REDUCTION DEGREE EFFECT IN SOFTENING AND MELTING PERFORMANCE FOR DIFFERENT METALLIC BURDEN[1]

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Abstract

The metallic burden reduction behavior is a prerequisite for stable blast furnace operation. Because of this, it is fundamental importance its knowledge, according to the characteristics of each material. In this paper are presented the results of pre-reduction behavior by one type of sinter and two types of pellets, and its effect on the region of the cohesive zone. The results indicated that a low reduced burden leads to decreased softening temperature, extending the zone of softening and melting, with consequent increase in pressure drop. In other words, the characteristics of pre-reduction of metallic burden may determine the blast furnace productivity, fuel consumption and operational stability.

Key words: Reduction degree; Cohesive zone; Softening and melting; Blast furnace.

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[1] *Technical contribution to the 6th International Congress on the Science and Technology of Ironmaking – ICSTI, 42nd International Meeting on Ironmaking and 13th International Symposium on Iron Ore, October 14th to 18th, 2012, Rio de Janeiro, RJ, Brazil.*

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1 INTRODUCTION

The blast furnace is a reactor that operates in countercurrent system, with the solid burden descending due to gravity, while the gases from tuyeres ascending through the voids in solid burden, consisting by ferrous materials and carbon. The carbon materials, except for the fuel injected, have three features in the blast furnace: chemical (iron oxides reducer), thermal (supply heat by combustion, for the reduction reactions) and structural (provide permeability to gases, in the dry and cohesive zone and support, in part, the solid burden through the formation of dead man, in the hearth). The iron bearing materials, besides this element and oxygen, have contaminants such as: silica, alumina, phosphorus and others. These contaminants, along with other compounds added to the blast furnace burden, incorporated in sinter and pellet or charged directly in the blast furnace, besides the ashes of the coke and coal injection, form the blast furnace slag.

Because of each component of the burden has its contaminants with own chemical composition, that individually contribute to the formation of blast furnace slag, it is assumed that the softening and final melting of each component are given in different temperatures. At this stage, the slag flows into the voids existing in the metallic burden to form a mass that difficult the gas flow ascending, causing large pressure drop of these gases. Whereas good permeability in the charge preparing region, i.e., low particle size dispersion and low fines generation, the cohesive zone becomes mainly responsible for the blast furnace production, because represents approximately 70 % of the pressure drop in the reactor.

This region, however, is influenced by the metallic burden and coke quality, by the conditions of the blast furnace, among others. In this paper, it is limited to an evaluation of the reduction degree effect of metallic burden on the behavior of the cohesive zone.

2 DEVELOPMENT

2.1 The Blast Furnace and the Cohesive Zone

Dissection studies, conducted in the 1960's e 1970's(1-3) showed that the blast furnace can be divided into five distinct regions(4): stack zone, cohesive zone, active coke zone, raceway and hearth. At that time, it was observed that the initial of the reduction takes place at temperatures around 700°C. Until the region of thermal reserve, a portion of approximately 33 % is reduced, i.e., the burden quickly reaches the condition of FeO. Thereafter, the processing behavior of FeO to Fe metallic (Figure 1) determines the large difference in fuel consumption and productivity of the blast furnace, and therefore, this phenomenon became the main focus of research since then.

Along the height of the furnace, the gases suffer pressure drop through the porous bed formed by descending solids. Measurements made in blast furnaces(5) show that the higher pressure drop occurs in the cohesive zone, Figure 2. In this region, also known as softening and melting zone, the gases can pass only through the coke. This is because of the layers of metallic burden are impermeable by slags, iron oxide and/or metallic iron in softening that fulfill the pre-existing voids in this region, thus preventing the ascending gas flow through them, Figure 3.

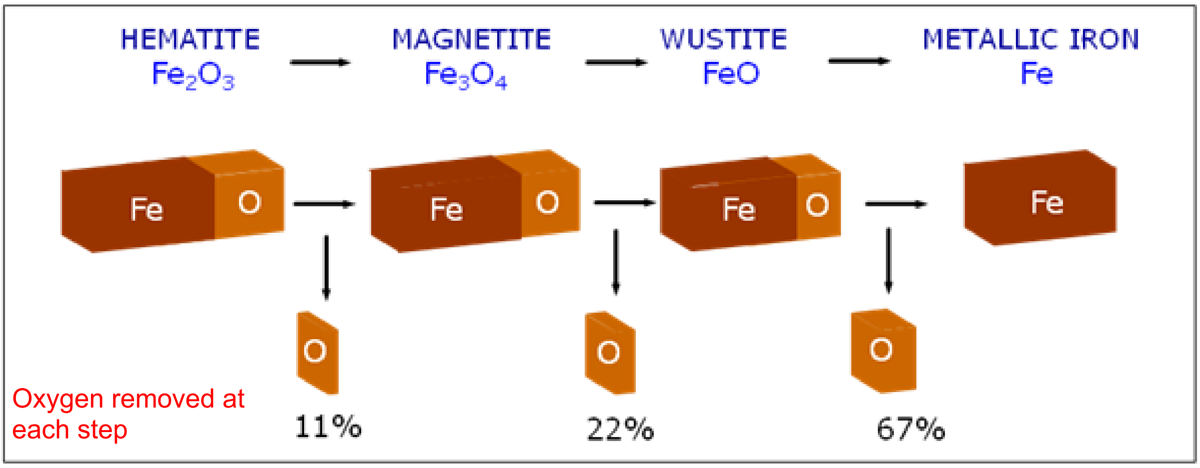


Figure 1. Behavior of metallic burden reduction.

