology most advantageous for its conditions [4, 5]. Tests carried out by

Hares Engineering and Kobe Steel at the Nishik laboratory have shown that all iron ore concentrates produced in CIS countries, including those from oxidized ores, can be effectively used in the ITmk3 direct reduction technology [6]. However, this technology involves the use of coal in the iron reduction process. Many CIS countries, including the Republic of Azerbaijan, have natural gas but lack coal reserves, with the exception of petroleum coke, which is successfully used in ferroalloy production. Therefore, for the Republic of Azerbaijan, the most suitable technology is the direct reduction of iron using converted natural gas (steam-reformed) as the reductant [7]. The research presented in this paper will focus on the modes and setups for producing DRI using converted natural gas as the reductant.

***The aim of this work*** is to select and justify an innovative technology for producing DRI from the Dashkesan iron ore deposit for use in electric steelmaking production.

## Materials for Research

The main components of the Dashkesan iron ore deposit include gangue rock consisting of iron, carbon, quartzite, and impurities (**Table 1**). The Dashkesan iron ore deposit belongs to the magnetite type. The specific chemical composition may vary depending on the section of the quarry and the depth of occurrence. The ore is characterized by the following average values: Fe — 35–45 %; $Fe_3O_4$ — 40–60 %; $SiO_2$ — 8–18 %; $Al_2O_3$ — 1–3 %; CaO — up to 1 %; MgO — up to 2 %; S — up to 0.1–0.2 %; P — up to 0.1 %. The composition of the converted natural gas is as follows: $CH_4$ — 85–96 %; $C_2H_6$ — 1–6 %; $C_3H_8$ — 0.1–2 %; $CO_2$ — 0.1–1 %; $N_2$ — 0.1–1 %.

The phase composition of Dashkesan iron ore consists of: $Fe_3O_4$ — 60–75 %; $Fe_2O_3$ — 5–10 %; $SiO_2$ — 10–15 %; chlorite/sericite — 2–5 %; carbonates ($KAlSi_3O_8$/$CaCO_3$) — 1–3 %.The phase composition of the concentrate is: $Fe_3O_4$ — 85–95 %; $Fe_2O_3$ — 2–5 %; $SiO_2$ — <3 %; impurities — <1 %.

The granulometric composition of the Dashkesan iron ore concentrate is presented in the **Table 2**.

When producing steel in basic steelmaking units, additional lime must be added to the charge to flux the gangue present in the DRI [7]. Therefore, for direct iron reduction, it is necessary to use high-grade iron ore raw materials with a gangue content of 1–4 %. With modern ore beneficiation methods, it is possible to obtain concentrates containing less than 1 % gangue; however, in this case, the beneficiation costs may exceed the benefits gained from reducing the amount of slag.

## Development of Innovative Technology for Producing DRI from Dashkesan Iron Ore

***Beneficiation method for obtaining iron concentrate and technological route for DRI production from the Dashkesan deposit.***

Dashkesan ore mainly consists of magnetite; therefore, the following operations were used for its beneficiation: crushing and grinding, magnetic separation, and flotation to remove non-magnetic impurities. To reduce the phosphorus content in the ore, dephosphorization by chemical etching was used; the P content in the concentrate after this was 0.045 %. The C content in the concentrate was <0.05. The technological route for obtaining DRI consisted of the following operations: raw material preparation, feeding the raw material into the reactor, generation of reducing gas, the reduction process at 800–1050 °C for 6–12 hours, product discharge, and gas removal and recirculation.

Typically, the degree of metallization of DRI used for steelmaking (($\varphi = 100\,\% \cdot Fe_{met}/Fe_{tot}$) ranges from 90–92 %. This indicator reflects the amount of oxygen or iron oxides present in the metallized materials, represented by FeO (unreduced oxides of the original raw material) and $Fe_2O_3$(products of secondary oxidation of DRI). With minimal error, it can be assumed that secondary oxidation is insignificant, and oxygen in the metallized materials is present mainly as wüstite $Fe_{0.947}O$.

In this case, the amount of iron oxides and oxygen can be determined using the following equations:

$$X_{FeO} = 1.302 \cdot X_{Fe_{tot}} (100 - \varphi)/100, \qquad (1)$$

$$X_O = 0.302 \cdot X_{Fe_{tot}} (100 - \varphi)/100. \qquad (2)$$

Here, $X_{Fe_{tot}}$, $X_{FeO}$ and $X_O$ — are the amounts of iron, iron oxide and oxygen, respectively, in mass fractions.

With a total iron ($Fe_{tot}$) concentration of 85–95 % and a metallization level of 92–96 %, DRI contains 0.4–2.7 % oxygen and 2.4–11.5 % FeO. During the smelting of metallized charges, Fe oxides are partially reduced by the carbon present in these same materials and in the molten mixture, partly mixing with the slag and being removed from the furnace together with it [8].

