Original Article
https://doi.org/10.4322/2176-1523.20181524

INFLUENCE OF CARBON CONTENT ON MECHANICAL PROPERTIES OF IRON ORE PELLETS

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Abstract

Solid fuels are added during the pelletizing process in order to reduce the natural gas consumption in the firing process and to obtain better temperature distribution inside the pellets for its induration. The purpose of this research was to evaluate the effect of the amount of carbon added to mixtures containing different types of pellet feed on the mechanical strength. The pellet mixtures were prepared with different dosages of anthracite (1, 1.2 and 1.4% of fixed carbon) and two different sorts of pellet feed. The mixing, pelletizing and firing stages were done on a pilot scale, and the fired pellets were subjected to the mechanical properties evaluation and microstructural analyses. It was found that when increasing the amount of anthracite, the compression and tumbler strength of the fired pellets decreased, which seemed to be related to the formation of a large number of pores and magnetite in the core of the pellets. When a larger amount of porous hematite and goethite were used in the pellet feed, larger quantities of magnetite were found in the microstructure of the pellets.
Keywords: Iron ore; Pelletizing; Anthracite; Mechanical strength.

1 INTRODUCTION

The mechanical properties of iron ore pellets have a significant influence on the performance of reduction reactors. Induration of green pellets occurs through the firing at high temperatures, and the thermal levels imposed in the process are related to the microstructure formed in the agglomerate which directly affects the mechanical properties of the fired pellets. During the firing process, the pellets undergo partial reduction due to the generation of reducing gases produced from reactions with the carbon contained in the mixture, and after consumption of the carbon, they undergo reoxidation due to the effect of the atmosphere in the oven. The extent of the reduction and reoxidation reactions depend essentially on the characteristics of the agglomerate (size, porosity and such), the proportion and the characteristics of the raw materials used (such as ore porosity, reactivity and amount of carbonaceous material and anothers) and on the processing conditions (temperature, heating rate and atmosphere) [1-3].

Solid fuels added during the process of pelletizing is done in order to reduce the consumption of natural gas in the firing process and to obtain better temperature distribution inside the pellets. This addition of fuel to the mixture also favors the reduction of the temperature gradient among the pellets situated on different regions on the bed, leading to more uniform firing and consequently to more efficient use of fuel and of the combustion air [1,3]. Recently, researchers have suggested the use of renewable fuels in the pelletizing process [4,5], which would contribute to increase the sustainability of these plants.

Although the addition of fuel to the mixture is beneficial to increased productivity, it may also be a limiting factor beyond certain levels with respect to the mechanical and metallurgical properties of the pellets. According to specialists on the subject, the quantity of solid fuel has an influence on the oxidizing conditions of the pellets and the stages of the firing process. Also, depending on the conditions during the firing of the pellets, the formation of different phases may occur on the interior and on the surface of the pellets which also influences its mechanical properties [1-3]. Dwarapudi et al. [2] observed that the increase of the carbon content in the green pellet promote the increase of magnetite as well the slag phase and decrease the hematite in the microstructure of the agglomerates. These authors also pointed that the increase of carbon content in the green pellet increases the mechanical properties (CCS and TI) until an optimum value and after decreases with the carbon content.

On the other hand, there is a consensus among specialists that the nature of the iron ore affect the quality of the pellets produced [6,7]. According to experiments carried out by Strezov et al. [8], the mechanical alteration

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caused by the thermal processing was very pronounced on goethitic ore while it was less expressive in hematite ore. Li et al. [9] affirm that the origin of the hematite (*in natura* or secondary) contained in the pellets interferes with the mechanism of the induration of the agglomerate. Recently, Pownceby et al. [10] observed phases formed using sintering tests with *in situ* in XRD and found that ore composition exercises great influence on some quality parameters of the agglomerate such as its mechanical strength.

In light of the fact that the mechanical properties of the pellets are very sensitive to the solid fuel added to the mixture and that this effect should vary for different types of iron ore, investigations on this subject are of great interest in order to optimize the use of natural resources in the ironmaking process.

