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THE STICKING PROBLEM DURING DIRECT REDUCTION OF FINE IRON ORE IN THE FLUIDIZED BED

PROBLEM 'STIKINGA' TOKOM REDUKCIJE RUDE GVOŽĐA, MALIH DIMENZIJA ČESTICA U FLUIDIZOVANOM SLOJU

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ABSTRACT

In this review paper described are possible chemical reactions and their thermodynamic analysis during direct reduction. The sticking mechanism during direct reduction in the fluidized bed was analysed, and the reasons for the sticking appearance explained. The most important parameters on the sticking were analysed. The ways for prevention and observation were considered. The plan for experimental investigations was proposed. The investigations could be performed in fluidized bed reactor. Coal will be used as inert material. Separately, the influence volatile content in the coal on the reduction process and sticking appearance, will be analysed. As results of these investigations would be some improvements of the method direct reduction of iron ore in the fluidized bed.

Key words: direct reduction, iron ore, fluidized bed, sticking, coal

APSTRAKT

U ovom preglednom radu su prikazane moguće hemijske reakcije tokom direktne redukcije rude gvožđa. Urađena je njihova termodinamicka analiza. Mehanizam nastanka 'stikinga' tokom direktne redukcije u fluidizovanom sloju je analiziran. Opisani su razlozi nastanka 'stickinga'. Analizirani su najuticajniji parametri koji dovede do pojave 'stikinga'. Mogući načini za prevenciju i detekciju stikinga su opisani. Napravljen je plan za eksperimentalna istraživanja. Eksperimenti bi mogli biti urađeni u fluidzovanom sloju. Kao inertni materijal, koristio bi se ugalj. Posebno bi bio analiziran uticaj početnog sadržaja volatila u uglju na proces redukcije i pojavu stikinga. Rezultati istraživanja, bili bi značajani za dalji razvoj tehnologije dorektne redukcije rude gvoždja u fluidizovanom sloju.

Ključne reči: direktna redukcija, ruda gvoždja, fluidizovani sloj, stiking, ugalj

1. INTRODUCTION

New processes for iron making were developed in the last few decades. One of the new processes for iron making is direct reduction (DR). Direct reduction is a procedure which reduces iron ore by gas or solids (e.g. coal) to solid sponge iron that comprises the gangue.

The iron ore usually consists of hematite (Fe_2O_3) and / or magnetite (Fe_3O_4) and iron content ranges from 50% to 70%. Transformation of the iron ore into iron in the iron making process is performed through the following steps: from hematite (Fe_2O_3) it transforms to magnetite (Fe_3O_4), and later to wustite (FeO) and finally to iron (Fe). Iron ore that contains lower iron content must be processed or enriched to increase its iron content. Often the ore is prepared by agglomeration and sintering before processing.

The reduction of iron ore oxides passes through the following main steps:

- mass transport of gaseous reactants to the external surface of iron ore particle,

- diffusion of the gaseous reactants through the pores of the particle to the internal surface,

- reduction of iron ore,

- diffusion of products from the pores of particles to the external surface,

- diffusion of products from the external surface.

During reduction of iron oxide volume change takes place due to change in structure, sintering of iron oxide and change in oxygen concentration in the lattice structure. Hexagonal hematite lattice transforms into cubic magnetite lattice, volume increases, the firmness of the ferrit oxide crystals weak [1-3], and numerous cracks occur (Fig. 1.1, Fig. 1.2). Very fast reduction of hematite to magnetite is followed by two phases with significant different rates of reduction. During reduction the surface structure of wustite becomes more porous (Fig. 1.3). When hematite iron ore is reduced to iron, the surface is much more porous than the wustite structure (Fig. 1.4).

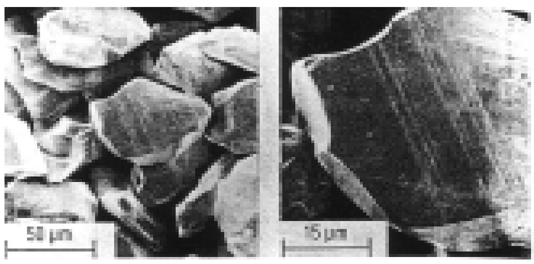


Fig. 1.1. Hematite iron ore [16]

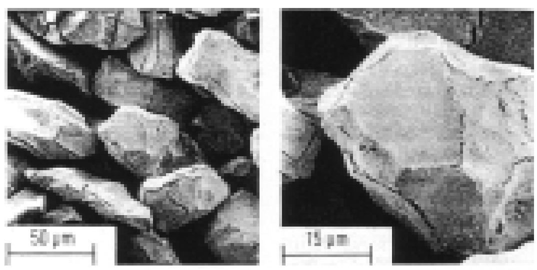


Fig. 1.2. Hematite iron ore reduced to magnetite [16]

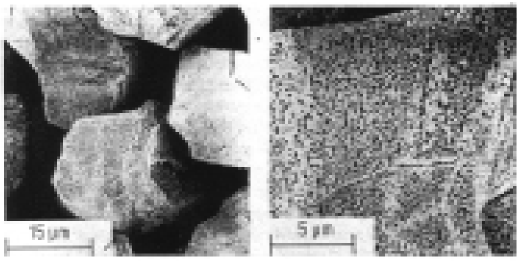


Fig. 1.3 - Hematite iron ore reduced to wustite [16]

