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Effect of different factors on low temperature degradation of hematite iron ore during reduction

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Abstract – Low temperature degradation (LTD) of iron oxides was investigated with the aim of understanding how natural iron ores degrade under different conditions. Minimisation of this degradation would increase the acceptance level of natural iron ores as feed materials without prior beneficiation. In addition to temperature and reduction gas composition, sample positioning in the reduction furnace and sample's original weight were also found to influence LTD. Samples placed in the top reaction zone of the furnace, which have the first contact with the reducing gas, were found to degrade 1.5 times more than those in the middle and bottom reaction zones. In addition, they presented a wide range of size in the disintegrated particles than those in the middle and bottom reaction zones. Furthermore, the samples with an original weight equal to or greater than 5 g, had a disintegration extent of less than 10%. Therefore, if the reduction gas comes into contact with a certain material first, before contacting the iron oxide, it may serve to reduce on LTD during reduction. Furthermore, in laboratory conditions, the occurrence of low temperature breakdown of the natural iron oxides can be minimised by using samples with an original weight equal to or greater than 5 g.

With the current trend of increasing production costs, there is a need to re-consider the use of natural iron ore as a raw material in the blast furnace (BF). This has the potential of making the steel production process more cost effective. Some of the reasons for a limited use of natural iron ore directly without beneficiation are its low temperature degradation strength and its wide range of softening and melting temperatures. However, recent research [1, 2] shows that some lump ores have better low temperature strengths than pellets and sinters. Over the years, low temperature degradation on natural iron ore, pellets and sinters has been studied and the efforts are summarised in Table 1 [1–17]. It can be seen that most research work on this subject has been carried out on sinters and pellets. However, some studies on natural lump iron ores have also been conducted in recent years. This trend needs to continue as an increased knowledge of the parameters that influence the behaviour of natural iron oxides during iron reduction can be used to optimise their direct use in the iron reduction processes.

From Table 1, it can be noted that two methods, ISO 4696 [18, 19] and RDI [12, 14], have mainly been used to determine the low temperature strength of iron oxides. They both measure the iron oxide strength against an abrasion loading. There are 2 versions of ISO 4696 (since 2007): one involving the use of CO-N_2 gas mixtures and the other CO-CO_2-H_2-N_2 gas mixtures. The ISO 4696 test method reports results as wt% of +6.3, +3.15 and −0.5 mm fractions. The iron ore has better resistance to disintegration due to abrasion loading when the wt% fraction of +6.3 and +3.15 mm is high and the fraction of −0.5 mm is low. On the other hand, the RDI test method reports results as wt% of fraction

Table 1. Some of the investigations carried out on low temperature strength of iron oxide.

Ref.	Authors	Year	ISO 4696				RDI*		SI**	Load	Iron oxide type		
			CO	CO_2	H_2	N_2	CO	N_2			Natural	Sinter	Pellet
(3)	H. Brill-Edwards, R.L. Samuel	1965			√								√
(4)	S. Watanabe, M. Yoshinaga	1968	√	√	√	–	√	√	√	√	√	√	√
(5)	N.A. Hasenack, H. Kister, et al.	1976	√	√	√	√	–	–		–	√	√	√
(6)	J.S. Padan, O. Singh, et al.	1978	√	√	–	√	–	–	√	–	√	–	–
(7)	H.W. Gudenau, H.Walden	1981	√	√		√	–	–		–	–	–	√
(8)	S.C. Panigrahy, M. Riguad, et al.	1984	–	–	–	–	√	√			–	√	–
(9)	T. Takada, H. Soma, et al.	1985								√	–	√	–
(10)	F. Adam, B. Dupre, et al.	1989	√	√									
(11)	M. Naito, A. Okamoto, et al.	1990	√	–	–	√	–	–		–	√	√	–
(12)	C.E. Loo & N.J. Bristow	1993	√	√	√	√	√	√		–	–	√	–
(13)	H.P. Pimenta, V. Seshadri, et al.	1993	√	√	–	√	√	√		–	–	√	–
(14)	C.E. Loo & N.J. Bristow	1994	√	√	√	√	√	√		–	–	√	–
(15)	Y. Wenhui	1996					√	√		–	–	√	√
(16)	H.P. Pimenta & V. Seshadri	2002	√	√	–	√	√	√		–	–	√	–
(17)	S.S. Gupta. B. Nandy	2002					√	√		–	√	√	
(1)	S.-L. Wu, H.-F. Xu, et al.	2009								√	√	√	√
(2)	W. Sheng-li, L. Xiao-qin, et al.	2011	√	√	√	√				√	√	√	√

* Reduction Degradation Index, ** Shatter Index.

−2.8 mm. The resistance to disintegration is better when the value is low.