By understanding the influence of the variables related to the addition of solid fuel to different iron ores used in pelletizing, it is possible to optimize the process in terms of natural gas consumption and of the mechanical properties of the pellets obtained. With this focus, this research proposed evaluates the effect of the quantity of carbon added to the pelletizing mixtures containing different types of pellet feed on the mechanical strength of fired pellets. The development of this study was carried out on pilot scale with iron ore mixtures that represent industrial practices.

2 MATERIAL AND METHODS

2.1 Raw Materials

The raw materials used in the production of the pellets were pellet feed, anthracite, limestone and a binding agent. The anthracite was added in three dosage levels, aimed at achieving the following contents: 1.0, 1.2 and 1.4% in mass of fixed carbon in the mixture. The proximate analysis and the calorific value of semi-anthracite used in this study are shown in Table 1, while its particle size distribution, which refers to a specific surface of 3636 cm^2/g is shown in Figure 1. The effect of the amount of solid fuel added to the pelletizing mixture was evaluated on two types of pellet feed, which have their chemical and mineralogical composition presented in Table 2. The samples of pellet feed differ mainly with respect to the contents of specular hematite and porous hematite. The pellet feeds were added to the green pellet in the proportion of 90% in mass with particles size below 0.044mm and surface area around 2000 cm^2/g.

2.2 Production of Pellets

The mixing, pelletizing and firing steps were conducted in pilot scale in order to follow the routes already employed on an industrial scale. The mixture used in the production of the pellets follows the proportion shown in Table 3. For the homogenization of the constituents of the mixture, an Eirich intensive mixer Vertical pilot scale for 15 seconds was used. In the pelletizing step, a metal disc mark Dravo-Lurgi-W model 3511-1 was used with

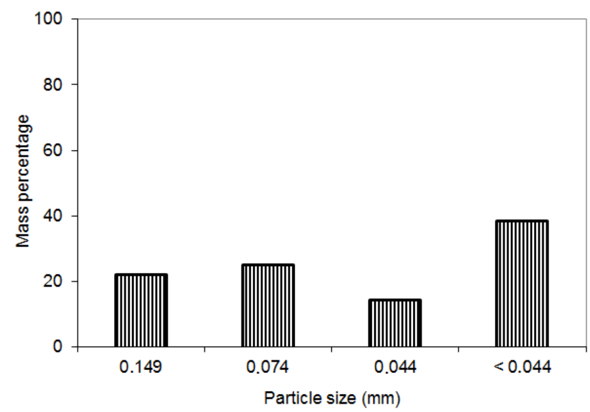

Figure 1. Particle size distribution of the anthracite used in the pelletization.

Table 1. Proximate analysis in mass % (in dry basis) and calorific value of anthracite

Fixed Carbon	**71.56**
Volatiles Matter	10.19
Ash	18.25
Calorific value (cal/g)	6409

Table 2. Chemical analysis and mineralogical composition in mass percentage of the pellet feed

	Fe	FeO	SiO_2	Al_2O_3	CaO	MgO	P	LOI	SH	PH	G	M
A	66.81	0.97	1.32	0.46	0.1	0.03	0.042	2.43	48.8	31.9	15.8	3.3
B	66.62	1.18	1	0.39	0.08	0.01	0.039	3.17	31.5	47.4	18.4	2.6

LOI = loss on ignition; SH = specular hematite; PH = porous hematite; G = goethite; M = magnetite.

Table 3. Composition in mass percentage of the pelletization mixtures

	Pellet feed	Anthracite	Limestone	Organic Binder
Mix 1	97.15	1.40	1.40	0.05
Mix 2	96.85	1.70	1.40	0.05
Mix 3	96.65	2.00	1.40	0.05

dimensions of 1000 mm diameter and 200 mm in depth, rotation speed of 15 rpm and 45 ° tilt.

The firing process of the green pellets was conducted in pot grate that simulates travelling grate induration furnace. To perform the firing, 16mm fired pellets were added to the pot grate bottom forming a 70 mm bed, aiming to support the load, provide permeability to the passage of gases and protect equipment. Green pellets with diameters between 16 and 10mm were subjected to firing under conditions of time, temperature and pressure that aimed to portray the reality of industrial processes (see the main steps of the burning process in Table 4).