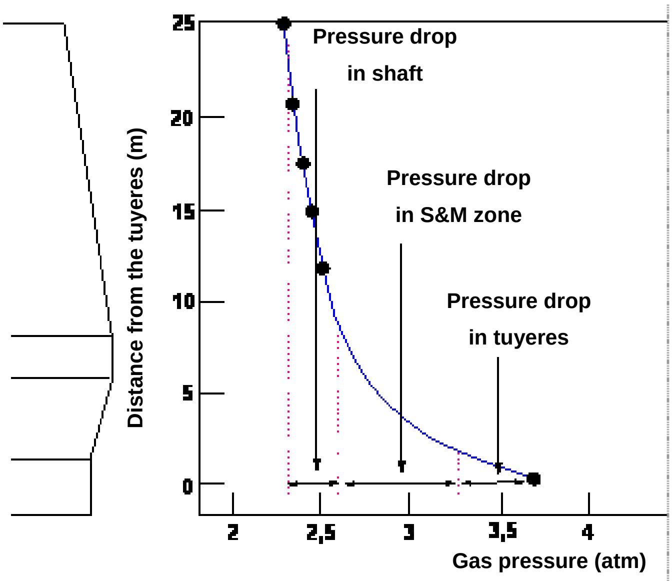


Figure 2. Distribution of pressure drop along the various regions of the blast furnace, according to Higuchi, cited by Gudenau(5).

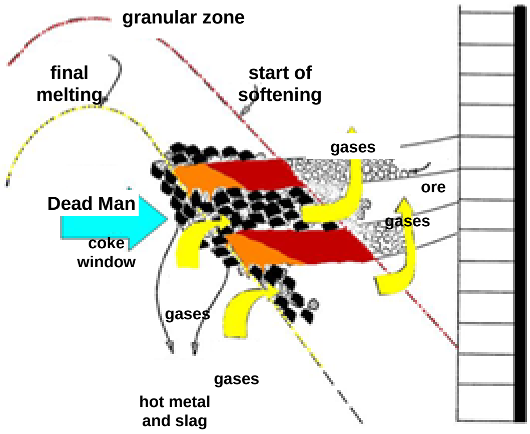


Figure 3. Detail of cohesive zone(6).

It is extremely important the metallic burden behavior during the whole heating, until the final melt, which is certainly related to their porosity and the behavior of these pores. After the cohesive zone, the reduction occurs by melt with an increase in fuel consumption. Therefore, it is important to know how the reduction occurs after the metallic burden passes through the zone of thermal reserve, specially before the initial softening as well as maintaining the high temperatures pores. This behavior affects the softening and melting zone, which has strong influence on the blast furnaces productivity. Thus, studies to understand their behavior can lead to increased productivity with consequent reduction in fuel consumption for hot metal production.

2.2 Blast Furnace Slag

As the metallic burden descends in blast furnace it is reduced by ascending reduction gas. At the cohesive zone, this burden is basically composed of metallic iron and slag, composed mainly by SiO_2, CaO, Al_2O_3 e MgO, with variable contents of FeO.

Near the cohesive zone the slag begins its softening process that develops until the initial drip. In this region, the slag, called primary, derived from each raw materials, initiates the process of softening and melting at different temperatures, depending on their chemical composition. According to MA(7), a way to classify the slag formed at different locations in the blast furnace may be as follows:

- primary – formed by gangue contained in each metallic burden;
- bosh – the primary slag after dissolving all components of fluxes and additives charged from the top, including some ash content contained in coke consumed for direct reduction and carburization (~50 kg/t HM);
- tuyere – formed by ash content of fuels burnt in front of tuyeres. When is used flux injection, is necessary to included them; and,
- final – a mixture of the bosh slag and tuyere slag formed, deducting the amount of SiO_2 reduced to Si.

The appropriate slag formation is an essential condition for getting a blast furnace smooth operation, as well as good quality for hot metal produced. This phenomenon includes the dissolution of iron ore gangue, fuels ashes and fluxes. They are desirable good properties of softening and melting, fluidity, desulfurization and maximum capacity for alkali removal from the blast furnace. It's desired low amount of primary slag and that its components (SiO_2, CaO, MgO, Al_2O_3, FeO e MnO) are in proportions that provide the formation of an eutectic point, about 1200 ºC.

The slag formation in the cohesive zone is an extremely complex process. It is initiated by the softening of the metallic burden, which is gradually increased until its melting, accompanied by the dissolution of different materials among them, as fluxes, ore gangue and ash from fuels consumption in the direct reduction and carburization, until the dripping of liquid material toward the hearth.