The main thermodynamic reactions for reducing iron and impurities from oxides are as follows:

1. $Fe_3O_4 + 4H_2 \rightarrow 3Fe + 4H_2O$ (at the temperatures above 910 °C);

**Table 1. Chemical composition of Dashkesan iron ore concentrate**

| Content of elements and compounds in iron concentrate, % (mass.) | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fe total | $Fe_2O_3$ | FeO | $SiO_2$ | CaO | MgO | $P_2O_5$ | $Al_2O_3$ | Mn | $TiO_2$ | $K_2O$ | $Na_2O$ | S | $V_2O_5$ | Zn | As | Pb | Ni | Cu | $Cr_2O_3$ | Other | Humidity |
| 60.75±0.5 | 58.2 | 24.6 | 7.26 | 4.52 | 0.63 | 0.06 | 2.01 | 0.58 | 0.15 | 0.08 | 0.2 | 0.07 | 0.02 | 0.02 | 0.02 | — | 0.001 | 0.001 | 0.008 | 1.39 | 6.0 |

**Table 2. Granulometric composition of Dashkesan iron ore concentrate**

| Granulometric composition, % | | | | |
|---|---|---|---|---|
| +35 mesh. | +70 mesh. | +150 mesh. | +200 mesh. | –200 mesh. |
| 1.4 | 11.0 | 16.7 | 12.9 | 58.0 |

2. $Fe_3O_4 + CO \rightarrow 3Fe + 4CO_2$ (hydrogen and CO can also reduce $Fe_3O_4$, and CO reduces $Fe_2O_3$ to $Fe_3O_4$).

Examples of equations and Gibbs free energy changes ($\Delta G$, kJ/mol at 1000 K):

$Fe_3O_4 + 4H_2 \rightarrow 3Fe + 4H_2O = -36$;

$FeO + H_2 \rightarrow Fe + H_2O = -14$.

All reactions have negative $\Delta G$, which means they are thermodynamically favorable at temperatures of 800–1050 °C.

The chemical composition of the obtained DRI is as follows: Fe 82–94 %; FeO 4–6 %; C 0.1–2.5 %; $Al_2O_3$ 0.1–0.5 %; $SiO_2$ 0.1–1.0 %; S < 0.02 %; P 0.1–0.05 %; impurities–traces (< 1 %); moisture/porosity 0.5–2 %. The phases present in the DRI are: Fe 85–92 %; FeO 5–10 %; $Fe_3O_4$ 1–3 %; slag phases < 1–2 %; porosity (moisture, voids) 1–3 % (by volume).

### *Degree of removal of C, P, S and non-ferrous metals from Dashkesan ore*

Carbon. In sponge iron, the carbon concentration can vary depending on the processing method. The SL-RN, Krupp, and FIOR processes yield DRI with 0.2–0.7 % C. The Purofer process gives, on average, 0.56 + 0.27 % C, while DRI produced by the Midrex process contains 0.8–2.2 % C; in this case, both the metal purity and the carbon content vary over a very wide range. DRI produced by the HYL process is characterized by an increased carbon concentration–up to 2.5 %; at the same time, for Midrex, although the carbon concentration can be adjusted over a wide range, the metal purity is lower [9].

When a gaseous medium (Purofer, Midrex) acts from the vapor–gas phase on the porous surface of DRI, “sooty” carbon deposits, which reacts with Fe to form cementite. The formation of $Fe_3C$ does not go to completion, and in the metallized product some sooty carbon remains, located both in the pores and on the outer surface.

For the use of metallized pellets (MP) in steelmaking, the presence of soot on their outer surface is not allowed, since it sheds during handling and transportation. This leads to a reduction in the carbon content of the pellets and to dust formation. Such dust generated during movement can contain up to 10 % carbon, and the presence of this amount of C worsens hygienic conditions in conveyor galleries and bunker areas and also increases the fire hazard.

Phosphorus. Since phosphorus is not removed during reduction, its concentration in metallized pellets is determined by the phosphorus content of the iron-ore feed. Lowering P is achieved through deep beneficiation of the minerals used for reduction. When the FeC content in the concentrate increases, the amount of P decreases [10]. With the exception of certain types of MP (e.g., HYL-Ca, Mexico), the phosphorus content in metallized materials (MM) does not exceed 0.030 % and is typically in the range of 0.010–0.020 %.

Sulphur. In the direct reduction process, large quantities of fired, unfluxed pellets (UFP) are used as feed. Most sulphur is removed during oxidizing roasting; therefore, the reductant is the main source of sulphur.

In solid-state reduction, the sulphur content in metallized materials (MM) can be high. In this case, reducing sulphur in the final product is achieved by adding fluxes to the mix ($CaCO_3$, $MgCO_3 \cdot CaCO_3$).

When a gaseous reductant is used, the product has a fairly low sulphur content — up to 0.003 % — because part of the sulphur is removed during reduction as $H_2S$ and CaS, and the sulphur level in the reducing atmosphere is low [10]. With the HYL process, desulphurization of the iron-bearing mineral is about 86 %, and with Purofer it is about 69 %.