During the descent in the furnace, iron oxides are subject to both abrasion and impact loading, which contribute to the mechanical degradation of the iron oxides during iron processing. This is because the sinters, pellets and/or lumps collide with each other and also with the furnace walls. This mainly leads to the formation of fines and dust. Low temperature degradation of iron oxide lumps during reduction processes causes major problems to the furnace operation. This is due to the formation of a mixed bed of widely varying particle sizes. The small particles locate in the interstices of the large particles and can significantly decrease the voidage of the mixed bed and thus penetration of the reduction gas through the mixed bed. Therefore, extensive studies have been conducted on abrasion loading, especially for sinters and pellets, as noted in Table 1.

The study areas tackled by the various authors are summarised in Table 2. All investigations indicate that a low temperature disintegration; thermal decrepitation and thermal degradation, of iron oxide occurs during a hematite reduction between 300 °C and 700 °C. A maximum degradation was observed for the temperature range between 500 and 600 °C [4, 6]. More specifically, thermal decrepitation occurs between 300 °C and 480 °C [4] and is mostly due to the evaporation of adsorbed water. In addition, thermal degradation occurs at temperatures above 480 °C. It can be explained by the apparent volume expansion, which occurs during hematite reduction to magnetite in this temperature range. The apparent volume expansion has been found to be approximately 25% [2, 3, 8, 17]. These expansions do not represent an intrinsic increase in the volume par say, but a change of the external dimensions of the specimen. This indicates that a considerable amount of void space is created within a specimen during a reduction process [3]. Moreover, it has been reported [2–6, 12, 14] that the disintegration of iron oxides during reduction processes significantly depends on the reduction gas compositions.

In general, there is need for further studies of the factors that hinder the direct use of natural iron ores in iron reduction. A low temperature strength is among the reasons for rejecting natural iron ores as a direct charge for iron reduction. With the influence of an abrasion loading on the process performance well described, it is also necessary to consider the extent of degradation of natural iron ores due to impact loading. In this study, some important factors that might have an impact on the low temperature

Table 2. Main topics investigated under low temperature degradation of iron oxides.

Reference	Main topics of investigations	Observations
(1)	Properties of lump ores and effect on BF operation	• Lump ores have a higher reducibility and a low temperature reduction strength than acid pellets
(2)	Study of the low temperature reduction degradation characteristics of different iron ores for different process conditions	• Lump ores degraded less than sinters and pellets • Lump ores are highly sensitive to a changed reduction gas composition • Lump ores present surface cracking, sinters integral cracking and pellets present degradation of surface stripping
(4)	Decrepitation of iron ore, swelling of iron ore and pellets and size degradation of sinter	• Sinter degradation depends on the initial sinter strength • Causes of abnormal pellet swelling; coarse magnetite grains, low firing temperature of pellet, rapid reduction of intergrown hematite and rapid growth of fibrous iron • Causes of iron ore decrepitation; structural difficulty in expelling combined water, parallel arrangement of elongated hematite or specularite
(5)	Pellet composition and effect on BF performance	• Disintegration at low temperature strongly depends on composition of the reducing gas; H_2 presence causes a higher disintegration
(6)	Decrepitation characteristics	• Degradation to fines is maximum between 400−600 °C • Degradation at a given temperature increases with time up to a certain temperature
(8)	Composition of flux constituents in BF burden and basicity ratio	• Use of MgO instead of CaO at a given basicity and an increase in the basicity index (increased flux addition) improves the reduction degradation strength
(11)	Characteristics of lump ores in comparison with sinters in terms of degradation, reduction and high temperature behaviour	• Degradation tendency of lump ores; decrepitation in upper shaft and reduction degradation in the middle shaft of BF • In-furnace degradation of lump ores is about half that of sinters • Optimum particle size of lump ores is 10 to 15 mm
(12, 14)	Determining the vulnerability of sinter phases to crack propagation	• A decrease of the fracture toughness of sinter mineral phases results in a deterioration of reduction degradation indices • Crack propagation is retarded when a crack runs into a very tough material • Pores can either increase or reduce the reduction degradation
(13, 16)	Influence of sinter properties on microstructure & reduction disintegration	• Extensive disintegration occurs during the first 30 minutes of reduction: reduction of secondary hematite and large pores during the initial reduction period • Presence of Al_2O_3 and TiO_2, brings about a relatively high degree of intensity of disintegration
(17)	Understand the cracking behaviour of sinters and ores; identify phases which become weak during reduction and effect of longer treatment time	• Ores disintegrated much less than sinters • *RD* calculation is better based on oxygen and iron balance • A significant degradation takes place when the rate of carbon deposition exceeds the oxygen removal

strength of lump iron ores were considered: (i) reduction temperature, (ii) reduction gas composition, (iii) original weight of the sample, and (iv) sample location in the furnace reaction zones. The former two parameters have been investigated and have been well described [2–4, 6, 13, 16, 20], but the latter two have not been well studied. Therefore, an influence of these parameters on the impact loading was studied systematically in the present work. An increased knowledge of the parameters that influence low temperature strength of natural iron oxides can be used to optimise their direct use in iron reduction processes. This would enable a cost reduction of iron production.