During the slag formation, considerable variations occur in its chemical composition and physical properties, may lead to worst burden permeability, such as: (a) physically, the burden, with the exception of coke, turns gradually from solid to pasty and finally to the liquid state. The burden empties decrease, worsening the permeability; and (b) chemically, the composition of slag formed depends not only on metallic burden, but also of its reduction degree up to its arrival in the cohesive zone and its distribution over the charging. Two main reactions take place at this stage: (i) reduction of the oxides remaining in the ore at a rate higher than during its descent to the granular zone, and (ii) dissolution of the slag fluxes, changing its basicity. Both reactions result in a change of viscosity and melting point of the slag formed. This process strongly affects the blast furnace performance, since it is directly related to its fuel consumption and productivity. Therefore, studies in this context are essential to allow greater steel industry competitiveness.

3 METHODOLOGY

It was studied one type of sinter and two types of pellets, as shown in Table 1.

Table 1. Chemical composition of raw materials

Identification	Sinter	Pellet B (PB)	Pellet A (PA)
Fe_T	57,69	66,18	64,12
FeO	5,710	1,410	0,280
CaO	9,750	2,399	1,201
SiO_2	4,750	2,560	5,359
Al_2O_3	1,043	0,485	0,630
MgO	1,763	0,056	0,461
Mn	0,680	0,076	0,139
P	0,047	0,021	0,021
K_2O	0,055	0,001	0,001
Na_2O	0,056	0,001	0,001
TiO_2	0,074	0,089	0,081
ZnO	0,003	0,007	0,001
S	0,025	0,002	0,002
B2 (CaO/SiO_2)	2,05	0,94	0,22

For the raw material characterization, tests were performed such as Degradation under Reducing (RDI), Reducibility (RI), Softening & Melting (S&M) and mineralogical analysis of samples according to standard procedure of the Reduction Laboratory - Usiminas Technology Center. The study of the reduction degree effect in the burden behavior in cohesive zone was based on the Ono's article(8), as detailed planning in Table 2.

Table 2. Planning of the tests

		Sinter	PB	PA
Particle size		(12~16) mm		
Pre-reduction	Temp.	900°C		
	Time (min)	30, 60, 90, 120, 150, 180 * Determined the reduction index after each test.		
	Gas	15 NL/min (CO = 4,5 e N_2 = 10,5)		
S&M		Heating at 1200°C, rate of 10°C/min, 7 NL/min of N_2		
		Maintained for 10 min at 1200°C, 7 NL/min of N_2		
		Applied load of 1 kg/cm^2 and started passing of reduction gas, 7 NL/min (CO = 2,1 and N_2 = 4,9) with heating at a rate of 5°C/min until complete melt.		
Microscopy	Optical	Preparation of the sample immediately after of pre-reduction test.		
	SEM	Analysis realized after optical microscopy.		
Porosimetry		Preparation of the sample immediately after pre-reduction test.		
XRD		Preparation of the sample immediately after pre-reduction test. Test immediately after sample preparation.		

At first, it was used the pre-reduction technique of metallic burden at different times of reduction, using the equipment for RI testing. Subsequently, part of the pre-reduced material suffered the softening and melting test (S&M) modified according to the methodology, the remaining part of the sample received optical and SEM microscopy, porosimetry and X-ray diffraction analysis.

4 RESULTS AND DISCUSSION

4.1 Results reduction

Initially, were performed tests of metallurgical evaluation of materials, Table 3.

Table 3. Initial results of reduction

Identification	**RI (%)**	**RDI (%)**	**TS (°C)**	**TF (°C)**	**ΔT_{SF} (°C)**	**S (KPa.°C)**
	Reducibility	Reduction Degradation Index	Softening onset temperature	Melting final temperature	Interval between the softening onset and melting final	Pressure drop
Sinter	80,68	29,11	1560	1654	94	5460
PB	64,68	9,54	1466	1482	16	488
PA	58,24	2,66	1448	1550	102	829

It may be noted that the sinter was the material that reached the highest degree of reduction and also the highest rate of degradation. In addition, showed a high pressure loss, far superior to the pellets. The exception of the degree of reduction, PB showed the best results considering the parameters evaluated here. Compared to PB, PA was better just in the reduction degradation index.

In figures 4 and 5 it is presented the main results related to pre-reduction test with subsequent softening and melting. Should not be directly compare the result of the raw material *in natura* to the other, since the methods used in the tests were different.