2.3 Assessment of the Fired Pellets

To evaluate the mechanical properties of the fired pellets resulting from the different combinations of adding anthracite and pellet feed quality, they were subjected to the cold crushing strength (ISO 4700) and tumbler index (ISO 3271). Still, in order to recognize how the parameters changed in the production of these pellets affect their mechanical properties, macroscopic and microscopic analyses were carried out to evaluate the microstructure (phases and pores) of the fired pellets. For this, an Optical Microscope Zeiss, Imager M2m model and software for Axio Vision 4.8 image analysis were used.

3 RESULTS

Initially, the results of the influence of variables proposed in the production of pellets on their mechanical properties will be presented and, following, the microstructure characteristics of these pellets.

3.1 Mechanical Strength of the Pellets

The influence of carbon added to the pelletizing mixture on pellet's compressive strength and tumbling are shown respectively in Figures 2a and 2b. It is noted that the cold crushing strength of the pellets decreased linearly and expressively with increasing anthracite content in the mixture. The average compressive strength of the pellets produced with 1.0% fixed carbon is almost twice the value obtained with pellets that were added 1.4%. To the dosage levels tested, the clear decreasing tendency of the tumbler index is also noticed when it has a higher amount of anthracite in the mixture. The increase of anthracite content in the mixture promotes heat input to the pellets, which dictates the nature of phases formed and the pores generated in the microstructure. Therefore, differences in the mechanical properties of the pellets should be related to microstructural aspects that also depend on different proportions of anthracite added. It is also possible to see from the graphs of Figures 2a and 2b that the mechanical properties of fired pellets are significantly influenced by the type of pellet feed used. In general, the use

Table 4. Induration machine parameters

	Time (s)	Differential pressure (mm H_2O)	Temperature (°C)	Oxygen flow (Nm^3/h)
Drying	460	350	220	-
Preheating	84	350	570	80
Firing	42	565	1220	80
Cooling	146	520	-	-

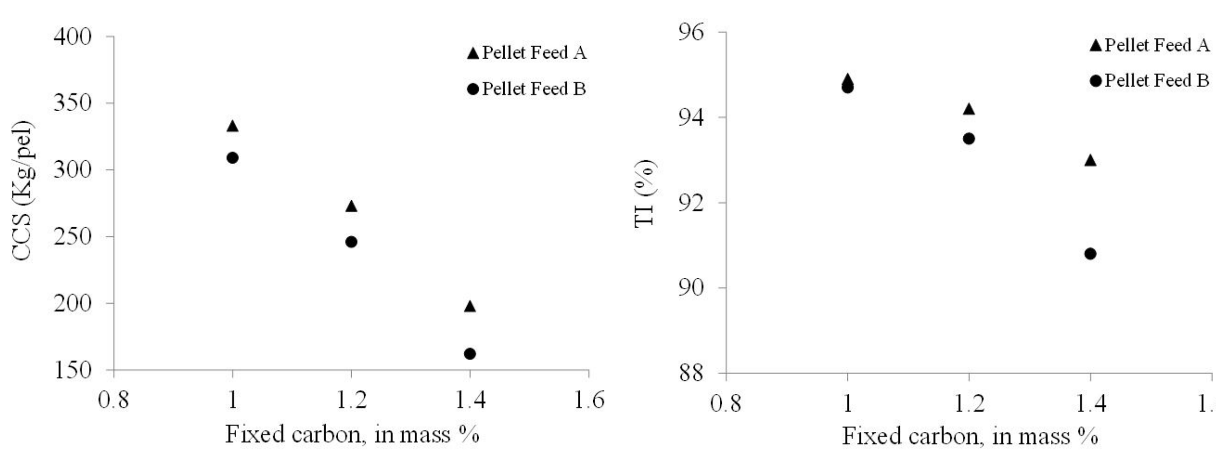

Figure 2. Influence of the fixed carbon content on cold compressive strength (a) and on tumbler index (b) of the fired pellets.

of the pellet feed B caused a decrease in CCS and TI of the pellets, and it was even more evident in that this increased the carbon content. The difference in mechanical strength between the pellets produced with the pellet feed A and pellet feed B must be related to the microstructure formed during the firing process. Being that the pellet feed B is richer in porous hematite and goethite, compared to the pellet feed A, it is possible that these phases have negatively affected the CCS and TI indexes. It is known that during heating, there is the decomposition of goethite crystallization water generating steam and an expressive volumetric expansion of this phase, promoting the appearance of cracks in the particles of the ore [8], which should be propagated in the agglomerate.