1 Materials and methods

1.1 Experimental procedure

The natural lump iron ores used in this study were collected from the Butare mines in the Muko deposits in south-western Uganda. The chemical composition of the

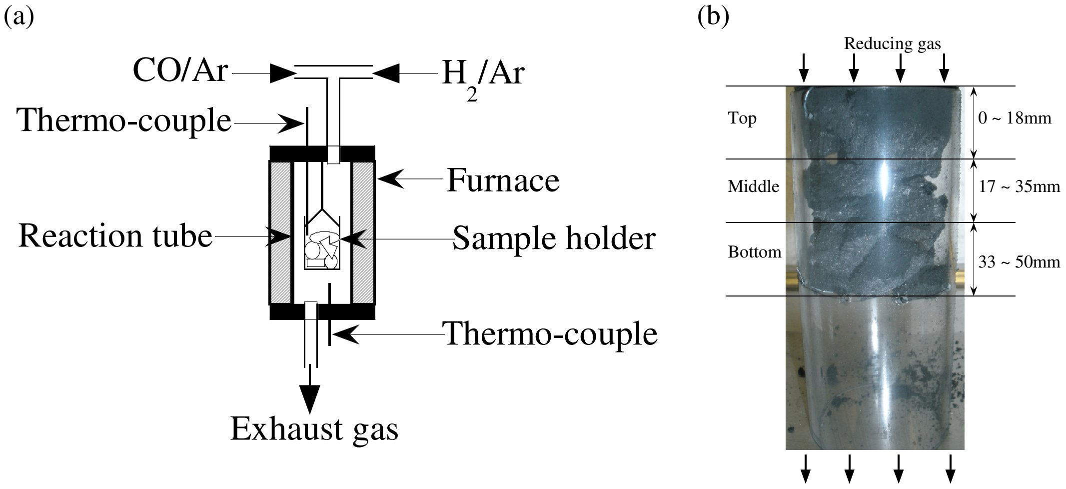

Fig. 1. Schematic illustration of the (a) equipment for the reduction experiments and (b) different reaction zones in the sample holder in the furnace.

tested samples was as follows (in wt%): 97.3 Fe_2O_3, 0.39 FeO, 0.98 SiO_2, 0.52 Al_2O_3, 0.01 P_2O_5 and 0.001 S. The samples consisted mainly of hematite with a 97.3 wt% Fe_2O_3 content. They had low gangue contents: 0.98 wt% SiO_2 and 0.52 wt% Al_2O_3, with small amounts of deleterious elements: 0.01 wt% P_2O_5 and 0.001 wt% S. A lump sample was crushed to pieces. Thereafter, about 20 of the resulting lump pieces (total weight was about 100 g) of the natural iron ore in the size range −40 + 10 mm were put in the sample holder. The experiments in this study were carried out in the reduction furnace illustrated schematically in Figure 1a. The sample pieces were put in a sample holder and demarcated into three zones as indicated in Figure 1b. In the discussion, all the sample pieces in the holder are referred to as batch and each piece as an individual.

The holder with the sample lumps was placed in the furnace and heated to the required temperature in the reaction zone (500 or 600 °C) under an Ar atmosphere. When the required reaction temperature was attained, the reduction gas mixture of H_2 and CO was turned on with a total flow rate of 0.5 L/min. The gas flow rates of H_2 and CO in the different experiments were varied in the following ranges: 0−0.3 L/min for H_2 and 0.5−0.2 L/min for CO. Thereafter, the experiment ran for 1 h. Finally, the sample was cooled down in the reactor at the end of the test. After the reduction experiment, analysis was performed on each individual lump piece.

1.2 Estimation of reduction degree

The achieved reduction degree (*RD*) of iron ore during reduction experiments was calculated using the following equation:

$$RD = \frac{\Delta W}{W_0 \cdot \%O/100\%} = 100\% \times \frac{W_0 - W}{[W_0 \cdot (\%Fe_2O_3 \cdot 48/160 + \%FeO \cdot 16/72)]} \qquad (1)$$

where parameter ΔW is the difference in sample weight before and after reduction, which corresponds to the amount of O_2 reduced during an experiment. The parameters W_0 and W are the weight of a sample before and after a reduction experiment respectively. The parameter %O is the weight percent of O_2 that can be removed from the Fe_2O_3 and FeO in a sample during a reduction experiment. Finally, the parameters $\%Fe_2O_3$ and %FeO are the weight percentages of the respective oxides in the natural iron ore. According to the iron-oxygen equilibrium diagram, FeO is unstable below 570 °C [21]. Since the maximum investigated