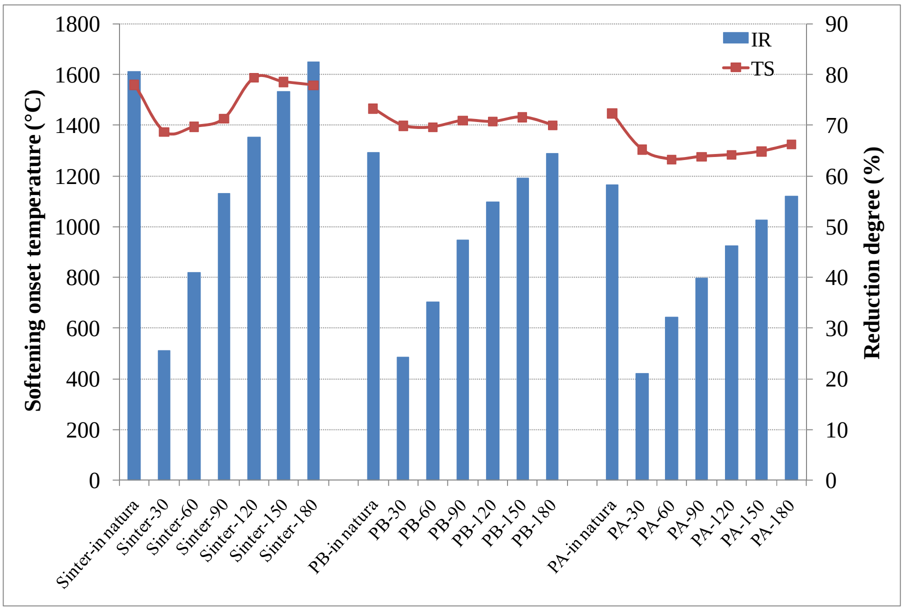


Figure 4. Reducibility (RI) and softening onset temperature (TS).

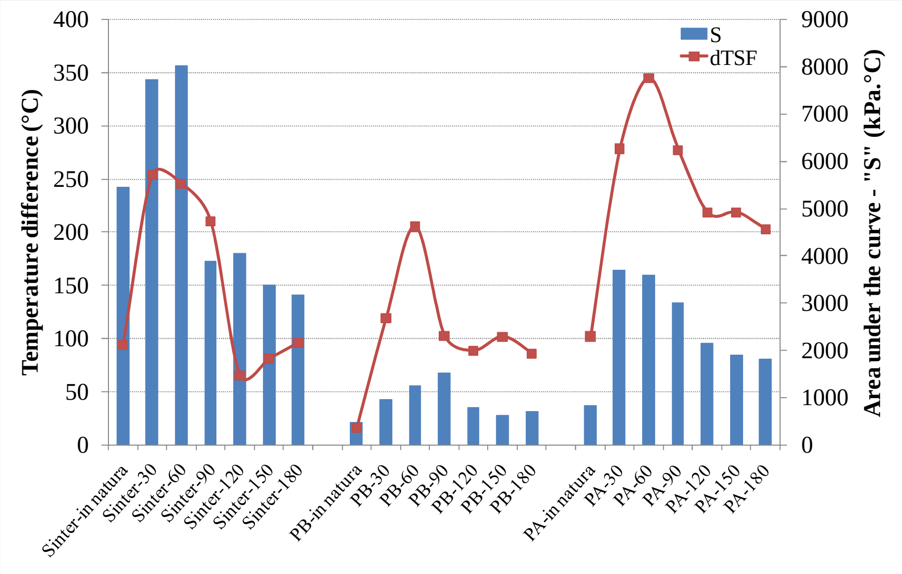
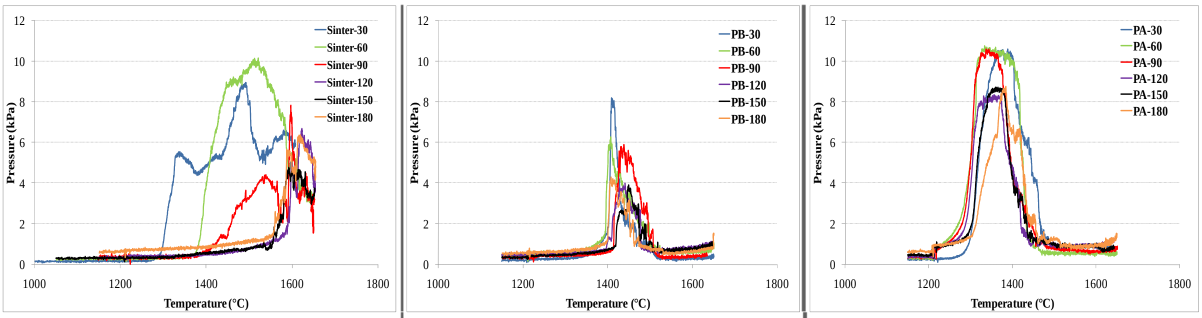


Figure 5. Pressure drop (S) and thickness of the cohesive zone (dTSF).

As expected, the reduction degree, Figure 4, has been increasing over time. The softening onset temperature (TS) has a different behavior among the sinter and pellets. In the sinter case, the pre-reduction of up to 90 minutes led to a decrease in TS in relation to sinter *in natura*, whereas greater reductions led to an increase in the value of TS. However, the final melting temperature did not suffer considerable variation. In the pellets case, TS value did not suffer wide variation in the degree of pre-reduction. Except for *in natura* material, when presented TS higher, the value of the softening onset temperature was close to 1,400°C for PB and 1,300°C for PA. However, there was a variation of the final melting temperature, causing cohesive zone enlargement and increased pressure drop, figure 5, when compared with the raw material. In all the evaluated cases, low degree of reduction involves large cohesive zone and higher pressure drop.

The results are graphically shown in Figure 6 of S&M.



