Effects of Graphite, SiO₂, and Fe₂O₃ on the Crushing Strength of Direct Reduced Iron from the Carbothermic Reduction of Residual Materials

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The effects of various additives (Fe₂O₃, SiO₂, graphite) on the crushing strength of direct reduced iron (DRI) were investigated. Using a mixture of various residual materials produced in a steel plant, the chemical composition was altered using various additives. The mixture was then agglomerated into a cylindrical pellet and reduced at 1250°C for 15 min. The DRI was then tested for its crushing strength. It was found that adding graphite resulted in more carbon remaining in the DRI. Although the metallization degree of DRI was increased, the crushing strength of DRI decreased due to the presence of discontinuous carbon granules in DRI. Adding SiO₂ caused the slag basicity (the ratio between CaO and SiO₂) to decrease. The addition of Fe₂O₃ consumed the carbon content in the pellet, reducing the metallization degree of DRI. The softening and melting temperatures of slag were adjusted by changing the slag basicity and FeO content. A proper amount of Fe₂O₃ or SiO₂ addition increased the crushing strength of DRI due to the softening of slag. Excessive Fe₂O₃ or SiO₂ resulted in the melting of slag, which decreases crushing strength. [doi:10.2320/matertrans.M2009299]

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1. Introduction

In integrated steelmaking processes, some dust and sludges, commonly called residual materials, are inevitably generated along with the production of steel. Dumping of residual materials is not allowed by environmental protection regulations.¹⁾ The main constituents of residual materials are iron oxides and carbon. Others compounds include metallurgical slag components, alkali oxides, and impurities such as chlorine, phosphorus, and sulfur from the iron and steel making processes. Due to the high levels of iron oxide and carbon content, residual materials can be converted into direct reduced iron (DRI) via carbothermic reduction, in which solid state iron oxides are reduced using carbon as the reducing agent. The reaction of iron oxides and carbon can be performed if both materials are agglomerated in the form of pellets. Its main advantage is related to the reaction rate because of the reactant spacing and size. A high degree of reduction can be obtained with reaction times ranging from 10 to 20 min at temperatures between 1150 and 1250°C. DRI is a high degree metallization pellet which can be charged into the blast furnace to produce hot metal and to decrease fuel consumption.^{2,3)} However, the permeability of the blast furnace deteriorates in case of breakage of the burden materials. To maintain good permeability of the blast furnace, sufficient mechanical strength (>0.60 kg/mm²) of DRI is required to avoid DRI breakage during storage, transportation, and charging.

Meyer⁴⁾ found that the strength of a DRI pellet depends on the bonding strength between metallic and slag phases. DRI crushing strength results from the bonding forces between grains and the structure of the bonding matrix in the pellet.

Basically, two types of inter-grain bonding exist in DRI: metallic bonding and slag bonding. Gupta *et al.*⁵⁾ found that the crushing strength of DRI can be improved in the metallic phase by increasing the reduction temperature and subsequent sintering, and in the slag phase by increasing the amount of suitable slag forming additives. In addition, Gupta *et al.*⁶⁾ demonstrated that carbonaceous materials can affect the crushing strength of DRI. Takano *et al.*⁷⁾ stated that higher content of the binder such as Portland cement and blast furnace slag can be used to maintain reasonable compression strength of DRI pellets after heating.

In the carbothermic reduction process, the chemical composition of the mixture of residual materials can affect the crushing strength of DRI. However, the chemical composition and production of dust or sludge are not stable in an integrated steel mill due to the inherent variation of steel and iron making conditions. In the present study, the chemical composition of a mixture of residual materials produced in a steel plant was altered using various additives. The mixture was then reduced at 1250°C for 15 min. The factors that affect the crushing strength of DRI were investigated.

2. Experimental Method

2.1 Sample preparation

2.1.1 Pre-treatment of raw materials

The raw material used in this study was a mixture of iron-oxide-containing residual materials. The materials were prepared with various formation ratios in an integrated steel plant. The chemical analysis of residual materials and the yearly production of wastes are shown in Table 1. The reference mixture (Case A), which was made of nine kinds of residual material, was composed of 28.82% oily dewatered sludge, 19.15% blast furnace sludge, 17.05% basic

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Table 1 Mixing ratio and chemical composition of the reference mixture (Case A) from residual materials.