The best results concerning to the CCS and TI indexes of the pellets were obtained with the combination of pellet feed A with 1.0% fixed carbon contained. For the test conditions imposed in this study, it was found that the anthracite content in the pelletizing mixture had a more significant influence than the type of pellet feed on the mechanical properties of fired pellets.

3.2 Structural Analysis of the Pellets

The images shown in Figure 3 refer to a polished section of the samples of fired pellets with different dosages of anthracite and pellet feed quality. From these images, it is noted an increase of porosity with the increase of the anthracite added to the mixture. In this macroscopic image, it is possible to see relatively large pores concentrated in the central regions of the pellet. Under the firing conditions of green pellets, anthracite undergoes volatilization and combustion, leaving pores / cracks within the agglomerate. The higher the anthracite content, the greater must be the number of macropores and cracks, since there is a more significant generation of gas inside the pellets, and, the closer to the core, the higher should be the difficulties for the gases output from the agglomerate. Furthermore, the macrospores are formed mainly in the center of the pellets, which concentrate the compressive forces during the CCS test. These results seem to be related to the mechanical properties set forth in the preceding item, wherein the increased amount of anthracite caused a decrease in CCS and TI. In such macrostructure analyzes, it was not possible to infer the resulting influence of using different types of pellet feed.

Figure 4 shows images of the pellet microstructures obtained with different tested compositions in three distinct regions with respect to the sample radius: shell, mantle and core. Through image analysis, it was possible to distinguish the presence of hematite (in white color) and magnetite (pink color) phases and the pores (in black).

It is noted that the outer layer of the pellets consists of hematite (secondary hematite) for all dosages of anthracite tested and pellet feed type. According to the characteristics of the induration process and the iron ore mixture used, this phase must be derived from the reduction of the primary hematite and its reoxidation.

The secondary hematite was also predominant in the intermediate region of the pellets produced with the pellet feed A, except for those produced with 1.4% fixed carbon, in which magnetite is the predominant phase. Regarding the intermediate region of the pellets produced with the pellet feed B, it is noted that magnetite is present even for a minimum content of anthracite, and for the higher levels (1.2 and 1.4% fixed carbon) this phase prevails.

At the core of the pellets, it is evident that the amount of magnetite increases with the addition of anthracite to both types of feed pellets tested. Overall, in this region of

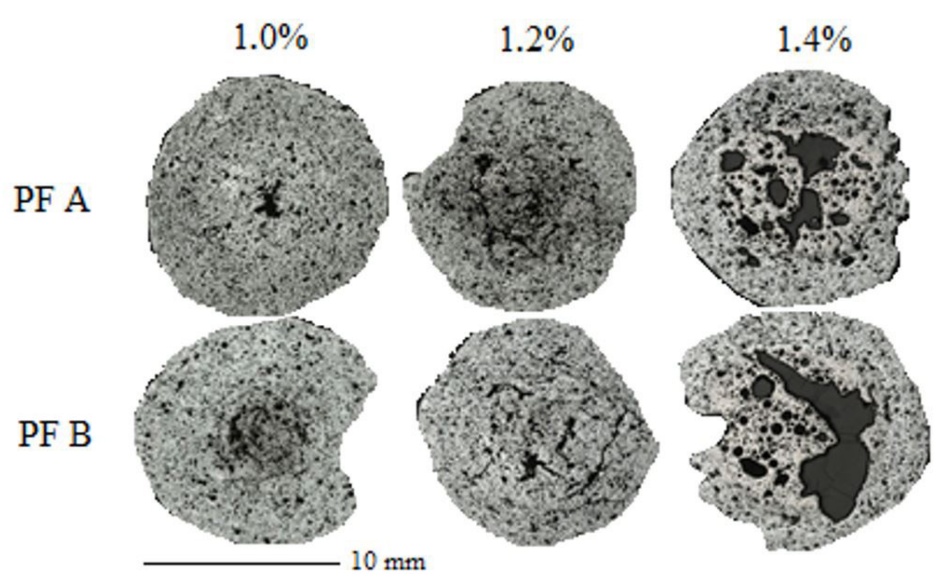

Figure 3. Micrograph of the pellets obtained with different fixed carbon content.