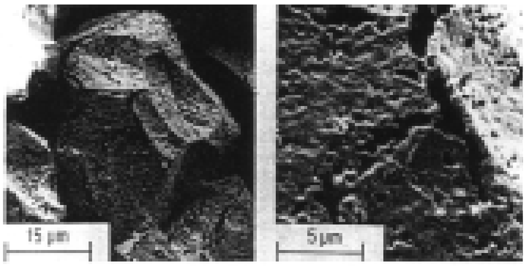


Fig. 1.4 - Hematite iron ore reduced to porous iron [16]

The fluidized bed is ideal for the reduction of iron ore because it enables conditions with high reduction velocity. The fluidized bed reduction process of iron ores is used in Circofer, Circored, Finmet, Iron Carbide processes [4, 5]. The fluidized bed processes are optimal for pre-reduction of the iron ore steps. The Circored and Circofer process use a circulating fluidized bed for prereduction up to 70% (short residence time) and a bubbling fluidzed bed reactor for final reduction (long residente time). The Circored process uses gas as only reducing agent while Circofer use gas and coal as well. Scheme of Circofer process is shown in Figure 1.5.

Fluidized bed has very intensive mixing and very high value of heat and mass transfer coefficient [6-10] and therefore, temperature distribution within the dense phase of fluidized bed is homogeneous.

The fluidized bed reduction process of iron ores has been developed as one of direct reduction process on iron making and as a pre-reduction process of ores within several smelting reduction processes as alternatives to blast furnace as well [2, 3, 10-12]. Reactors are fed with ore fines and thus no palletising is needed [10-13].

One of the main problems during reduction in fluidized bed is appearance of sticking. This unintentional agglomeration of fine ores is the reason for numerous breakdowns in fluidized bed, making it a serious problem of defluidization that appears during production of the sponge iron. The sticking among individual ore particles can make continuous operation impossible. The beds defluidize partially or completely and particles adhere to the reactor walls and lower pipes making continuous operation impossible [1-3, 12, 14-16]. Sticking could spread out over the whole fluidized bed during very short time.

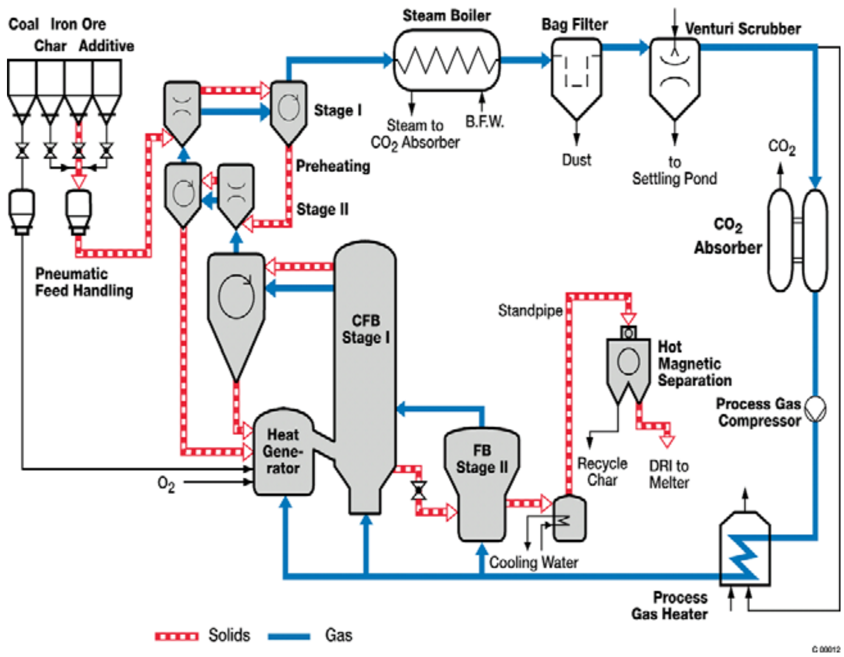


Fig.1.5. Scheme of the Circofer process.

Under certain operation conditions, it can occur as agglomeration of fine ore (sticking) and / or fine ore with wall (plating) (see [3, 12]). Also, during direct reduction with pellets due to change in volume swelling and disintegration occur (for example see [17-21])

In this paper the problem of sticking during direct reduction of fine iron ores in fluidized bed is considered.

2. THERMODYNAMICS ANALYSIS

Some of the chemical reactions that occur during direct reduction of iron ore by gases, CO and H_2 respectively were analysed.

I) Reduction with CO

- Reduction of hematite:

$$3\,Fe_2O_3+CO(g)=2\,Fe_3O_4+CO_2(g) \quad (1)$$

- Reduction of magnetite:

$$Fe_3O_4+CO(g)=3\,FeO+CO_2(g) \quad (2)$$

- Reduction of wustite:

$$FeO+CO(g)=Fe+CO_2(g) \quad (3)$$

- Reduction of magnetite to Fe bellow 570°C:

$$Fe_3O_4+4CO(g)= 3Fe+4CO_2(g) \quad (4)$$

Besides the above mentioned reactions, the next two reactions are possible:

- Boudouard reaction:

$$C+CO_2(g)=2CO(g) \quad (5)$$

$$- 2 CO(g)=C+CO_2(g) \quad (6)$$

The thermodynamic analysis was performed and the free energy and enthalpy depend on are shown in the Fig. 2.1-2.2.