Source	Production (ton/year)	Mixing ratio (%)	Chemical Composition (mass%)												
			C	T. Fe	Fe (+0)	Fe (+2)	Fe (+3)	SiO ₂	Al ₂ O ₃	CaO	MgO	Zn	Pb	K	Na
BOF Dust	4,200	3.26	11.10	30.29	0.00	12.2	18.09	4.89	1.38	26.82	4.87	0.83	0.23	0.28	0.23
BOF Slurry	21,970	17.05	1.40	63.80	0.58	56.11	7.11	1.79	0.21	5.07	0.91	0.32	0.09	0.05	0.22
BF Flue Dust	3,426	2.66	39.00	31.80	0.00	3.44	28.36	6.26	2.60	4.47	0.81	0.05	0.02	0.09	0.11
IWI Fly-Ash	5,500	4.27	2.60	23.34	0.00	0.95	22.39	17.55	7.58	21.67	2.87	0.06	0.02	0.99	0.79
BF Hi-Zn Sludge	11,833	9.19	32.50	30.60	0.00	3.51	27.09	6.37	2.35	4.16	0.72	2.84	0.93	0.12	0.23
BF Sludge	24,669	19.15	35.70	28.67	0.00	4.45	24.22	6.13	2.51	6.05	0.85	1.72	0.45	0.12	0.20
Oily Mill Scale	17,460	13.55	0.70	73.74	0.10	53.37	20.27	1.20	0.14	0.08	0.04	0.01	0.01	0.02	0.08
Oily DW Sludge	37,125	28.82	6.50	49.75	0.00	26.98	22.77	2.26	0.49	12.55	0.84	0.16	0.06	0.02	0.10
CRM Sludge	2,640	2.05	9.90	28.01	0.00	4.09	23.92	4.76	0.73	17.67	4.15	0.64	0.02	0.09	0.25
mixture	128,823	100	13.74	46.91	0.11	26.36	20.44	4.05	1.35	8.31	1.02	0.73	0.21	0.11	0.19

Table 2 Compositions of mixtures with various additives blended into Case A before reaction.

Code	Sample	Basicity	Chemical Composition (mass%)					
			C	T. Fe	Fe	FeO	Fe ₂ O ₃	Slag
A	100% Case A	2.05	13.74	46.91	0.11	33.89	29.20	14.73
AC-2	98% Case A + 2% graphite	2.05	15.47	45.98	0.11	33.21	28.62	14.44
AC-4	96% Case A + 4% graphite	2.05	17.19	45.04	0.11	32.53	28.03	14.14
AC-6	94% Case A + 6% graphite	2.05	18.92	44.10	0.10	31.86	27.45	13.85
AS-5	95% Case A + 5% SiO ₂	0.89	13.05	44.57	0.10	32.20	27.74	18.99
AS-10	90% Case A + 10% SiO ₂	0.55	12.37	42.22	0.10	30.50	26.28	23.26
AS-15	85% Case A + 15% SiO ₂	0.38	11.68	39.88	0.09	28.81	24.82	27.52
AF-10	90% Case A + 10% Fe ₂ O ₃	2.05	12.37	49.22	0.10	30.50	36.28	13.26
AF-15	85% Case A + 15% Fe ₂ O ₃	2.05	11.68	50.38	0.09	28.81	39.82	12.52
AF-20	80% Case A + 20% Fe ₂ O ₃	2.05	10.99	51.53	0.09	27.11	43.36	11.78

oxygen furnace slurry, and 13.55% oily mill scale. The rest of the residual materials were basic oxygen furnace dust, blast furnace flue dust, waste incinerator fly-ash, blast furnace high-zinc sludge, and cold-rolling sludge. Each source material was first dried at 105°C in an oven and then weighed according to the mixing ratio (Table 1). All the residual materials were then blended uniformly in a mixer.