### *Impurities of certain metals*

Direct-reduced iron (DRI) from the Dashkesan concentrate usually contains small amounts of Cr, Ni, Cu, Pb and other metals, because the ore feed is low in these elements. The relatively low concentration of such impurities in the Dashkesan iron ore concentrate, together with their partial removal during oxidizing treatment, reduction, and pellet smelting, creates conditions for producing steel with negligible contents of Pb, Sb, Zn and some other non-ferrous metals. This level of cleanliness cannot be achieved if the ore is heavily contaminated with these elements.

It has been determined that Zn is removed during metallization (up to 93 % of its initial concentration) and during smelting, i.e., under processing conditions. No Zn removal was observed during oxidative roasting. During roasting, the removal and reduction of Pb are not very significant; most of it evaporates during smelting. At low Sn concentrations in the concentrates, its removal is relatively small. The same applies to Sb: at a concentrate content of 0.0039%, it dissolves completely in the metal [11].

These laboratory results show that steel produced from a direct-reduction charge depends on the quality of the iron-ore feed and can dissolve impurities of certain metals at the level of 0.0001–0.0011 % each. It may be noted that in steel made in electric steelmaking furnaces using metallized pellets (MP), the contents of Cr, Ni, and Cu are each below 0.0109 %, and Pb, Sn, As, Zn, and Sb are each below 0.0009 %.

Nitrogen and Hydrogen. Because nitrogen has a low tendency to be reduced and a low partial pressure in reducing gases, its low content in the iron-ore feed results in a low nitrogen content in the metallized material (MM) reduced by gas — about 0.0029 %. The hydrogen content in the reduced product can reach 145 $cm^3$/100 g; this figure also includes hydrogen adsorbed on surface moisture. However, the hydrogen content in steel produced using pellets is no higher than in heats made from scrap charges [11].

### *Physical properties of direct-reduced iron from Dashkesan ore*

The degree of iron reduction was calculated by the formula: $\alpha = (m_o - m_t)/(m_o - m_f) \cdot 100\,\%$, where $m_0$ is the initial mass of the sample (iron oxide), $m_t$ is the sample mass at time t, and mf is the mass of fully reduced iron. The reduction rate was determined from the change in sample mass over time according to $\tau = d\alpha/dt$, where $\tau$ is the reduction rate (%/min or mol/($cm^2$)), $\alpha$ is the degree of reduction, and t is time. Bulk density was determined according to GOST 15139-69 / ISO 3923-1 (free-fall method): the material is poured into a graduated container from a specified height without compaction; bulk density is calculated as $\rho = m/v$, where m is the material mass and v is the container volume. Apparent density was determined according to GOST 18898-73 / ISO 3923-2 (weighing in air and in a liquid). Pellet compressive strength was measured per GOST8269.0 / ISO 4700, and abrasion per ISO 3271. Thermal conductivity was studied by the steady heat-flow method according to GOST 30256 / ISO 8302, and the angle of repose according to GOST 25607-94 / ASTM C1444. To obtain pellets, disk drums were used to mix the concentrate with water and bentonite. Then, using a disk pelletizer, spherical pellets were formed. Characteristics of the disk pelletizer: disk diameter — 5–7 m; tilt angle — 40–55 °; rotation speed — 5–15 rpm; productivity — 20–150 t/h. The pellets were then dried and fired at 1200–1350 °C in a converted natural-gas atmosphere. Dryers and kilns: rotary dryer for removing moisture, kiln: length — 30 m, diameter — 3 m. The average fired-pellet diameter was 9–16 mm. Steel scrap and metallized pellets (MP) mainly differ in the following physical properties: piece size, apparent density, and specific surface area (**Table 3**). Differences in thermal conductivity and strength are derivative of these properties. For direct-reduced iron (DRI), the oxidation rate at normal and elevated temperatures is important. This indicator is a purely physical property, but it largely depends on thermal conductivity and strength [12].

### *Piece size*

The size of metallized pellets (MP) or concentrate used in steelmaking is usually 3–20 mm. The lower limit is set to reduce dust carryover in continuous furnaces and to suppress oxidation during melting of the charge.

The maximum piece size is determined by how the charge is fed into the furnace and by the allowable lump size of the primary feed for the reduction units.

When metallized pellets (MP) are used, the 8–15 mm fraction typically accounts for 86–93 %. Ore and pellets usually tend to break down during reduction, so the share of fine fractions (2.5–7.5 mm) can reach up to 35 %, although this is not always the case.

### *Bulk density and apparent density*

The bulk density of pellets varies within a relatively narrow range (see Table 3) and is higher than the bulk density of high-quality obsolete scrap, at 1.2–1.5 t/m³. Therefore, bunker and bin capacity is used more efficiently for pellets than for scrap. Among metallized materials (MM), briquettes have the highest bulk density. The apparent density of DRI (the ratio of a particle's mass to its volume bounded by the external surface) is determined by the true (pycnometric) density of iron and its porosity, and ranges from 6.7 to 7.43 g/cm³ (**Fig. 1**).