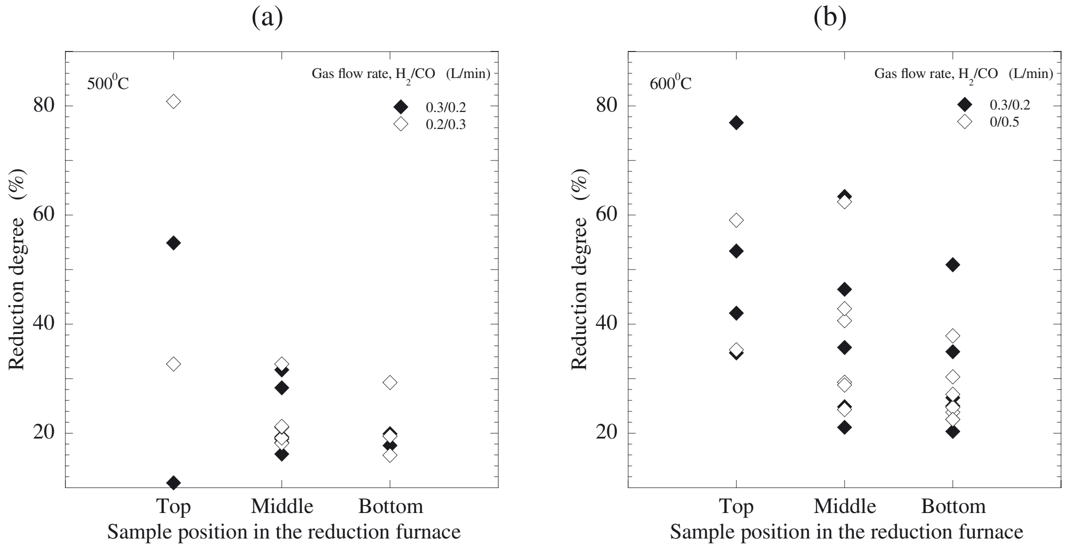

Fig. 2. Reduction degree of the sample lumps from the different reaction zones for the various gas flow rates and temperatures: (a) 500 °C and (b) 600 °C.

temperature was 600 °C, the FeO component was not considered in calculating the *RD* value.

1.3 Determination of low temperature strength of the natural iron ore

The iron oxide resistance to low temperature degradation was estimated by the determination of the mechanical degradation (*MD*), which is used to characterize the resistance to impact loading. This was accomplished by dropping individual sample pieces four times onto a steel plate from a height of 2 m [4, 6, 22]. The initial weight of the individual sample pieces before the drop test (W_{bt}), as well as the weight of the largest unbroken parts after the test (W_{at}) was measured. Thereafter, the extent of mechanical disintegration (*MD*) of the iron ore was calculated using the following equation:

$$MD = 100\% \times (W_{bt} - W_{at})/W_{bt} \qquad (2)$$

2 Results and discussion

2.1 Influence of sample position on low temperature strength

The impact of the sample position in the furnace on the low temperature strength was studied. More specifically, each batch in the sample holder was divided into three zones (top, middle and bottom), as illustrated in Figure 1b. It should be pointed out that the reduction gas in the given furnace was flowing through the top, middle and bottom zones of the sample batch respectively. Therefore, the top zone received the highest reaction potential of the reduction gas compared to the middle and bottom zones of the sample holder.

The *RD* values determined in the reduction experiments at 500 and 600 °C are shown in Figure 2 for the different mixtures of H_2 and CO. It can be seen that the samples in the top zone attained higher *RD* values than those in the bottom zones at both experimental temperatures. The samples in the middle zone had intermediate values of *RD*. It can be noted that *RD* values of up to 80% were realised in samples from the top zone of the furnace at both 500 °C and 600 °C. This can be explained by the higher reduction potential of the gas in the top zone because the reduction gas was flowing through the furnace from top to bottom, as illustrated in Figure 1b. As the gas passes through the iron ore charge, the reduction potential of the gas mixture decreases from the top to the bottom due to the reaction with iron oxides. Moreover, similarly as observed by