(a) sinter (b) PB (c) PA

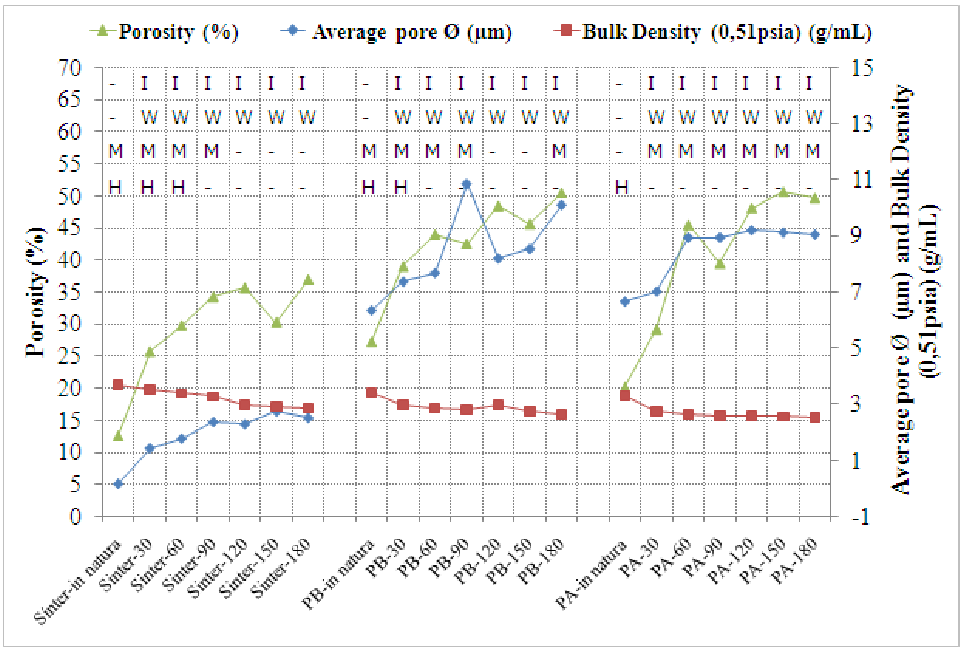
Figure 6 . Graphic results of material reduction after pre-reduction, pressure versus temperature.

The results clearly show the burden reduction degree effect in the furnace behavior, especially in the cohesive zone region. In all cases, higher degree of reduction resulted in a delay in the softening onset temperature, reduced cohesive zone thickness and pressure drop. This result was further evidenced by sinter, materials that reached the highest reduction rate. The PB had the best melting behavior, in terms of thickness of the cohesive zone and pressure drop in the blast furnace.

ISSN 2176-3135

4.2 Porosimetry Results

It was conducted by means of mercury porosimetry, an analysis sequence to verify the porosity behavior, after the material pre-reduction, Figure 7. It is observed that while there is hematite (H) available, the porosity increase is continuous, when it begins to form wustite (W) begins the stabilization of the porosity. In sinter, the average pore diameter is increased over time, with rapid reduction in density, which indicates continuous reduction increase. In PB case also occurs pore diameter increase, but for PA, after 60 minutes of reduction, the average pore diameter is virtually stable, which may have affected the process of reduction.



I: metallic iron; W: wustite; M: magnetite; H: hematite

Figure 7. Porosity results of the raw material, before and after pre-reduction.

It can be affirmed that the materials studied show different behavior when subjected to the pre-reduction process. This behavior is reflected in its porosity, which allows, in the future, to identify the impact of this parameter for the reduction process.

4.3 XRD Results

From Figure 8, it is possible to see the X-ray diffraction results, performed on Bruker D8 Advanced, equipped with tube Co and 2θ configuration. It is a qualitative analysis, since only identifies the occurrence of the mineral phases, by comparison of diffraction patterns obtained from known standards.

The sinter is constituted by hematite and magnetite mixture, while pellets are mainly hematite. Confirming the results shown in Figure 4, it can be observed from the curve that shows the presence of metallic iron, increased speed reduction to sinter, followed by the PB, and, thirdly, PA.