The high porosity of metallized materials (MM) (48–68 %) is governed by the porosity of the original iron-ore feed (in pellets it can reach up to 35 %) and by the shrinkage in oxide volume that occurs during reduction. Apparent density affects the melting of metallized pellets (MP) during continuous charging into the liquid bath. Particles that are denser than the liquid slag (2.8–3.3 g/cm³) melt more intensively than lower-density particles, because the charge sinks to the slag–metal interface, where heat transfer is higher than in the slag [13].

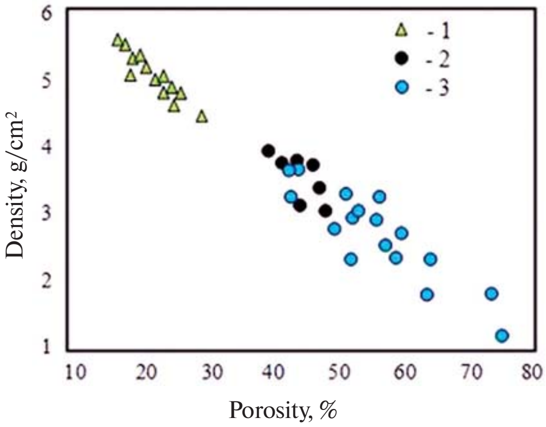

**Fig. 1. Relationship between apparent density and porosity of metallized materials (MM):** 1 – briquettes; 2 – ore; 3 – pellets

### *Surface*

DRI has a very large specific surface area, which includes the external surface of the pieces and the internal surface of open pores (the latter exceeds the former by several orders of magnitude). The specific surface area of metallized materials (MM) is 0.2–1.1 m²/g, and in some cases reaches 3.1 m²/g. For steel scrap, this value is 1.6–302 m²/t. This has a significant effect on the oxidation rate of sponge iron and scrap, which differ markedly [14]. The high specific surface area of direct-reduced iron can be explained by its high porosity and the relatively small pore size formed as the crystal lattice changes during the transformation of oxides into metallic iron. Micropores are mainly 0.1–6 μm in size, with more than 90 % of the pore volume accounted for by pores larger than 1 μm.

**Table 3. Physical properties of direct reduced iron and steel scrap**

| Material | Size of pieces, mm | Bulk density, t/m³ | Apparent density, g/cm³ | Total porosity, % |
|---|---|---|---|---|
| Metallized pellets | 2.6–20.2 | 1.5–2.2 | 2.6–3.2 | 46–72 |
| Metallized ores | 2.6–20.2 | 1.7–2.2 | 3.6–3.1 | 46–52 |
| Briquettes: | | | | |
| cold briquetting | up 72 | 2.75 | 4.1 | 26–32 |
| hot briquetting | 72 | 3.25 | 5.89 | 16–22 |
| Steel scrap | 6–2540 | 0.4–2.85 | — | — |

### *Strength*

The compressive strength of metallized pellets (MP) is directly proportional to the properties of the fired pellets (strength, composition) and to the reduction temperature. For unfluxed pellets, the strength is 490–1470 N/pellet. This strength level limits the formation of fines and allows for the transport, storage, and charging of pellets into steelmaking units.

### *Thermal conductivity*

For certain pellets and pieces of DRI, the thermal conductivity coefficient is $\lambda^{pel}$ = 2.3–9.3 W/(m·K); for a packed layer it is $\lambda^{pel}_{sin}$ = 0.35–1.05 W/(m·K). The thermal conductivity of solid iron is 29–70 W/(m·K), while that of a lightweight charge (sheet, wire, turnings) is 0.87–2.3 W/(m·K), i.e., about the same as a DRI charge. Combined with the high specific surface area and chemical activity, the low thermal conductivity of reduced iron leads to an increased tendency to oxidize. Depending on the reduction method and temperature, the onset temperature of intensive oxidation is about 170–300 °C. At these temperatures, the heat released by oxidation exceeds the rate at which it can be removed by thermal conduction [15].

### *Other properties*

The angle of repose of pellets is about 34–40°, and it is somewhat higher for finer particles. DRI with a metallization level above 80 % and gangue content below 12 % has sufficient electrical conductivity to ignite an arc in an electric furnace without special measures. Direct-reduced pellets are magnetic; when an electromagnet is used for loading metallized pellets, the handling rate is quite normal—comparable to loading high-quality steel scrap.