The Basicity (CaO/SiO₂) of the mixture, which is defined as the mass percent of CaO to that of SiO₂, was 2.05 and the total iron content was 46.91% for Case A, as shown in Table 2.

2.1.2 Mixture and agglomeration

As shown in Table 2, the addition of 2, 4, and 6% graphite in Case A, which had a basicity of 2.05, decreased the total iron content from 46.91 to 45.98, 45.04, and 44.10%, respectively. Adding 5, 10, and 15% SiO₂ in Case A decreased the basicity from 2.05 to 0.89, 0.55, and 0.38, and reduced the total iron content to 44.57, 42.22, and 39.88%, respectively. The addition of 10, 15, and 20% Fe₂O₃ in Case A, while maintaining the basicity at 2.05, increased the total iron content to 49.22, 50.38, and 51.53%, respectively. The prepared residual materials were mixed uniformly with light starch water and placed into a steel die (8 mm in diameter and 10 mm in height) to be pressed into cylindrical pellets. The pellets were dried at room temperature for subsequent reduction reaction experiments.

2.2 Characterization

2.2.1 Carbothermic reduction experiment

For all specimens shown in Table 2, pellets with the same composition were placed onto a ship-shaped crucible (50 mm in length × 14 mm in width × 7 mm in depth) in a horizontal tubular furnace with an inner tube diameter of 31.75 mm, as shown in Fig. 1. The pellets were then reduced at 1250°C in an argon atmosphere (1 Nℓ/min) for 15 min. When the reaction time was reached, the samples were quickly taken out and placed into a cooling container for quenching in a high-flow-rate argon stream to prevent re-oxidation. The samples became DRI after the carbothermic reaction. The microstructure of DRI samples was observed using a metallographic microscope. The analysis results of DRI sample composition are given in Table 3. The metallization degree was calculated using:

$$\text{Metallization degree (\%)} = \frac{\text{metal iron in DRI}}{\text{total iron in DRI}}$$

2.2.2 Crushing strength test

The size of each DRI sample was measured with a vernier. Each sample was then placed on the stage of a universal testing machine (Cometech, Model: QC508B1, maximum load of 500 kg) to measure its crushing strength. Each pellet was loaded slowly at room temperature until yielding occurred. The minimum load required for breakage/deformation of the pellet was recorded in kilograms. The measurement unit in

Fig. 1 Schematic illustration of apparatus with a horizontal tubular furnace used as a high temperature reactor to produce DRI pellets.

Fig. 2 Crushing strength of DRI for various graphite additions in Case A (1250°C, 15 min).

Table 3 Chemical composition of DRI (reaction condition: 1250°C, 15 min).

Code	Sample	Chemical Composition (mass%)						Metallization Degree (%)
		C	T. Fe	Fe	FeO	Fe ₂ O ₃	Slag	
A	100% Case A	0.37	74.62	56.22	23.55	0.21	19.17	75.34
AC-2	98% Case A + 2% graphite	2.11	74.68	61.96	16.52	0.00	18.97	82.97
AC-4	96% Case A + 4% graphite	4.65	71.44	59.63	17.46	0.00	17.83	83.47
AC-6	94% Case A + 6% graphite	7.64	69.70	56.56	18.32	0.00	17.05	81.15
AS-5	95% Case A + 5% SiO ₂	1.26	67.68	51.69	21.17	0.00	25.43	76.37
AS-10	90% Case A + 10% SiO ₂	2.35	64.00	47.10	21.92	0.00	28.11	73.59
AS-15	85% Case A + 15% SiO ₂	2.42	60.45	42.90	20.07	2.84	31.30	70.97
AF-10	90% Case A + 10% Fe ₂ O ₃	0.46	74.75	49.69	31.07	1.28	16.96	66.47
AF-15	85% Case A + 15% Fe ₂ O ₃	0.65	74.51	40.10	39.51	5.26	13.65	53.82
AF-20	80% Case A + 20% Fe ₂ O ₃	0.54	75.18	38.02	42.97	5.34	12.55	50.57

the study was the ratio of load to forced area. At least eight pellets obtained under the same conditions were measured to compute an average value for DRI crushing strength.