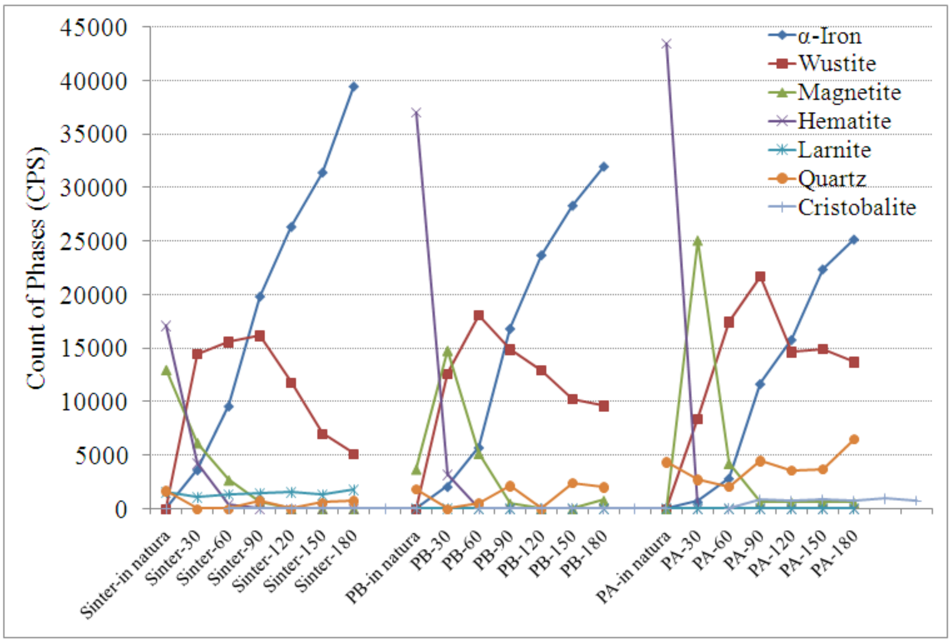


Figure 8. Raw material XRD results, before and after pre-reduction.

The hematite appears only in the sinter with pre-reduction of up to 90 min and PB, which suffered pre-reduction of 30 min. The sinter strongly magnetite has eliminated this stage for pre-reduction over 90 min. Already for the pellets, has been rapid transformation of hematite to magnetite, and the latter remains even after 180 min pre-reduction. Also is observed a strong presence of wustite, especially for the PA. According is known by metallurgists, the presence of this material in the working zone results in higher fuel consumption by reducing melt.

4.4 Microscopy Results

Optical microscopy provides more details about the material and the quantification was performed by point counting in reflected light optical microscope (Carl Zeiss Axio M1m). It was used polarized and normal light with intensity set at about 7 volts, through the objective lens, 10x, 20x, 50x and ocular lens with 10x.

The quantitative analysis results are shown in Figure 9. Corroborating with XRD results, presented in the previous section, there is a greater development to the sinter reduction (has more metallic material), followed by PB, and finally the PA. Moreover, it is important to highlight the continuing evolution in the sinter porosity and for PB, while PA remained high porosity in all tests, but low reduction rate.

The calcioferrite is evidenced only for the sinter, and disappears at 90 minutes of pre-reduction. Is noted the presence of magnetite at all levels, and by XRD this stage is practically extinct after 90 minutes of pre-reduction.

The explanation is that, at microscopy, it was not separated the magnetite from wustite.

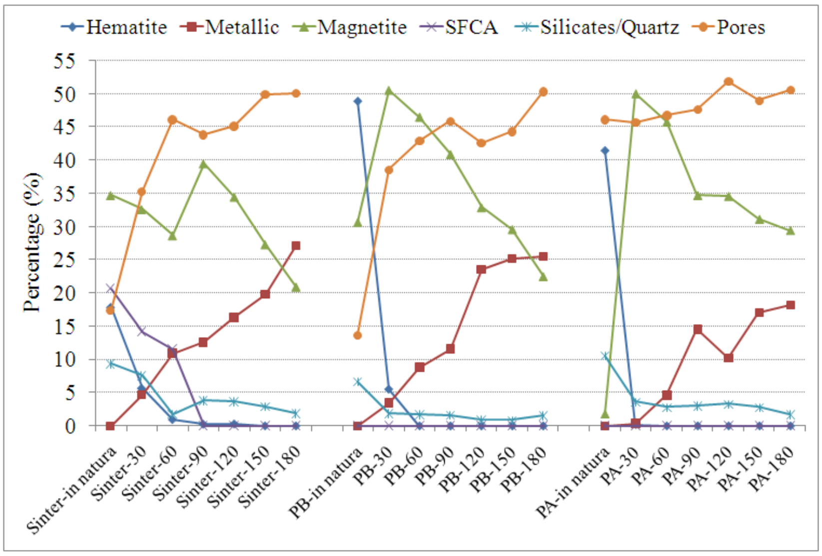
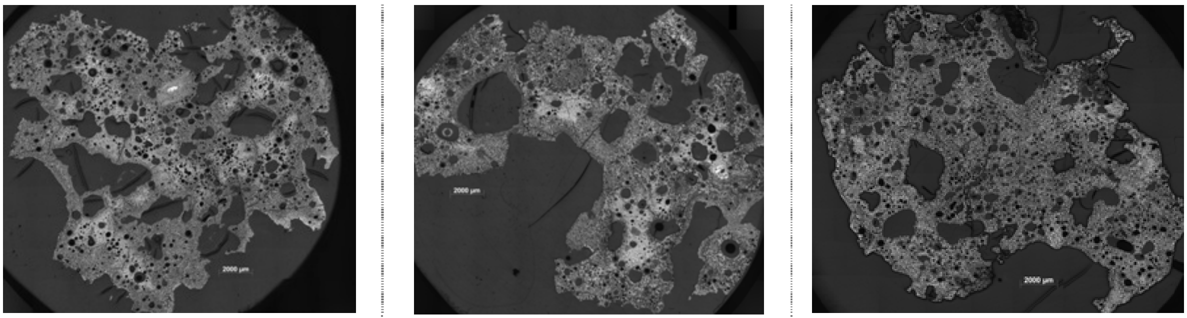
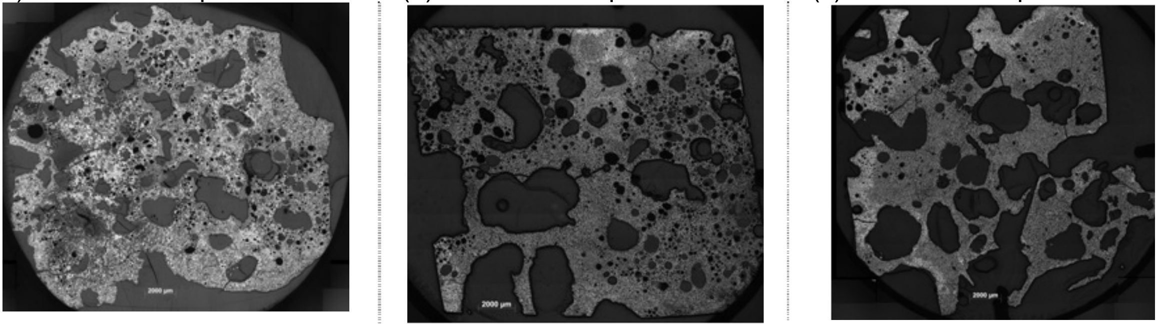