### *Secondary oxidation of metallized feed and ways to prevent it*

Exposure to an oxidizing gas containing oxygen and sulphur can lead to secondary oxidation of DRI. This gas may also contain halogens; in the absence of moisture, their effect is different. If pellets leave the reduction unit at an elevated temperature, this type of oxidation often occurs. Therefore, improper cooling of sponge iron permits secondary oxidation. In the cold state, DRI is not in equilibrium with the surrounding atmosphere; consequently, the most common and hazardous forms of oxidation during subsequent storage and transportation are chemical and electrochemical oxidation, especially in the presence of moisture. In such cases, electrochemical processes intensify on the DRI surface, with the clean metal acting as the anode and its oxides as the cathode. Significant amounts of ferrous and ferric hydroxides, as well as oxides, form as a result of these processes. The rate and nature of these processes depend on atmospheric temperature and humidity, and on the presence of salts, sulphur compounds, etc. [15].

Studying the oxidation of DRI during storage in an unheated building and in the open air is of practical interest. During storage, the metallization degree fell over 76 days from 98.5 % to 93.9 %, and over the next 170 days to 89.9 %. When stored outdoors for 150 days in winter, the metallization degree decreased by up to 75 %; with further storage for 162 days in the spring–summer period, there was a sharp drop from 90.79 % to 58.3 %. These results show that moisture plays a major role in the oxidation of metallized feed. In the absence of moisture, oxidation does not develop significantly.

In the presence of moisture, iron oxidation proceeds with the release of an excessively large amount of heat. In large volumes of material this heat is not dissipated; as a result, the temperature of the DRI rises, which in turn accelerates the oxidation process.

We conducted an additional study on oxidation processes in large volumes of DRI. Metallized iron ore produced in a rotary kiln was placed into two lidded 15-ton bunkers. In one bunker, it was sprayed with slightly acidic water to simulate rain during loading. In this case, the temperature rose to 45–55 °C, and the metallization degree decreased from 94.5 % to 89.9 %. After 180 h, the temperature returned to its previous level [16].

The study of pyrophoricity (spontaneous ignition in air at room temperature) of metallized feedstock shows that it depends on several factors, chief among them the reduction temperature. The pyrophoricity threshold (by reduction temperature) differs for various substances. For example, for hematite reduced with hydrogen it is about 580–555 °C, and for magnetite about 515–445 °C. Metallized feedstock produced at reduction temperatures above these values is not pyrophoric.

Our studies indicate that metallized feedstock produced at high reduction temperatures, when stored and transported for long periods in the absence of moisture, practically does not oxidize. Short-term storage in a humid environment, followed by transport over moderate distances, does not pose a risk of significant re-oxidation. However, if loading and unloading are carried out in rainy weather and the DRI is then transported or stored for a long time, there is a danger of a substantial increase in re-oxidation in stockpiles, accompanied by self-heating.

Methods to protect DRI from re-oxidation for safe (non-pyrophoric) transport can be classified as follows: treatment in a less oxidizing atmosphere; compaction; and treatment with water or other liquids and solutions. As an example, we present results from passivating pellets with a metallization degree of 93–96 % (from Dashkesan concentrate) in a gas atmosphere containing various amounts of oxygen. In the experiments, the oxygen concentration in the passivating gas was varied from 2.5 to 34 %, the temperature from 265 to 855 °C, and the treatment time from 15 to 135 minutes. The tests show that at processing temperatures not exceeding 265 °C, oxidation begins only in the surface layers of the pellet, creating an oxide film 0.08–0.20 mm thick. No oxidation of the core is observed; however, as temperature increases, oxidation proceeds through the entire pellet, and the iron oxides do not form a continuous protective film on the surface. A similar pattern was observed when treating pellets with steam. During 3.5 months of storage of pellets treated in a gas atmosphere containing about 2.6 % oxygen, at temperatures not exceeding 250 °C, no secondary re-oxidation was observed (with a 1.6–2.6 % loss in metallization) [16].

Metallized materials (MM) can be passivated in special containers equipped with devices that provide for the supply and removal of an oxidizing gas, such as air. The gas is introduced at set intervals, after which the container is hermetically sealed and left in this state until the oxygen has reacted with the pellets.

### *Compaction*

Hot briquetting (HB) is one of the most effective methods for reducing the reactivity of DRI with moisture and oxygen. DRI produced by the Purofer process is discharged from the furnace while hot and can be partially or fully hot-briquetted immediately (**Fig. 2**). During compaction, DRI is transferred from the container to a receiving hopper for conveying, and from the hopper it is fed by a screw feeder into a briquetting press. The press capacity is 25 t/h; the 914-mm rolls apply a force of 3.6 MN. The briquettes leaving the press are joined by webs into a continuous strip, which goes to a separator where the briquettes are separated from each other. The briquettes are then fed onto a vibrating conveyor and cooled with water to 80–120 °C. Briquettes of 950 × 50 × 20 mm have a density of up to 5.9 g/cm$^3$.