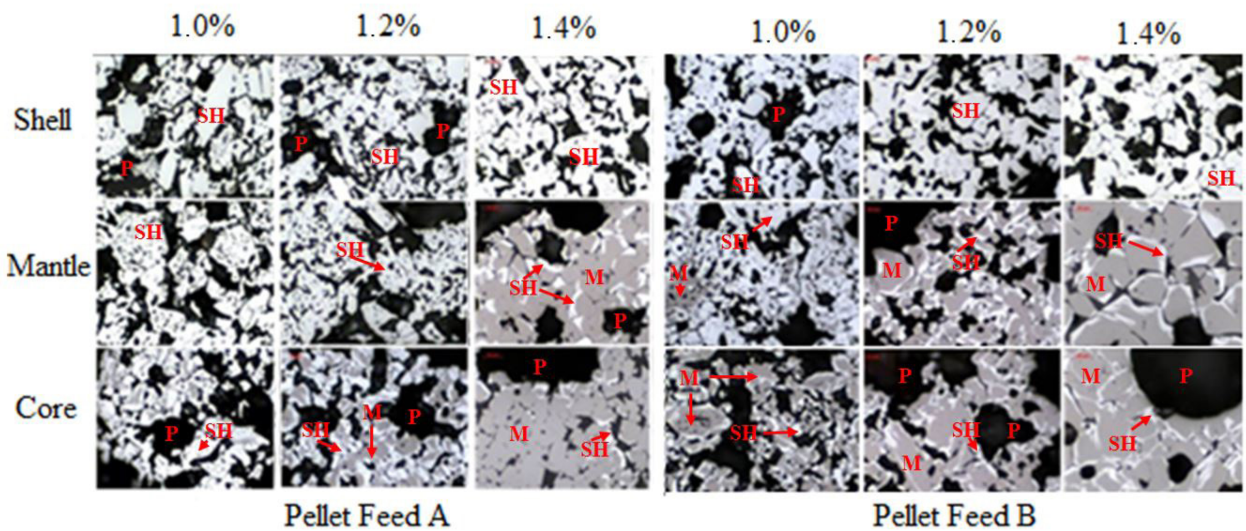

Figure 4. Micrographs (magnification 500x) of pellets produced with different mass percentage of anthracite and pellet feed type. SH = secondary hematite; M = magnetite; P = porous.

the pellet, there is a predominance of magnetite phase with the formation of secondary hematite at grain boundaries of magnetite, except for those produced with 1% fixed carbon and pellet feed A, wherein the proportion of secondary hematite is quite significant.

The prevalence of the hematite phase on the outer layer of pellets is consistent due to the oxidant atmosphere in the pelletizing bed in contact with the pellets during the induration process. On the other hand, the interior of the pellet is not subject to the direct action of the atmosphere of the external environment, and there is the presence of a reducing material inside the agglomerate. The increase in carbon content is believed to promote a decrease in the oxygen potential inside the pellets, keeping the environment subtly reductive for a longer period and thus, probably preventing the re-oxidation of the magnetite formed. In the case of the pellets produced with the pellet feed B, it is possible to see that there is still a more expressive presence of magnetite compared to those obtained with pellet feed A. Probably, this behavior is associated with the greater reducibility of porous minerals (hematite and goethite), compared to higher density minerals (specular hematite). The combination of greater reducibility and higher carbon contents must be to contribute to form more wustite in the inner regions of the pellets, that will re-oxidize to form magnetite or fayalite (if there is not time for the re-oxidation), but without reaching a complete re-oxidation to hematite.