Figure 9. Quantitative materials analysis.

The results showed that the high temperatures behavior is considerably different for each material, developing according to the pre-reduction time. By Figures 10 to 12 have a display sequence of the materials pre-reduction.



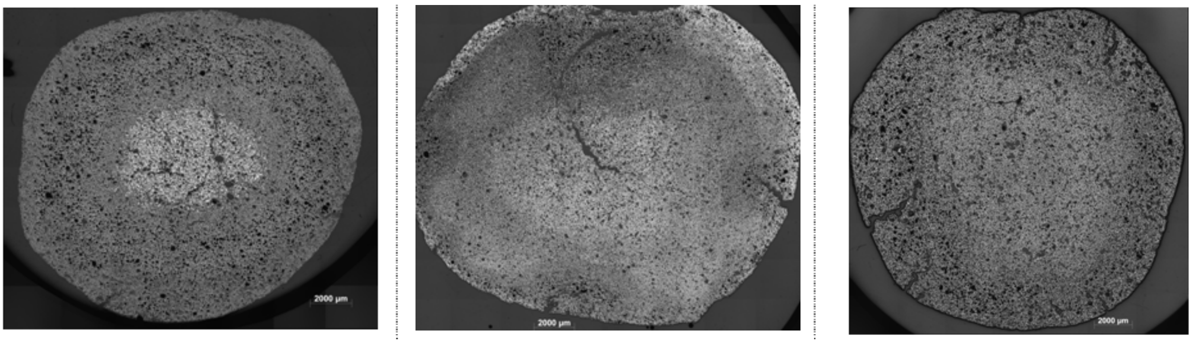
(a) 30 minutes of pre-reduction | (b) 60 minutes of pre-reduction | (c) 90 minutes of pre-reduction



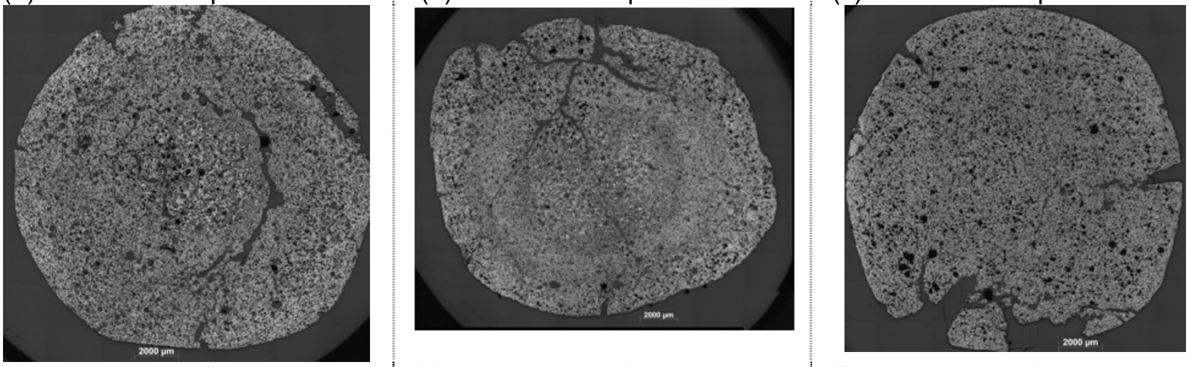
(d) 120 minutes of pre-reduction | (e) 150 minutes of pre-reduction | (f) 180 minutes of pre-reduction

Figure 10. Optical microscopy of sinter, following pre-reduction sequence.

For sinter, the reduction behavior is more clearly perceptible. The lighter region in the Figure 10 indicates the reduced material. After pre-reduction, it has been observed hematite, calcioferrites and silicates as well as hematite transformation to magnetite, and later in wustite. In the darker area, it was also possible to observe the presence of unreacted flux, and sinter porosity evolution. Even after 180 minutes of pre-reduction, still observing the quartz particles presence in the widespread structure as well as calcioferrite within silicates.