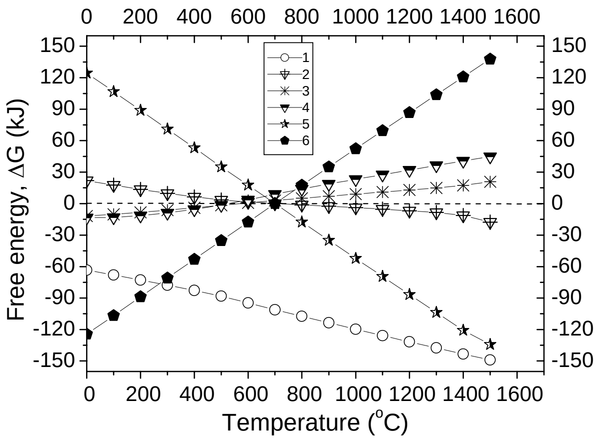


Fig.2.1. Dependence of free energy on temperature for reduction with CO

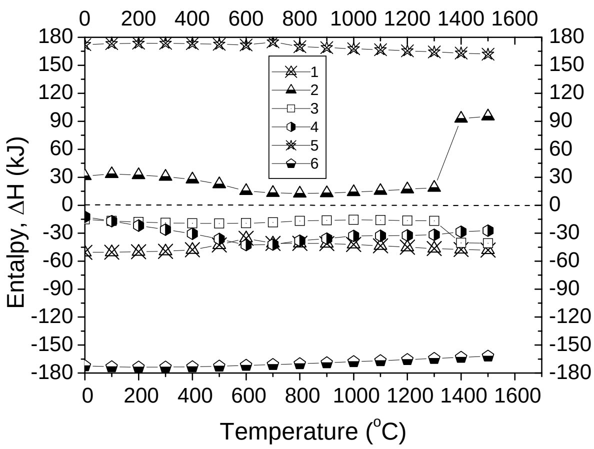


Fig.2.2. Dependence of enthalpy on temperature for reduction with CO

On the basis of results shown in Fig.2.1, it could be said that in the case of reduction with CO, the most probability has the reaction (1). The minimal chance on the basis of performed thermodynamic analysis has the reaction (3). The reaction (5) is possible at higher temperature, and reaction (6) at lower temperatures as it is written in the literature. The reaction (2) starts at temperature about 700°C.

On the basis of results presented in Fig.2.2, it could be said that reaction (6) is highly exothermic, and the reaction (5), carbon gasification, is highly endothermic and occurs at high temperatures.

II) Reduction with H_2

H_2 reduction of hematite:

$$3\,Fe_2O_3 + H_2(g) = 2\,Fe_3O_4 + H_2O\,(g). \qquad (7)$$

- H_2 reduction of magnetite:

$$Fe_3O_4 + H_2(g) = 3\,FeO + H_2O(g) \qquad (8)$$

- H_2 reduction of wustite:

$$FeO + H_2(g) = Fe + H_2O(g) \qquad (9)$$

- H_2 reduction of magnetite to Fe bellow 570°C:

$$Fe_3O_4 + 4\,H_2(g) = 3Fe + 4H_2O(g) \qquad (10)$$

The thermodynamic analysis was performed and the free energy and enthalpy are shown in the Fig. 2.3-2.4.

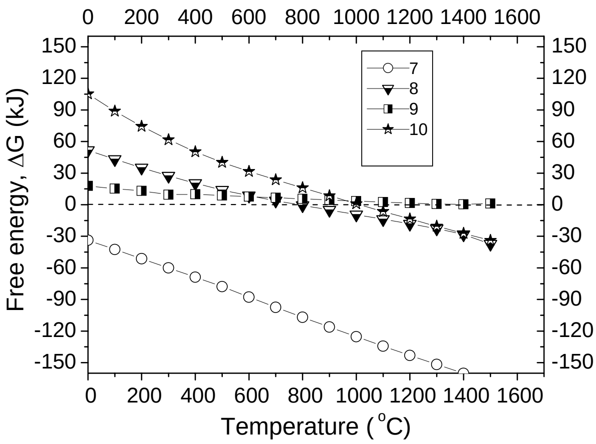


Fig.2.3. Dependence of free energy on temperature for reduction with H_2.