4 DISCUSSION

According to the results obtained, there is a clear influence of the varied parameters in the experiments of this study (carbon content and kind of pellet feed) on the macro and microstructure of the fired pellets, which are reflected in their mechanical properties. The results obtained from the macro and microstructural analysis of the pellets indicate that there is an increase in the carbon content in the pellet, a trend of macropores and magnetite formation in the central region of the agglomerate. Moreover, the presence of magnetite extends beyond the core of the pellet when pellet feed B was used in the mixture. A lower mechanical strength of the pellets is probably associated with a lower formation of secondary hematite during the firing process [2,9], since the recrystallization mechanism is recognized as one of the main hardening means of the agglomerates. The presence of macropores, which corresponds to a void of considerable volume inside the pellets, should also negatively affect their mechanical properties. In addition, the microstructure differences observed between the core and the outer layer of the pellets, characterizing a dual microstructure of hematite on the surface and magnetite and pores in the core, should impair the performance of the pellet in terms of mechanical properties [2].

The diagram shown in Figure 5 aims to elucidate the results found in this study from the raw materials tested. It presents a qualitative influence of iron ore reducibility and carbon content in the green pellet on the microstructure and mechanical strength of the fired pellets. Such representation shows that the lower the reducibility of iron ore and the lower the carbon content, the higher the mechanical strength of the fired pellets is, which is related to the microstructure formed. On the other hand, the increased carbon content in the pellets produced with high reducible iron ore in the green pellets should lead to a negative scenario regarding the mechanical strength.

The results show that for the firing conditions carried out in this work, which sought to represent the industrial

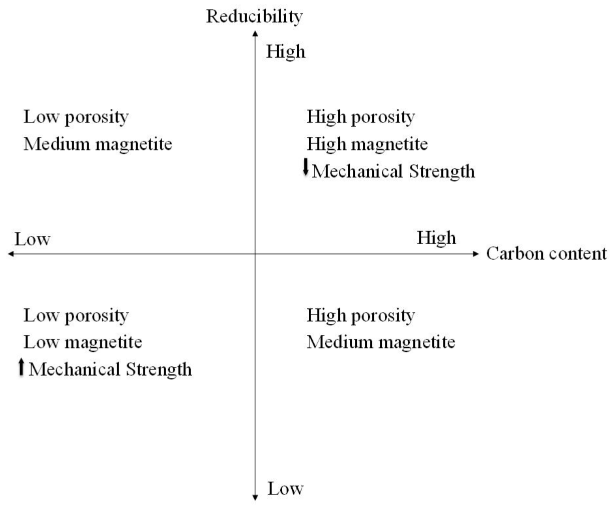

Figure 5. Schematic figure of the qualitative trends found in the fired pellets for the tested raw materials.

practice, the limitation related to the carbonaceous material addition in the pelletizing mixture varies according to the iron ore used and with the restrictions of objectified quality. To enable the use of larger amounts of solid fuel as well as introduce new ores in the mixture, while maintaining the quality in terms of mechanical properties of the pellets, it seems to be a crucial pass to understand the behavior of the raw materials and mixtures in the pilot plant aiming to adjust the characteristics of the induration process (time, temperature heating rate, ...) of the pellets.

5 CONCLUSIONS

In this work, an investigation of the influence of different carbon dosages in the pelletizing mixture for different iron ore mixtures used on an industrial scale was done. It was found that both the carbon content and the pellet feed characteristics used in the mixture had an influence on the mechanical properties of the pellets. However, for the conditions tested, the carbon content was shown to have greater influence on the evaluated quality parameters.

It was observed that increasing the quantity of carbon in the pelletizing mixture resulted in a decrease in the cold crushing strength (CCS) and the tumbler index (TI) of the fired pellets. Under the conditions tested, increasing the quantity of carbon led to the formation of a larger quantity of large pores and magnetite in the core of the pellets. Furthermore, when pellet feed with a more significant amount of porous hematite and goethite content was used in the pellet mixture, it was observed, in general, the presence of an increased amount of magnetite in the microstructure of the pellets. It is believed that this higher porosity and higher magnetite content have been responsible for the declining of the mechanical strength of the pellets. Finally, it was seen that the different pelletization mixtures proposed in this study had a greater impact on the cold crushing strength of the pellets than the tumbler index.

Acknowledgements

The authors express gratitude to CAPES-PROEX, CNPq and FAPEMIG for accomplishment and support of this work.

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Received: 19 Sep. 2017
Accepted: 23 Jan. 2018