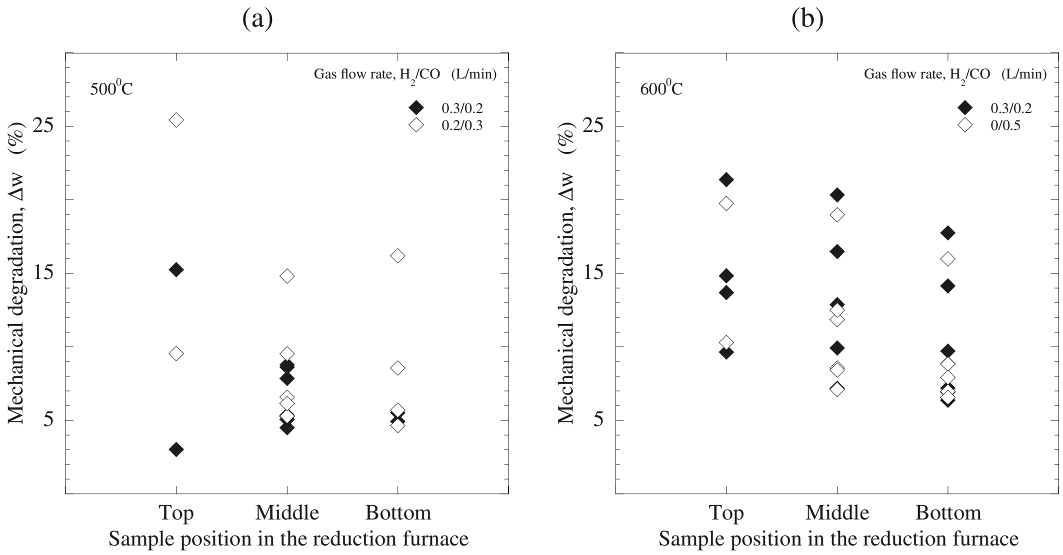

Fig. 3. Mechanical degradation of the sample lumps from different reaction zones for various gas flow rates and temperatures: (a) 500 °C and (b) 600 °C.

Padan et al. [6], the *RD* values obtained in this study also increased with an increased temperature. This was particularly true in the middle and bottom zones. At 500 °C, maximum *RD* values of 33 and 29% were achieved in the middle and bottom positions. However, the maximum values in the middle and bottom zones at 600 °C were 63 and 51%. This is due to the fact that at a temperature of 500 °C the reduction process is just starting to take place. However, thereafter it increases with an increased temperature [6]. Although the reduction potential for the CO gas at 500 and 600 °C was expected to be higher than that for the H_2 gas, the results obtained in this study at both temperatures did not show a clear tendency of an increased reduction degree with an increased portion of CO in the gas mixture. This may be explained by the long time (1 h) at which the samples were held at the given temperatures in these reduction experiments. Furthermore, by the higher impact of the sample location in the furnace reaction zones on the *RD* values.

Since a low temperature degradation (LTD) occurs due to a hematite transformation to magnetite, it can be expected that the mechanical degradation of the hematite iron ore during the reduction experiment will be proportional to the *RD* values achieved at a given temperature. The extent of disintegration of the iron ore samples after a reduction and a performance of the drop test is illustrated in Figure 3. It can be seen that the mechanical degradation (*MD*) of the iron ore samples is related to the furnace position. Higher *MD* values were obtained in the top zone (3–25% at 500 °C and 10–21% at 600 °C). Then, the *MD* values decreased till 5–16% at a 500 °C temperature and till 6–20% at a 600 °C temperature in both the middle and bottom zone. It was found that the obtained difference between the *MD* values in the top and the other zones can be more than 2 times, particularly at 500 °C temperature. However, a small additional pressure of a charge column in the sample holder cannot explain such a large difference of mechanical degradation of ore lumps from different zones because the height of the iron ore charge in the sample holder was only 50 mm.

These significant differences of LTD of the iron ore lumps for the same reduction experiment parameters can be explained by the different extent of the hematite-magnetite transformation in the different reaction zones of the sample holder. The relationships between the mechanical degradation and reduction degree of the sample lumps after reduction experiments at different gas

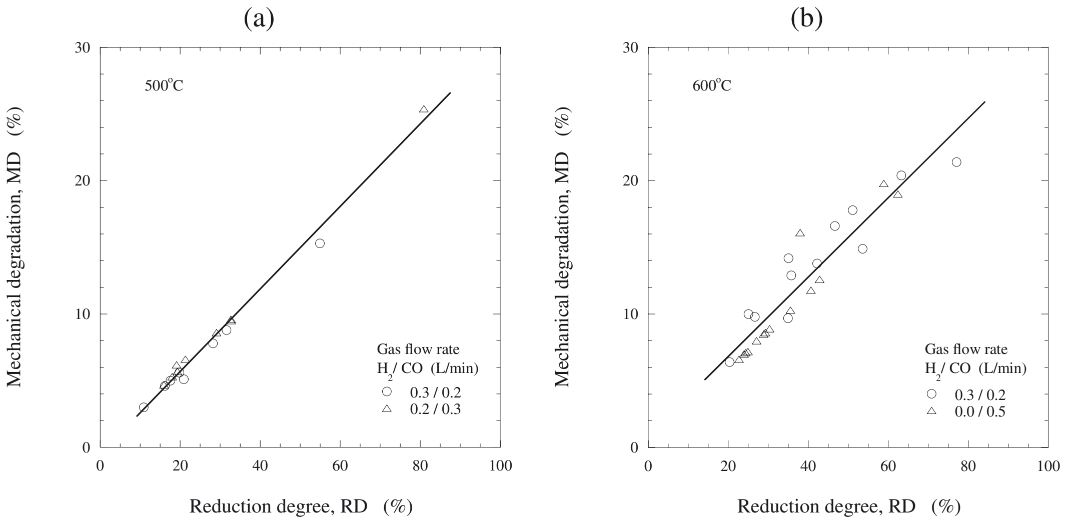

Fig. 4. Relationship between the mechanical degradation and reduction degree of the sample lumps after reduction experiments at different gas flow rates and temperatures: (a) 500 °C and (b) 600 °C.