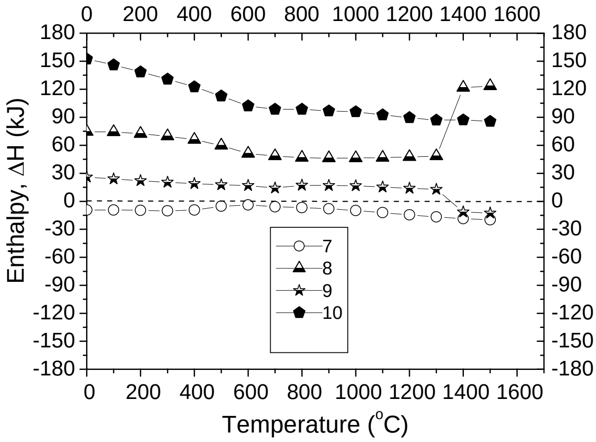


Fig.2.4. Dependence of enthalpy on temperature for reduction with H2

On the basis of results shown in Fig. 2.3, it could be said that in the case of reduction with H_2, the most probability has the reaction (7). The minimal chance on the basis of performed thermodynamic analysis has the reaction I. The reaction I is possible at higher temperature,

On the basis of results presented in Fig. 2.4, it could be said that reactions (8), (9) and (10) are endothermic, and the reaction (7) is exothermic. The reactions with H_2 are mostly endothermic and occur at higher temperatures compared with CO.

III) Reduction with coal

The mechanism reduction iron ore by coal is shortly explained in the text below.

When heated, coal particles undergo severe devolatilization producing solid char (coke), tar and light gases, as illustrated by the following reaction:

coal→ char (coke, C) + tar + gases (e.g. $H_2(g)$, $CO(g)$, $CO_2(g)$, $N_2(g)$, $C_nH_m(g)$)

These reactions could start from about 300 to 500°C. Gaseous products of reactions initiate the first step reductions and provide carbon for gasification reactions.

Coal goes through the primary devolatilization between 420 and 460 ºC, releasing tar, followed by secondary reactions at temperatures above with the release of light gases. CH_4 is released primarily between 450 and 700 °C, whereas H_2 and CO are released at higher temperatures becoming a reductant source for ore reduction. Carbon gasification with CO_2 and H_2O occur at temperatures above 800 ºC to produce CO and H_2 for iron oxides reduction, which are represented with Boudouard reaction (5) and with reaction (11):

$$C+H_2O(g) = H_2(g)+CO(g) \qquad (11)$$

The CO_2 and H_2O source for gasification reactions is generated from the reduction of iron oxide by CO and H_2, respectively.

Comparing with conventional reduction of iron ore in a flowing reducing gas, as the major difference in the reduction by coal could be mentioned:

- presence of endothermic reactions of devolatilization of coal and gasification of carbon by CO_2 and H_2O,
- large specific area of ore and coal particles that are separated by a distance in microns,
- gases generated in chemical reactions, play an important role in convective heat and mass transfer during reduction, and for the same reduction degree, lower temperature is required etc.

3. STICKING

Sticking occurs mostly during metallization of ore, sometimes accompanied with fibrous irons, and depends strongly on the kind of iron ores [3, 11, 12]. Sticking appears in such conditions as high temperature, small particles of ore, low gas velocity etc. Sticking is one of the main problems during direct reduction of iron ores. Bridges between grains are built. Sticking can lead to genesis of the hard layer. The continuous solid bed interrupted by channels develops as a result of sticking in fluidized bed.

As it was mentioned, sticking of the fine ores is the reason for numerous breakdowns in fluidized bed. The solid bed changes into a continuos solid bed interrupted by channels and reduction rate decreases. The main part of the layer is not touched by gas and the reduction can not be finished [3, 12, 16].

Sticking could be caused by many reasons [3, 12, 16] such as:

- low melting eutectic mixture iron grains soften and stick together,
- a little gangue in the iron ore and under special conditions fibrous precipitates grow, two fibrous iron become hooked to each other and finally crystallize, etc.

On the basis of the experiments performed with CO or CO/CO_2 for reduction, three different types of sticking were recognized [3, 12]:

1) The first type of sticking appears when some ore particles precipitate by the metal iron with the fibrous shape on the grain surface. This kind of sticking is initiated by the contact of the needles that hook mechanically the grains together and appears at temperatures above 600°C. While the grains are temporally bounded the fibers are growing and sintering. Under these conditions high number of agglomerations will be built up quickly. They could make worse to fluidize and offer favourable conditions for sticking. Good

diffusion conditions and lower reduction velocity supported this kind of sticking. This type of sticking appears in the attendance of sulphur as well. Sulphur arrives in the process by reduction gas, coke or coal.

2) The second way of sticking is caused by higher quantity of fresh precipitated iron. This iron has got a high activity and due to this tendency it leads to a build-up of small surfaces. If the quantity of freshly precipitated iron is too big it leads to sticking. Between iron ore parts appears high adhesion energy and that carries out to agglomeration.

3) The third type of sticking appears at temperatures above 850°C. The reason is a liquid phase within the overheated zone. This can be stimulated by presence of gangue, because there is a build up of low melting eutectic phases (CaO-SiO_2-FeO) that stick together in an iron ore particle. This type of sticking occurs after reduction degree of 33% that occurs in the presence of wustite.

A strong sticking tendency of the ores was measured at temperatures above 810^{o}C. When temperature increases, some compounds of the iron ore start to soften and melt. It could be induced the sticking of third kind [3].

The reasons for this type of the sticking could be as well [24]: high temperatures, direct iron to iron contact, high metallization step, long contact time. With the transformation porous wustite arises to an agglomerate appearance if in the ore gangues are present, which form low melting eutectics with the wustite. The iron ore grains with the help of this partial melting can stick together [1].