3. Results and Discussion

3.1 Carbon addition effect

Figure 2 shows the crushing strength of DRI pellets with the addition of various amounts of graphite into Case A (as listed in Table 3) and reduced at 1250°C for 15 min. Table 3 shows the chemical compositions of the DRI samples.

As shown in Fig. 2, the crushing strength of DRI for Case A was 1.66 kg/mm² after the reduction reaction. The crushing strength with the addition of 2% graphite was 0.71 kg/mm². Adding a small amount of graphite to Case A drastically decreased the crushing strength of DRI. The composition of DRI samples with 2% graphite addition was compared to that for Case A, as shown in Table 3. Only 0.37% carbon remained in the DRI for Case A. Adding 2% graphite in Case A resulted in 2.11% carbon remaining in the DRI. Moreover, the metallization degree of DRI for Case A increased from 75.34 to 82.97% with the addition of 2% graphite. This shows that the addition of 2% graphite increased the reduction of iron oxide to metal iron. However, excessive carbon remained in the DRI sample.

During the reduction reaction, carbon reduces iron oxide to metal iron and forms metallic bonds, which benefits the crushing strength of DRI.⁴⁾ In this case, the metallization degree of DRI was increased by carbon addition. However, the crushing strength of the DRI deteriorated.

Figure 3 shows the cross sectional photographs of metallographic observation of various DRI samples. Figure 3(a) shows the cross sectional micrograph for Case A. A Continuous phase of metal iron can be observed in the matrix. Figure 3(b) shows the cross sectional micrograph of metallographic observation for the DRI sample with 2% graphite addition. It can be seen that carbon granules remained among the continuous phase in the matrix. The continuous phase of metallic bonding was partly broken up by carbon granules, which resulted in the discontinuous phase. This in turn decreased the crushing strength of DRI.

As shown in Fig. 2, the crushing strengths with the additions of 4 and 6% graphite were 0.52 and 0.30 kg/mm², respectively. Adding more graphite to Case A decreased the crushing strength of DRI. Table 3 shows that increasing the amount of graphite added increased the amount of carbon that remained in the DRI. Although the addition of graphite increased the metallization degree of DRI, it is not benefited for DRI crushing strength. The discontinuous phase of

Fig. 3 Cross sectional photographs of metallographic observation (OM $\times 50$) for (a) Case A; (b) 2% graphite; (c) 4% graphite; and (d) 6% graphite.

Fig. 4 Crushing strength of DRI for various SiO₂ additions in Case A (1250°C, 15 min).

metallic bonding was broken up by carbon granules, as shown in Fig. 3(c) and (d), which deteriorated the crushing strength of DRI.

3.2 SiO₂ addition effect

Figure 4 shows the crushing strengths of DRI for Case A with 5, 10, and 15% SiO₂ addition were 2.18, 0.98, and 1.28 kg/mm², respectively. The crushing strength of DRI for Case A was 1.66 kg/mm². The addition of 5% SiO₂ increased the crushing strength of DRI. The main chemical composition of the slag series is CaO-SiO₂-MgO-Al₂O₃. The initial composition of the slag in Case A was 8.31% CaO, 4.05% SiO₂, 1.35% Al₂O₃, and 1.02% MgO (as shown in Table 1). In order to discuss the effects of slag bonding in

Table 4 Effect of adding SiO₂ on the slag composition before reaction.