flow rates and temperatures are shown in Figure 4. It can be seen that although the flow rates of H_2 (0–0.3 L/min) and CO (0.2–0.5 L/min) in the gas mixture were varied in a wide range, the *MD* values in these experiments do not show a clear dependency on the gas composition. Furthermore, the relationships between the *MD* and *RD* values can be described very well by the following linear functions:

$$\%MD_{500} = 0.309 \times (\%RD_{500}) - 0.473, \quad R = 0.995 \tag{3}$$

$$\%MD_{600} = 0.300 \times (\%RD_{600}) + 0.737, \quad R = 0.942 \tag{4}$$

where the parameters $\%MD_{500}$ and $\%MD_{600}$ are the values of mechanical degradation (in percentage) of iron ore samples after reduction experiments at 500 and 600 °C temperatures, respectively. The parameters $\%RD_{500}$ and $\%RD_{600}$ are the values of reduction degree (in percentage) of these samples during reduction experiments at the appropriate temperatures. Also, *R* is the correlation coefficient, which in both cases is larger than 0.94. This illustrates that the correlations in equations (3) and (4) are very strong.

Overall, the obtained results mean that the mechanical degradation of natural hematite iron ore lumps during reduction at the given temperature range mainly depends on the fraction of reduced hematite, which is directly proportional to the value of the reduction degree.

2.2 Influence of sample weight on reduction degree and mechanical strength

In this study, the influence of the initial sample weight (W_0) on the reduction degree and mechanical degradation of the natural hematite iron ore was investigated. The *RD* values achieved during reduction experiments at different compositions of reduction gas and temperature are shown in Figure 5 for iron ore lumps taken from the top (T), middle (M) and bottom (B) reaction zones of the sample holder. It can be seen that the *RD* values obtained at 500 °C did not show clear relations to the original weight of the sample lumps and to the location of samples in different reaction zones. However, the *RD* values for most samples obtained at 600 °C decrease significantly with an increasing initial sample weight. For instance, the *RD* values of the samples with an initial weight of less than 5 g are higher than for those with an initial weight larger than 5 g by 15–25% on the average. Some samples with an initial weight of 3.5–4.5 g achieved

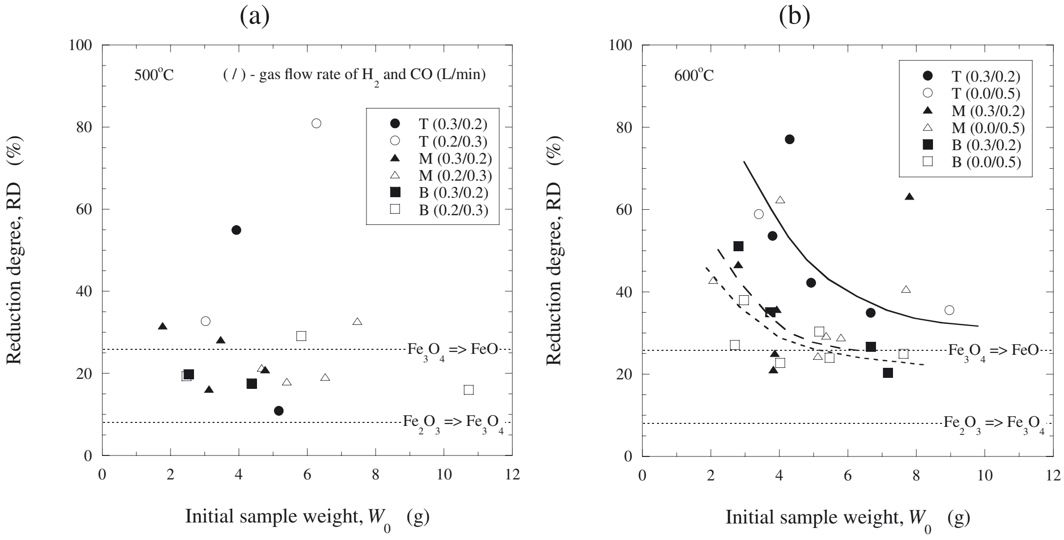

Fig. 5. Relationship between the reduction degree and initial weight of the sample lumps in different reaction zones for various gas flow rates and temperatures: (a) 500 °C and (b) 600 °C. T, M and B are the top, middle and bottom reaction zones.

RD values ranging from 60 to 80%. On the other hand, samples with an original weight larger than 5 g have *RD* values of 27 ± 5% on average. It should be pointed out that similar relationships between the *RD* and W_0 values were obtained for samples taken from each reaction zone. However, the *RD* values for the samples taken from the top reaction zone are larger than those from the middle and bottom zones. More specifically, they are 25–35% for samples with $W_0 < 5$ g and 10–15% for samples with $W_0 \geqslant 5$ g. Furthermore, it can be seen in Figure 5 that although the contents of H_2 and CO in the reduction gas mixture were varied in a wide range (0–60 vol.% H_2 and 40–100 vol.% CO), the *RD* values for samples having different initial weight do not show a clear dependency on the gas composition.