During reduction of hematite ore by gaseous reduction means, three morphological types of metallic iron (precipitations) are recognized [3, 12, 16, 21]: dense, porous and fibrous (see Fig.3.1).

Dense (Fig.3.2.a) is formed at lower temperature and high reduction potential. Porous (Fig.3.2.b) and fibrous (Fig.3.2.c) are formed at higher temperatures. The precipitations are the main reason for different diffusion conditions and nucleation during the reduction. The chemical composition, especially some accompanying elements has a strong influence on the precipitation morphology of iron. Dense and fibrous are two extreme cases and hence the porous kind is intermediate stage between these two morphologies.

The best iron precipitate is the porous one because very high reduction degree can be reached (temperature above 850°C). The dense iron layer obstructs the reduction of the inner part of an iron grain. The worst iron-fibrous surface structure has the fibrous precipitate. These precipitates become hooked to each other and sticking takes place.

At lower temperatures, 600-750°C, dense iron layer is produced. If temperature increases, the surface structure becomes more porous. When the gas mixture approaches composition of the equilibrium line of Fe/FeO the fibrous iron growth increases (Fig.3.2). It was shown that in the mixture iron whiskers grow up from the surface and not from the top [16]. The fibrous morphology causes the formation of iron whiskers or iron) needles. The one examples for the appearance sticking during reduction from wustite to iron is shown in the Fig.3.

It is shown that in a mixture of $CO-CO_2$ with contents of CO near the phase boundary ferrous wustite the needle formation is distinctive in the temperature range from 700 to 900°C.

Fibrous area becomes larger by adding CaO, and smaller by adding SiO_2. Both components CaO and SiO_2 make active CaO passive and stimulate the dense precipitations.

For Circofer iron making process, high temperatures above 900°C are necessary (due to Boudouard reaction) at these temperatures. Sticking at above temperatures could be avoided by using gasful coal, because it forms char during the process which disables sticking in the luidized bed. For production char carbon ratio in the reduction zone of 30% was necessary. At mentioned temperatures porous or fibrous precipitations could be noticed.

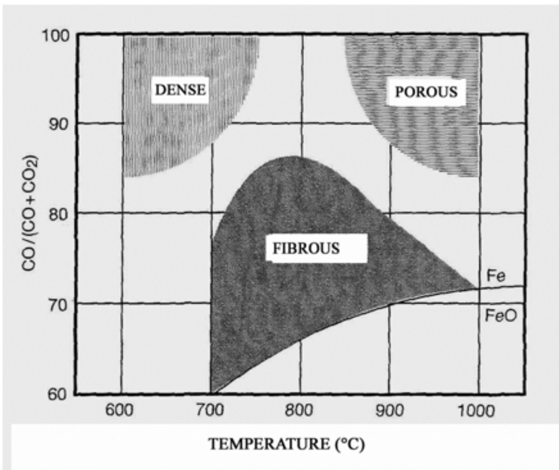
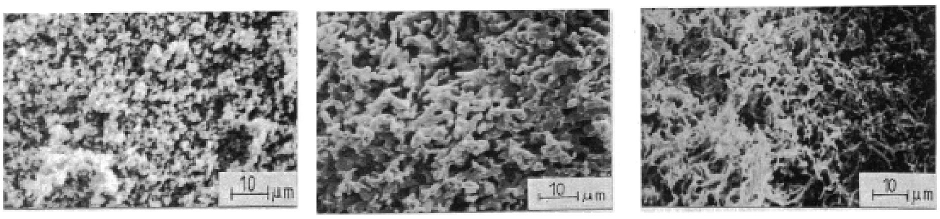
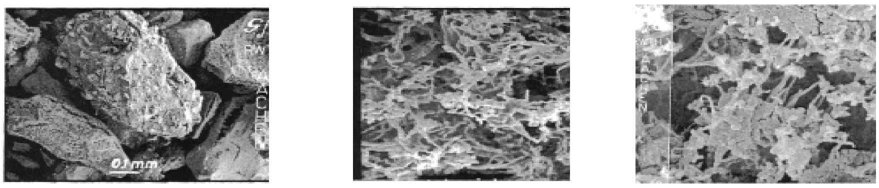


Fig. 3.1. The main regions of existence of different precipitates during reduction of iron [3].



a) Dense precipitation b) Porous precipitation, c) Fibrous precipitation
Fig. 3.2. Precipitation behaviour during reduction of iron ore [22].



a) The first whiskers at porous wustite. b) Sponge iron with intensive fibrous precipitation. c) The sticking.

Fig.3.3. The mechanism appearance sticking during reduction from wustite to porous iron [21]

4. THE IMPORTANT PARAMETERS

The important parameters that could be influenced on the sticking are considered in this paragraph.

On the basis of the investigations presented in the previous literature, the sticking process could be influenced by the next most important parameters: the temperature, the type and the size of iron ore, outside shape of grain, gas velocity, addition of inert components such as coal, addition of CaO, SiO_2, Al_2O_3, cement, the content of the gangue, number of reduction step, addition of the hydrogen in the gas mixture [1-3, 12, 16, 23, 24].