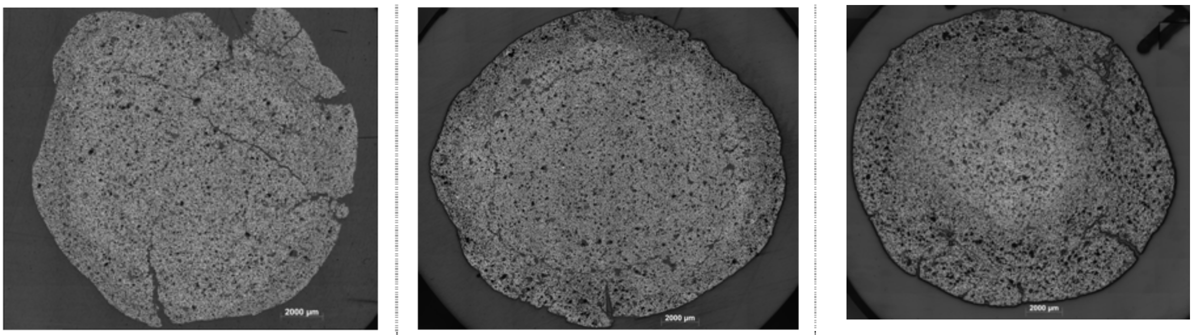
(a) 30 minutes of pre-reduction (b) 60 minutes of pre-reduction (c) 90 minutes of pre-reduction



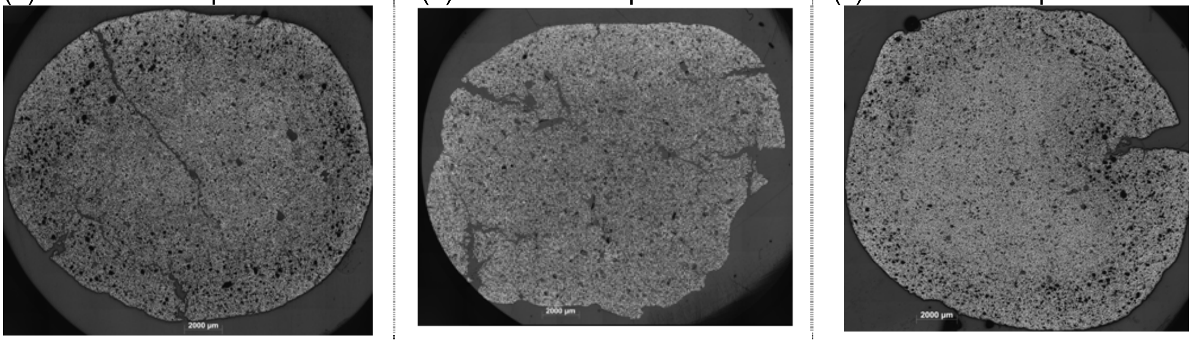
(d) 120 minutes of pre-reduction (e) 150 minutes of pre-reduction (f) 180 minutes of pre-reduction

Figure 11. Optical microscopy of PB, following pre-reduction sequence.

PB presented fairly homogeneous structure after reduction, clearly demonstrating its characteristic topochemistry reduction, with distinct regions on the porosity (a peripheral region very porous and inner region more compact), and many cracks in the peripheral region. With 180 minutes of reaction, it was observed even enough iron in the form of wustite, however, it showed more porous.



(a) 30 minutes of pre-reduction (b) 60 minutes of pre-reduction (c) 90 minutes of pre-reduction



(d) 120 minutes of pre-reduction (e) 150 minutes of pre-reduction (f) 180 minutes of pre-reduction

Figure 12. Optical microscopy of PA, following pre-reduction sequence.

PA presented a very porous structure. It was observed quartz presence and large cracks spread throughout the structure. The metal presence evolution was very shy. After 180 minutes of reduction, the presence of metal was most notable (although less frequent than sinter and PB) together with many cracks and pores.

5 CONCLUSION

Evaluation of pre-reduction effect in the cohesive zone showed that distinct materials tested (sinter and two types of pellets) have behavior completely different. This is a reflection of their chemical, physical and porosity properties, which allows, in the future, identifying the impact of these parameters in the reduction process. For all materials tested, low reduction degree implies in wider cohesive zone, with consequent increase in pressure drop. Even after 180 minutes of pre-reduction, there was a strong wustite presence, especially for PA, which reflects in increased fuel consumption by melt reduction.

The sinter analyzed was more magnetite, and the pellets predominantly hematites. As peculiar characteristics, stands out calcioferrite in the sinter, high porosity of PA and magnetite presence in PB. About pre-reduced material, for sinter it was observed unreacted flux, and quartz particles spread in the structure. PB showed characteristic structure to topochemistry reduction. It was observed distinct regions regarding the porosity, periphery very porous and middle more compact. Many cracks in the peripheral region. PA presented a very porous structure. Moreover, it could observe the quartz and large cracks presence scattered throughout the structure. The metallic iron evolution was very shy.

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