Ore fines are subsequently reduced with hydrogen. They are also subjected to hot compaction. Briquettes measuring 95 × 65 × 30 mm, weighing 555–1050 g, with an apparent density of 5.9 g/cm$^3$, a bulk density of 3.4 t/m$^3$, and a relative density of 19–23 % are produced on a two-roll press. Storage of these briquettes in an open yard for about three months does not lead to a significant loss of metallization. The metallization level in the surface layer of the stockpile decreased by 5.5–6.5 % compared to the initial value (94 %); in a 0.6 mm layer it decreased by 1.1–3.7 %; below this layer, the metallization level practically did not change [17].

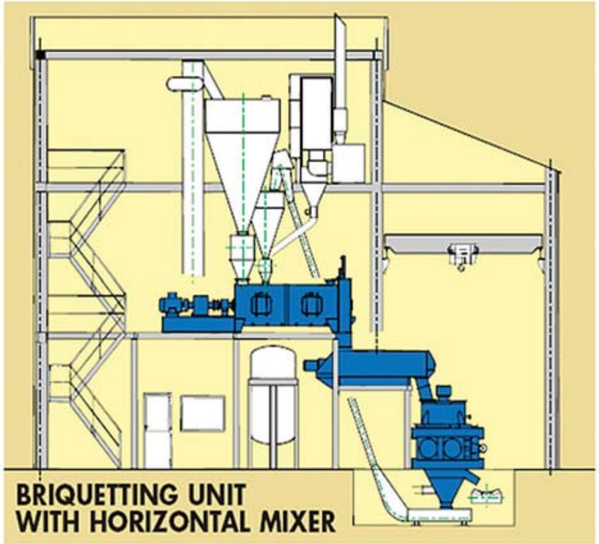

**Fig. 2. Installation for compacting liquefied gas using the Purofer method**

### *Treatment with aqueous solutions, liquids, and substances*

We carried out experiments to assess the benefits of using various protective coatings to prevent DRI oxidation. Many coating options were studied (oils, alkalis, cements, various synthetic coatings, etc.). Corrosion-resistance tests were performed in a chamber maintained at 60 ± 2 °C, into which a gas mixture of water vapor, $SO_2$, and $CO_2$ was alternately introduced. The results (after 8 cycles) for coatings applied to DRI from Dashkesan concentrate, reduced with hydrogen at different temperatures, are shown in **Table 4**. The table indicates that various polymers yielded very good results. Nevertheless, their use is limited, since sulphur and halogens are not permitted in coatings—they can adversely affect steel quality and also increase costs.

**Table 4. Protective properties of polymer coatings**

| Coating | Metallization level | | Coating technology |
|---|---|---|---|
| | Initial | final | |
| Epoxy resin | 95 | 94,5 | Immersion |
| Polyvinyl chloride | 95 | 91 | «» |
| Resol | 95 | 90 | «» |
| Styrene | 95 | 85 | «» |
| Phenolic resin | 95 | 91 | Surface shell |
| Polyurethane foam | 90 | 83–88 | «» |
| Material without protection | 95 | 61 | «» |

The consumption of such coatings—phenolic resin, for example—is 2.2–3.2 kg per 1 ton of DRI, which, at current global prices for these resins, only slightly increases the cost per ton of DRI. When cheaper acetaldehyde and phenol are used instead, the DRI cost rises. Applying layers of cement, alkali, or collodion does not yield positive results. Oils, in some cases, provide a good effect, but somewhat inferior to plastic (polymer) coatings.

## Discussion of the results of using DRI from Dashkesan ore in electric steelmaking

The basis of the sponge iron (DRI) is Fe with a C content of 0.3–0.6 % to 1.9 %, which also contains some amount of unreduced Fe oxides (2.5–11.5%) and gangue (mainly $SiO_2$ and $Al_2O_3$), the amount of this gangue may not exceed 2.5–6.5 % of the GF mass. Low content of S, P, Cu, Ni, 12 Cr and other impurities is a distinctive feature of this raw material. Impurities of Pb, Sn, Bi, Zn, As, Sb are usually contained in steel scrap. This smelting process simplifies the technology and results in the production of high-quality steel (the total concentration of impurities in steel is reduced by 3–10 times compared to smelting steel scrap). When the MP content in the charge is no more than 20–25 % of its mass, the electric smelting technology does not differ significantly from the conventional one. However, processing the charge, consisting mainly of MP, requires the use of an innovative approach. The following are the features of the innovative approach: after the formation of a bath of liquid metal in the furnace, continuous loading of MP is necessary proportional to the rate of electric power supplied to the furnace; the periods of