The sticking temperature and reduction degree depend on gas velocity [3, 12, 25]. If reduction gas velocity increases the sticking temperature increases (Fig. 4.1) and reduction rate decreases [26].

The sticking tendency depends strongly on the temperature. The sticking could not be observed at temperatures bellow 600°C [3, 24]. With lower reduction temperatures occurs diffusion slowly, and one homogeneous structure with dense participation formed, low reduction degree and longer reduction time could be achieved. At higher temperatures occurs higher reduction degree [1, 2, 10, 26-29]. If the temperature increases the iron ore will start to soften and to smelt. In a normal industrial plant the reduction temperature has to be below this fusion point. If the temperature rises above this point, sticking occurs and gas utilisation will decrease. This kind of sticking is not stopped by an increase in the velocity of gas reduction. The reduction degree and sticking tendency depending on the temperature are shown in Fig. 4.2. and Fig.4.3., calculated on the basis experimental results performed by Aran, [2].

The tendency for particles to stick together is directly proportional to the adhesive force and area of contact and inversely proportional their momentum [30]. The external shape of iron ore is affected on the sticking as well. Spheroid shape has minor tendency to sticking compared with angular shape [25].

The sticking tendency increases for small size of particles. It could be explained that particles have a lower kinetic energy [1, 2, 29]. Greater particles have a greater mass and thus greater momentum, and lower tendency to sticking. For the iron ore size up to 0.25mm, the particle size did not have influence [23]. The sticking appeared for ore Carajas, the particle size 60-90μm at temperature 800°C, and for the size 90-150μm at temperature 900°C [3].

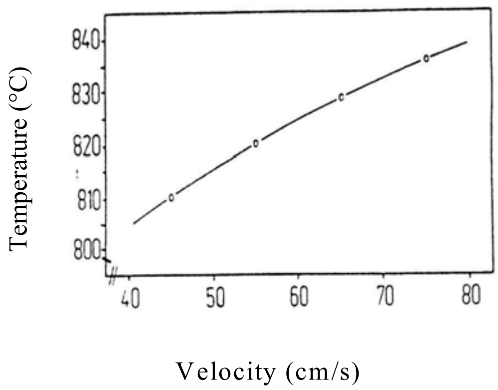


Fig.4.1 - Influence of gas velocity on the sticking temperature [16]

The reduction degree depends on reduction time as well. If reduction time increases the reduction degree increases (for example see Fig.4.3, calculated on the basis experimental results performed by Aran, [2]).

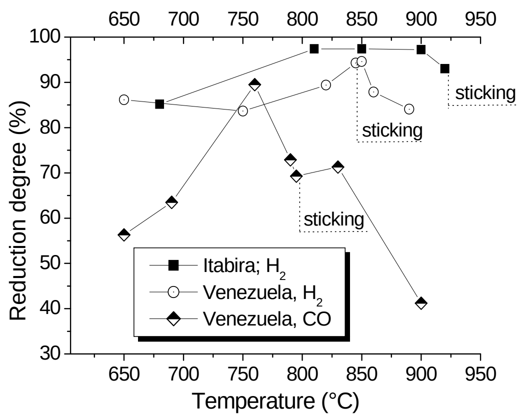


Fig. 4.2 - Reduction degree depend on temperature, iron ore and gas for reduction (calculated on the basis results, [2])

Iron formed by gaseous reduction (CO or H_2) is always porous, independently of initial structure of hematite that could be porous or dense as well. The greater pore surface area of the oxide creates the greater pore of the iron formed by reduction. Also, the pore structure obtained by CO reduction is coarser than that by H_2 reduction [28, 31]. The reason for such manner could be slower reduction rate with CO compared with H_2 [25].

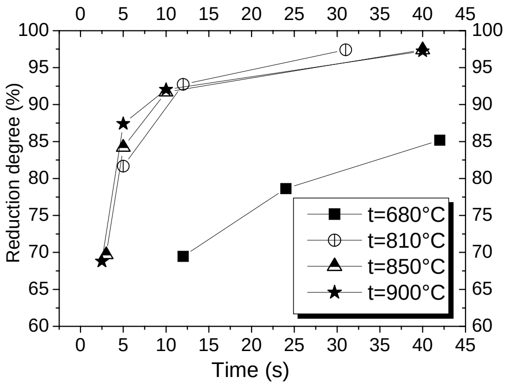


Fig. 4.3. Reduction degree depend on time and temperature (calculated on the basis results,[2])

The reduction rate was greater for H_2 reduction compared with CO reduction [2, 10, 32] (Fig.4.4). It was recorded maximum swelling for reducing with CO. Reduction with pure H_2 showed maximum contraction of 24%. Swelling at initial stages of reduction was attributed to anisotropic transformation from hexagonal structure of hematite to cubic structure magnetite. Swelling in the middle and last stages of reduction generally depends on the formation of gas bubbles at the iron / wustite interface, which could cause fracture of the iron layer and disintegration of iron grains. [32].