The results of the mechanical degradation of the natural iron ores with the initial weight of the samples are given in Figure 6. It can be seen that the relationships between the *MD* and W_0 values have similar trends, as those obtained for *RD* values at the appropriate temperatures. Thus, the disintegration does not change much with a changed initial sample weight at a 500 °C temperature. However, in the reduction experiments at 600 °C, the mechanical degradation of the iron ore lumps decreases with an increased initial weight of samples. For instance, the *MD* values for samples with $W_0 < 5$ g varied from 7–21%. The *MD* values decreased to 5–10% on average for samples with $W_0 \geqslant 5$ g. Moreover, the *MD* values for samples taken from the top reaction zone are larger than those from the middle and bottom zones. More specifically, they are 6–8% larger for samples with $W_0 < 5$ g and 2–4% larger for samples with $W_0 \geqslant 5$ g. This shows that the original weight of the samples has an influence on the low temperature strength of natural iron oxides.

Thus, the low temperature strength of the natural iron ores is influenced by the position of the sample in the furnace and the original sample weight. Samples in the top reaction zone of the furnace with a weight less than 5 g have significantly higher *RD* values at given temperatures than those in the middle and bottom zone as well as for those with weights larger than 5 g. The mechanical degradation of hematite iron ore lumps at higher *RD* values were also considerably higher due to the formation of internal pores and cracks in the iron oxide samples during the reduction of hematite. Presumably, the cracks developed during the hematite-magnetite transformation. Thereafter, they easily and quickly propagated through the small size lumps when subjected to impact

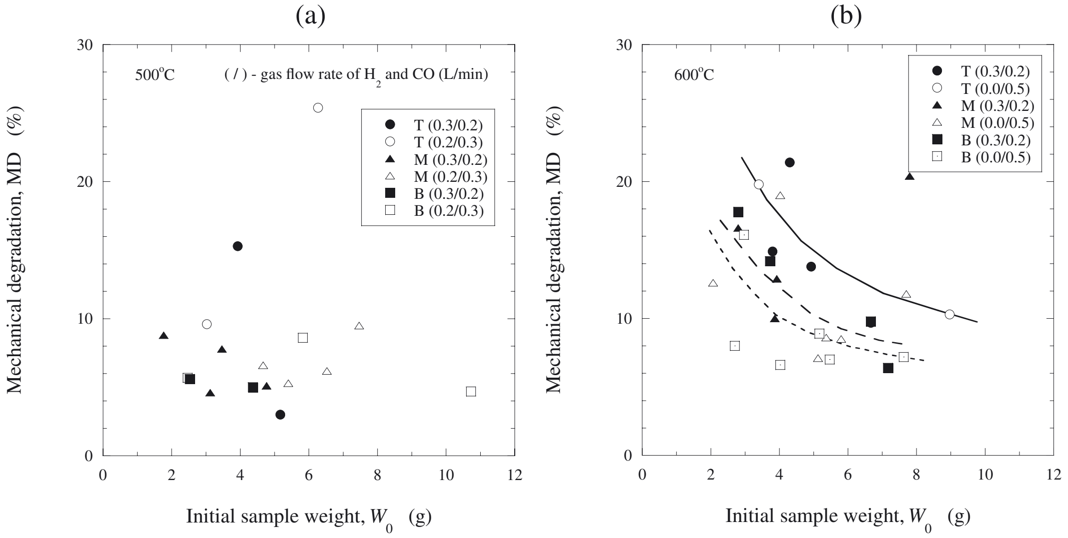

Fig. 6. Relationship between the mechanical degradation and initial weight of the sample lumps in the different reaction zones for various gas flow rates and temperatures: (a) 500 °C and (b) 600 °C. T, M and B are the top, middle and bottom reaction zones.

loading. Thus, disintegration took place. Therefore, iron ore samples with an initial weight less than 5 g cannot withstand impact loading during their descent in the furnace, though they achieve high *RD* values.

3 Conclusion

An impact of some important factors of the reduction process on the low temperature disintegration of natural hematite iron ore lumps was investigated in laboratory scale experiments. More specifically, the studied factors were temperature, gas composition, original weight of the sample lumps and their location in the reaction zones of the furnace. The reduction degree (*RD*) and mechanical degradation (*MD*) were determined for sample lumps taken from different reaction zones (top, middle and bottom) after reductions at temperatures of 500 and 600 °C. The main specific conclusions can be summarized as follows:

1. Although the contents of H_2 and CO in a reduction gas mixture were varied in a wide range (0–60 vol.% H_2 and 100–40 vol.% CO), the reduction degree (*RD*) and mechanical degradation (*MD*) values obtained in this study did not show a clear dependency on the gas composition.
2. The *RD* values for samples taken from the top reaction zone of the furnace obtained at both temperatures of 500 °C and 600 °C were higher than those for the samples taken from the middle and bottom reaction zones. The *RD* values reached a maximum of 80% at both 500 °C and 600 °C, in the top zone. The maximum *RD* values in both the middle and bottom reaction zones were 29–33% at 500 °C and 51–63% at 600 °C respectively. This is due to the higher reduction potential of the gas in the top zone of furnace compared to the lower zones.
3. The mechanical degradation (*MD*) values for the samples from the top zone were higher than those from the middle and bottom zones. They were found to be 3–25% at 500 °C and 10–21% at 600 °C in the top zone. The *MD* values in the middle and bottom zone were 5–16 at 500 °C and 6–20% at 600 °C, respectively. It was noted that the *MD* in the top reaction zone can be 2 times higher than in the other zones, particularly at 500 °C.
4. The mechanical degradation is directly proportional to the reduction degree of the sample lumps. It can be explained

by the formation of internal pores and cracks in the sample lumps during the reduction of hematite iron ore. These relations can very well be described by linear functions for the data at 500 and 600 °C.

5. The *RD* and *MD* values obtained at 500 °C did not show clear dependencies on the initial weight of the sample lumps (W_0). However, the *RD* and *MD* values for most samples obtained at 600 °C decrease significantly with an increasing W_0 value. Thus, the *RD* values of the samples with $W_0 < 5$ g are higher than those with $W_0 \geqslant 5$ g. Moreover, the samples with $W_0 < 5$ g degrade about 1.5 times more than those with $W_0 \geqslant 5$ g.

References

[1] S.L. Wu, H.F. Xu, Y.Q. Tian, *Ironmaking and Steelmaking* **36** (2009) 19-23

[2] W. Shengl-Li, L. Xiao-qin, Z. Qi, X. Jian, L. Cheng-Song, *J. Iron Steel Res.* **18** (2011) 20-24

[3] H. Brill-Edwards, R.L. Samuel, *J. Iron Steel Institute* **36** (1965) 361-368

[4] S. Watanabe, M. Yoshinaga, *TRANSACTIONS, Society of Mining Engineers* **241** (1968) 1-15

[5] N.A. Hasenack, H. Kister, R.B. Vogel, K.H. Van Toor, *Society of Mining Engineers, AIME* **260** (1976) 263-267

[6] J.S. Padan, Onkar Singh, K.N. Gupta, *NML Technical Journal* **20** (1978) 35-36

[7] H.W. Gudenau, H. Walden, Investigations on the stability of iron ore pellets during low temperature reduction, 3rd International Symposium on Agglomeration, Nurnberg West Germany, 1981

[8] S.C. Panigrahy, M. Rigaurd, J. Dilewijns, *Iron and Steel International* **57** (1984) 29-30, 32-33

[9] T. Takada, H. Soma, T. Irita, E. Kamisaka, M. Isoyama, A. Suzawa, *Transactions ISIJ* **25** (1985) B-235

[10] F. Adam, B. Dupre, C. Gleitzer, *Solid State Ionics* **32/33** (1989) 330-333

[11] M. Naito, A. Okamoto, K. Nakamura, K. Yamaguchi, Nippon Steel, 1990

[12] C.E. Loo, N.J. Bristow, Resistibility of iron ore sinters to low-temperature reduction degradation, 6th International Symposium on Agglomeration, Nagoya, 1993

[13] H.P. Pimenta, V. Seshadri, T. de Aguiar Pacheco, A.T. Azevedo, Characterization of structure of blast furnace sinter and its behaviour during reduction at low temperatures, 6th International Symposium on Agglomeration, Nagoya, 1993

[14] C.E. Loo, N.J. Bristow, *Trans. Inst. Min. Metall. C* **103** (1994) 91-168

[15] Y. Wenhui, *Iron and Steel* **31** (1996) 41-44

[16] H.P. Pimenta, V. Seshadri, *Ironmaking and Steelmaking* **29** (2002) 169-173

[17] S.S. Gupta, B. Nandy, *Tata Search*, 2002

[18] Iron ores for blast furnace feedstocks – Determination of low-temperature reduction-disintegration indices by static method – Part 2: Reduction with CO and N_2. British Standards Institution, British Standard, BS ISO 4696-2:2007, London, 2007

[19] Iron ores for blast furnace feedstocks – Determination of low-temperature reduction-disintegration indices by static method – Part 1: Reduction with CO, CO_2, H_2 and N_2. Swedish Standards Institute, International Standard, ISO 4696-1:2007(E), Switzerland, 2007

[20] A. Pineau N. Kanari, I. Gaballah, *Thermochim. Acta* **447** (2006) 89-100

[21] D. Bruce, P. Hancock, *British Corrosion Journal* **4** (1969) 221-222

[22] V. Kumar, S. Jena, S.K. Patel, *Mineral Processing and Extractive Metallurgy* **29** (2008) 118-129