**Table 5. Comparison of technical and economic indicators for smelting 09G2S steel**

| Indicator | 100% scrap | Scrap + DRI (50/50) |
|---|---|---|
| Furnace capacity | 50 t | 50 t |
| Charge composition | 50 t scrap | 25 t scrap + 25 t DRI |
| Energy consumption | 400–450 kWt·h/t | 550–650 kWt·h/t |
| Heat time | ~45–60 min | ~60–75 min |
| Liquid steel yield | 98–99 % | 95–97 % |
| Iron (Fe) loss in slag | 0.8–1.2 % | 1.5–2.5 % |
| Impurities in steel (S, P) | May be higher | Lower (cleaner metal) |
| Electrode consumption | 1.5–1.8 kg/t | 2.0–2.5 kg/t |
| Off-gas generation (CO, $H_2$, dust) | Medium | Higher (more dust and gas) |
| Charge cost (approx.) | Lower | Higher (DRI is costlier than scrap) |
| Control of chemical composition | Limited | Better controlled |
| Steel quality (cleanliness) | Depends on scrap | Higher (lower P, S, Cu, etc.) |
| Dependence on scrap imports | High | Reduced |

melting and oxidation (decarburization) must be combined; due to the low content of S and P in the charge, the process of steel smelting is simplified. To ensure the boiling of the bath and melting of the charge when loading the MP, the level of metallization of the pellets must be within certain limits; the rational amount of pellets in the charge must be 55–65 % of its mass, since with a higher amount of MP, the duration of melting and smelting of the charge increases [17].

At the amount of 45–55 % of the charge mass, the melting was started with loading of steel scrap and loaded into the furnace in one portion. The charge was melted in the “Baku Steel Company” in a 50-ton electric arc furnace. After loading of the charge, voltage is applied and at the end of the scrap melting, pellets are continuously loaded into the metal liquid bath; the pellets are loaded into the electric zone of the furnace using an automated system through an opening located in the furnace roof. The pellet loading rate must be matched to the electric power supplied to the furnace. In this case, the bath temperature must be 40–50 °C higher than the melting temperature of the charge, since at a lower level of superheating the melting process is delayed.

The periods of loading and melting of the charge are combined with oxidation periods. At the same time, the combination of these periods should ensure continuous oxidation of carbon in the metal. In order to carry out boiling, the level of metallization of pellets should be at the level of 91–96 % (if the content of the remaining $O_2$ is less than this level, the boiling of the bath is insufficient). In addition, with an insufficient level of metallization, due to the endothermic reaction of reduction of iron oxides, the energy consumption increases significantly. The MR should contain a certain amount of carbon to ensure boiling of the bath, however, if the carbon content is insufficient, a carburizer must be blown into the bath to ensure boiling of the bath.

To intensify the melting process of the charge, lime must be loaded into the furnace to slag the acidic gangue ($SiO_2$ and $Al_2O_3$) of the pellets. The degree of slag basicity in view of the low concentration of S and P in the pellets may be lower than in melting on a charge of steel scrap and be 1.6–2.1. At the end of the melting process, it is necessary to ensure the required concentration of C in the smelted steel: in the case of a shortage of C, carburizers were blown into the bath, and in the case of excess C, the bath was oxidized by short-term blowing of $O_2$. To carry out the final part of the melting, various options are carried out after the end of the process. A variation of this is heating the metal to the required level, and then pouring it into a ladle, in which the steel is processed outside the furnace; another variation is carrying out a short-term finishing of the steel in the furnace, during which heating, deoxidation and alloying are carried out.

Using DRI, a low-alloy steel grade 06G2S with the following content (% (mass.): C ≤ 0.12; Si = 0.5–0.8; Mn = 1.3–1.7; Cr ≤ 0.30; Ni ≤ 0.30; Cu ≤ 0.30, intended for oilfield applications, was produced. The steel was melted in a 50-ton electric arc furnace from a 1:1 charge of scrap and metallized pellets (MP).

A comparison of the technical-economic indicators for heats on steel scrap versus heats using DRI is presented in **Table 5**.

As the table shows, 100 % scrap is more advantageous in terms of energy consumption and heat time, but the quality depends on the contamination level of the feedstock. Using scrap+DRI produces higher quality steel.

## Conclusions

1. It has been established that the iron ore from the Dashkesan deposit consists mainly of $Fe_3O_4$ (magnetite) and silicate-bearing gangue. The magnetite content in the ore is 55–61 %, and the gangue, in addition to silicon oxide, contains oxides of Al, Ti, Mn, Mg and Ca, as well as a small amount of sulphur.

2. An analysis of existing technologies for producing sponge iron (DRI) from iron ore showed that, under the conditions of the Republic of Azerbaijan, the most suitable reduction process is the use of steam-reformed natural gas, which is available in sufficient quantities.

3. The high porosity of DRI from Dashkesan ore (45–70 %) is due to the porosity of the original iron-ore materials and the shrinkage of oxide volume during reduction. Apparent density influences the melting of metallized pellets during continuous charging into the liquid bath: denser metal particles melt faster than less dense ones.

4. Under conditions where iron oxidizes in the presence of moisture, a substantial amount of heat is released. In large charge masses this heat is retained; as a result, the

temperature of the DRI rises and the oxidation processes are activated. To protect DRI from secondary oxidation, the following measures are recommended: treatment in a mildly oxidizing (controlled) atmosphere; briquetting; and treatment with aqueous solutions and other liquids and substances.