On the basis of the investigations attempted to determine the influence of hydrogen additions to a gas mixture of carbon monoxide and carbon dioxide, it was concluded that gas utilization and reduction degree increase slightly and the temperature decreases [16]. The result of small additions of hydrogen is that the fibrous iron growth decreases and stops if the hydrogen addition increases greatly.

Ideally, hydrogen reduction would imply low CO_2 emissions. Steel industry contributes around 6% to the total anthropogenic emissions of CO_2. To apply hydrogen as reductant could be an alternative. The resulting off-gas is H_2O which could be separated easily by condensation [13].

Experimental measurements have proven that for ores with higher amount of gangue the sticking tendency is smaller. A possible explanation is that in ores with high portion of gangue the number of the iron atoms at the surface of freshly reduced iron ore particle is lower than in ores with little gangue [2]. On the other side, in ores with higher portion of gangue, melting temperature decreases what could induce sticking of the third kind.

In contrast to the untreated sample the samples with additions of inert material such are MgO, CaO and $A1_2O_3$, cement showed a stronger tendency towards the reduction of grain and the sticking can be avoided or decreased at least [3, 12, 14, 25]. It was not noticed sticking behaviour at temperature about 900°C, with Carajas in the case of additions: cement, $A1_2O_3$, MgO, CaO [3]. Additions SiO_2 showed a weaker tendency towards reduction of grain. During investigations with ore Carajas by additions SiO_2 appeared the agglomeration, but with high reduction degree [3]. The sticking tends to be preferred at conditions, as is sulphur additions [3, 25]. The coating could be useful to prevent sticking and it depends on strongly of type iron ore. For example with ore Carajas can be avoided sticking by coating with cement, MgO and Al_2O_3. On the other side, with ore Sishen could be avoided sticking only by addition cement [3].

At temperatures above 900°C the sticking of third kind occurs and it could be avoided by addition of inert component such as coal or coke particles. It could be a good alternative for preventing sticking [2, 16, 23, 26]. Carbon could deactivate freshly reduced iron at surface and could be used as a source of energy. This type of sticking could be avoided, if 2-3 batch quantity of inert components is added. When using gas-rich coals, soot formation decreases the sticking tendency. Also, sticking can be avoided by using carbon of over 30 % in the reduction zone [23]. The coal and iron ore mixture was prepared in a furnace at various temperatures by heating rate of 10ºC/min, under Ar atmosphere, in the 20:80 mass ratio [35]. It was observed that reduction of hematite to magnetite was completed by CO and H_2 as the product of coal devolatilization (between 500-670°C). At higher temperatures, reduction was performed by CO and H_2 as a product of char gasification.

The addition of inert components helps to prevent sticking, but on the other hand there are problems bound with introduction of the inert components into the process, as: high processing cost, high portion of inert material, problem of separation between sponge iron and inert material [12].

A mixture of a sticking ore with a non sticking one, in given experimental conditions, could prevent the sticking and help achieving a longer process duration and higher reduction degree [1, 2]. Mixing Venezuela iron ore size 0,3-1mm (sticking alone at 860°C, after 6 min.) with Itabira iron ore, using H_2 as reducing gas, after 60 min. reduction degree more than 90% at 900°C was measured (Fig. 4.5).

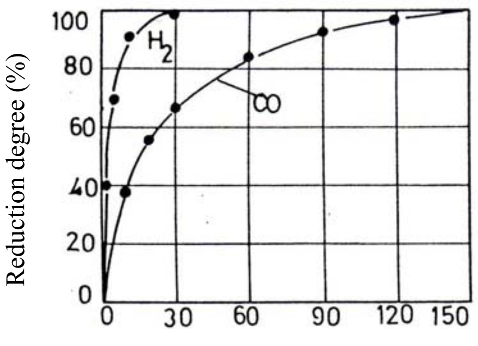


Fig.4.4. The comparison of the reduction rate for H_2 and CO [2].

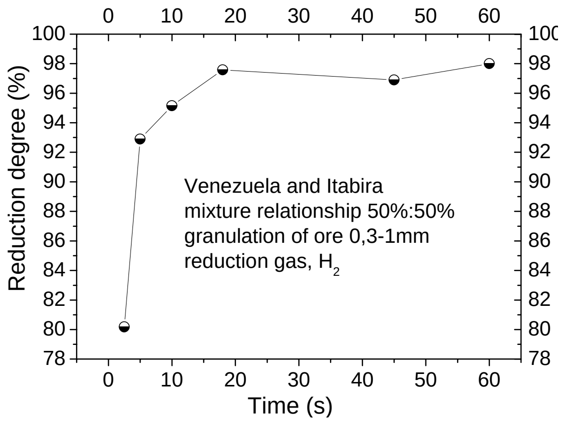


Fig. 4.5. Reduction degree depend on time for mixture two iron ores at temperature of 900°C (calculated on the basis results, [2], see Fig.4.2. as well)

5. PREVENTION AND OBSERVATION

Based on the analysis considered in previous paragraphs, some methods for prevention and observation sticking process are considered.

Temperature should be below the fusion point. In that case, it will be disabled soften and smelt processes. For experimental investigations should be chosen as low as possible temperature, with aim to prevent the sticking occurrence.

For experimental investigation in fluidized bed is useful to apply two steps reduction, the first step at lower temperature and the second step with higher temperature and reduction degree.

The specific conditions for the fibrous precipitate are good diffusion conditions and low nucleation density. The combination between high nucleation density formed in the pre-reduction and the high diffusion conditions caused by high temperatures during end-reduction are responsible for morphology similar to porous precipitate during the reduction under normally fibrous conditions.

When chosing the experimental conditions, care should be taken that both - contact area among iron fines - as well the adhesive forces are as small as possible. High velocity could be used. With higher gas velocity higher critical temperature for sticking can be reached.

The additions H_2 in reducing gas gave higher rates of reductions. Hydrogen content in reducing gas has great influence on the types of precipitation and with small additions of H_2, fibrous iron grow decreases and stops if H_2 additions increases greatly.

The addition of inert component is solution to avoid sticking during reduction in fluidized bed as well. The addition of cement is the good method for sticking prevention. It was showed that low content Al_2O_3 could not prevent sticking, but on the other hand high content Al_2O_3 (above 5%) can support to avoid sticking fine ore. The traces Al_2O_3 in wustite promotes the formation dense iron. Also, the suitable addition up to 5% CaO and 10% MgO can help to avoid the sticking. The coating with additive is meaningful only if the ore does not disintegrate during reduction too strongly. It depends on strongly of type iron ore.

Addition of coal or char (coke, C) to ore is good solution to avoid sticking during reduction, particularly in fluidized bed. The volatile in the coal plays an important role during initial steps of iron ore reduction, providing enough energy for complete reduction of hematite and magnetite and later for reduction magnetite to wustite. The reduction of wustite to iron occurs by gases as product of gasification.

By visual observation reduction process is possible to fix moment of the sticking which has not been possible with other testing equipment. This method for detection the sticking is possible to apply for example in fluidized bed reduction of iron ore.

Optical microscopy and image (quantitative) analysis could be very useful for detecting the change size of iron ore during reduction process. The change of size could be due to transformation lattice structure during reduction and due to sticking occurrence as well.

The most investigators were used scanning electron microscopy (SEM) for observation and detecting sticking process [1-3, 10, 16, 22, 28, 31, 33, 34], for examples see Fig. 3.2 and 3.3).

With the help of SEM was proven that the kind of iron precipitations has of large influence on the sticking. By ores with dense or little porous iron precipitations no or relatively weak sticking was observed, whereas with sponge iron with highly porous structure fibrous precipitations with intensive sticking was observed [2]. Bright shell of metallic iron on the outer surface, grey core on wustite and dark core of iron oxide was observed by SEM [3, 10, 22, 31, 33, 35]. On the basis SEM observation chronological development of fibrous iron growth was represented. Also, it was showed that the whisker grows up from surface and not from top [16].

The ore particles were observed in temperature interval, 560-1000°C by SEM [34]. It was seen a dense phase at 560°C, with some macro pores randomly scattering throughout particle. In the 670°C sample, cracks within the particle were observed, indicating thermal decomposition occurred below this temperature. The ore particle heated to 840°C developed a porous system due to the reduction reaction. The bright shells were observed in the samples heated to 950 and 1000°C.

6. CONCLUSION

This paper considers the sticking problem that occurs during direct reduction of iron ore in fluidized bed. The sticking mechanisms are explained. The main parameters on the sticking behaviour were analysed. The methods for prevention and observation are discussed.

The new experimental investigations conducted with the aim to find a solution for sticking prevention are proposed as well. As inert material char and coal would be used. Based on the measurement with coal, the influence of volatiles on the sticking occurrence could be estimated.

Investigations will be done in fluidized bed reactor at two temperatures: 800°C and 950°C, with the aim to observe the influence of temperature on sticking. Influence of the following parameters could be investigated: types of iron ore, types of coal (or char), volatile content in the coal (or char) particles, temperature etc. on the sticking process.

As iron ores would be used: Carajas and Hammerslay. Carajas [3] showed lower tendency to sticking comparing with Hammerslay [36]. Influence of ratio coal and iron ore mixture will be investigated. The mass ratio of iron ore and coal in the 80:20 and 50:50 could be used.

For different process regimes, the correlations for the heat transfer coefficient (given as functional dependence of dimensionless Nusselt number on different parameters) and the mass transfer coefficient (given as functional dependence of dimensionless Sherwood number on different parameters) correlations will be determined. Different process parameters will be followed such as: temperatures of fluidized bed, size of particles, kind of particles, gases for fluidization, fluidization velocity.

The first experiments could be performed by gas mixture H_2-CO and N_2. Based on these measurements, the conditions where the sticking occurs will be found. In the second step of investigations, the inert component will be used. As inert component char and coal will be chosen. In measurements with char, reduction could be achieved by gases generated in gasification process as well. Influence of volatile content in the original coal on the sticking prevention could be investigated on the basis of experiments with coal.

Some of the experiments will be done two times at the same conditions with the aim to confirm their reproduction. After reduction, the samples will be cooled in atmosphere of inert gas (N_2) and later taken out from fluidized bed reactor.

The main aim of these investigations is to find a suitable solution for preventing sticking. On the basis of these investigations methods for sticking prevention could be proposed.

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