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## REFERENCES

1. Zhang T., Lei C., Zhu Q. Reduction of fine iron ore via a two-step fluidized bed direct reduction process. *Powder Technol.* 2014. 254. pp. 1–11. DOI: 10.1016/j.powtec.2014.01.004.
2. Yi Ly., Huang Zc., Heng P., Jiang T. Action rules of $H_2$ and CO in gas-based direct reduction of iron ore pellets/ *J. Cent. South Univ.* 2012. 19, pp. 2291–2296. DOI: 10.1007/s11771-012-1274-0.
3. Sen R., Dehiya S., Pandel U., Banerjeee M. K. Utilization of low grade coal for direct reduction of mill scale to obtain sponge iron: Effect of reduction time and particle size. *Procedia Earth Planet.* 2015. Sci. 11. pp. 8–14. DOI: 10.1016/j.proeps.2015.06.003.
4. Gordon Ya. M., Kumar S., Freislich M., Yaroshenko Yu. G. Modern technologies of iron and steel production and possible ways of their development. *Izvestiya vysshikh uchebnykh zavedeniy. Chernaya metallurgiya*. 2015. Vol. 58. No. 9. pp. 630–637.
5. Cheng P., Wang B., Wang X., Xiao W. Effects of Recycled Sponge Iron on Phosphorus Recovery from Polluted Water. *Minerals.* 2022. 12 (6). p. 730. DOI: 10.3390/min12060730.
6. Anameric B., Kawatra S. K. Properties and features of direct reduced iron. *Miner. Process. Extr. Metall.* Rev. 2007. 28 (1). pp. 59–116. DOI: 10.1080/08827500600835576.
7. Chen H., Zheng Z., Chen Z., Bi X. T. Reduction of hematite ($Fe_2O_3$) to metallic iron (Fe) by CO in a micro fluidized bed reaction analyzer: A multistep kinetics study. *Powder Technol.* 2017. 316. pp. 410–420. DOI: 10.1016/j.powtec.2017.02.067.
8. Dey N. R., Prasad A. K., Singh S. K. Energy survey of the coal based sponge iron industry. *Case Stud. Therm. Eng.* 2015. 6, pp.1–15. DOI: 10.1016/j.csite.2015.04.001.
9. Dilmaç N., Yörük S., Gülaboğlu S. M. Determination of reduction degree of direct reduced iron via FT-IR spectroscopy. *Vib. Spectrosc.* 2012. 61. pp. 25–29. DOI: 10.1016/j.vibspec.2012.03.008.
10. El-Geassy A. A. Gaseous reduction of $Fe_2O_3$ compacts at 600 to 1050 °C. *J. Mater. Sci.* 1986. 21 (11). pp. 3889–3900. DOI: 10.1016/0168-7336(87)80032-3.
11. Guo D., Zhu L., Guo S., Cui B., Luo S., Laghari M., Chen Z., Ma C., Zhou Y., Chen J., Xiao B., Hu M., Luo S. Direct reduction of oxidized iron ore pellets using biomass syngas as the reducer. *Fuel Processing Technology*. 2016. 148. pp. 276–281. DOI: 10.1016/j.fuproc.2016.03.009.
12. Lee Y. S., Ri D. W., Yi S. H., Sohn I. Relationship between the reduction degree and strength of DRI pellets produced from iron and carbon bearing wastes using an RHF simulator. *ISIJ Int.* 2012. 52 (8), pp. 1454–1462. DOI: 10.2355/isijinternational.52.1454.
13. Leshchenko I. P., Tereshchenko V. T., Martynov O. V., Trakhimovich V. I., Borzenkov D. V. The use of sponge iron in steel smelting. *Metallurgist.* 1973. 17 (7). pp. 491–494. DOI: 10.1007/bf01094155.
14. Liu G., Strezov V., Lucas J. A., Wibberley K. J. Thermal investigations of direct iron ore reduction with coal. *Thermochim. Acta.* 2004. 410. pp. 133–140. DOI: 10.1016/s0040-6031(03)00398-8.
15. Wang Z., Chu M., Liu Z., Chen S., Xue X. Effects of temperature and atmosphere on pellets reduction swelling index. *J. Iron Steel Res. Int.* 2012. 19 (10). pp. 7–12. DOI: 10.1016/s1006-706x(12)60144-7.
16. Lin H. Y., Chen Y. W., Li C. The mechanism of reduction of iron oxide by hydrogen. *Thermochimica Acta*. 2003. 400 (1–2). pp. 61–67. DOI: 10.1016/s0040-6031(02)00478-1.
17. Mombelli D., Cecca C. D., Mapelli C., Barella S., Bondi E. Experimental analysis on the use of BF-sludge for the reduction of BOF-powders to direct reduced iron (DRI) production. *Process Saf. Environ. Prot.* 2016. 102. pp. 410–420. DOI: 10.1016/j.psep.2016.04.017.