Code	Sample	Slag Composition (mass%)			
		CaO	SiO ₂	MgO	Al ₂ O ₃
A	100% Case A	56.4	27.5	6.9	9.2
AS-5	95% Case A + 5% SiO ₂	41.6	46.6	5.1	6.8
AS-10	90% Case A + 10% SiO ₂	32.2	58.7	3.9	5.2
AS-15	85% Case A + 15% SiO ₂	25.7	67.0	3.2	4.2

DRI, these four constituents were added up and counted as 100%. Then, the slag composition becomes 56.4% CaO, 27.5% SiO₂, 6.9% MgO, and 9.2% Al₂O₃, respectively. The addition of SiO₂ in Case A led to a change in the slag composition (see Table 4). From the slag composition in Table 4, the CaO-SiO₂-5%MgO-Al₂O₃ phase system,⁸⁾ which is close to the composition of the slag series and available in the literature, was employed to examine the melting temperature of the slag. In general, slag basicity is used to determine the thermodynamic and kinetic equilibrium between the ionic components of the slag and the liquid metal. In a previous study,⁹⁾ it found that slag basicity and FeO content affect the softening and melting temperatures of slag. Furthermore, Fe₂O₃ and FeO can influence the melting temperature of the slag according to the phase diagrams CaO-SiO₂-Fe₂O₃¹⁰⁾ and CaO-SiO₂-FeO.¹¹⁾ It is well known the reduction reactions proceed along the sequence of Fe₂O₃ → Fe₃O₄ → FeO → Fe. The reduction of Fe₂O₃ by carbon occurs in two stages: it is first reduced to FeO, and then to Fe. The reduction of FeO to Fe was found to be slower than the reduction of Fe₂O₃ to Fe₃O₄ and that of Fe₃O₄ to FeO.¹²⁾ So the effect of Fe₂O₃ on the slag only acts

on the preliminary step of the reduction reaction. Besides, the content of Fe_2O_3 remaining in DRI was very little, as seen in Table 3. In order to discuss the relationship of slag basicity and iron oxides, FeO is considered the main iron oxide (Fe_2O_3 , Fe_3O_4 , and FeO) in the pellet during and after the reaction. Therefore, the FeO content represents the total content of FeO and Fe_2O_3 in the discussion here, and the FeO content is used to discuss the combined effects of FeO and Fe_2O_3 on the softening and melting temperatures of the sample, as shown in the relationship:

$$\text{Effect of FeO content on the slag} = \frac{\text{FeO} + \text{Fe}_2\text{O}_3}{\text{FeO} + \text{Fe}_2\text{O}_3 + \text{Slag}}$$

Table 5 shows the effect of mass percentage of FeO on the slag phase before and after the reaction stage.

The Basicity of Case A was 2.05. According to the $\text{CaO-SiO}_2\text{-5\%MgO-Al}_2\text{O}_3$ phase system in Fig. 5, the liquidus temperature of the slag was higher than 1600°C (point a). No

reports could be found on the softening and melting temperatures of the $\text{CaO-SiO}_2\text{-5\%MgO-Al}_2\text{O}_3\text{-FeO}$ slag. Therefore, the phase diagram¹¹⁾ of ternary slag ($\text{CaO-SiO}_2\text{-FeO}$) in Fig. 6 was employed to examine the softening and melting temperatures of the slag. The FeO content in the slag phase

Fig. 5 Phase diagram of quaternary slag ($\text{CaO-SiO}_2\text{-5\%MgO-Al}_2\text{O}_3$).⁸⁾

Fig. 6 Phase diagram of ternary slag ($\text{CaO-SiO}_2\text{-FeO}$).¹¹⁾

Fig. 7 Cross sectional photographs of metallographic observation (OM $\times 50$) for (a) Case A; (b) 5% SiO₂; (c) 10% SiO₂; and (d) 15% SiO₂.

during the reaction process changed from 81.1 to 55.4%. Figure 6 shows that the liquidus temperature of the slag increased from 1290 to 1570°C. This indicates that the melting temperature of the slag was much higher than the reaction temperature (1250°C). Therefore, the slag did not melt or even soften. For metallographic observations, the samples were quickly removed and placed in a cooling container to be quenched with a high-flow-rate nitrogen stream after the reaction was completed. Figure 7(a) shows the cross sectional photographs of metallographic observation of the DRI samples of Case A. The continuous phase in the matrix for Case A was metal iron.

The addition of 5% SiO₂ changed the slag composition (as shown in Table 4) and decreased the slag basicity to 0.89 (as shown in Table 2). According to the CaO-SiO₂-5%MgO-Al₂O₃ phase system in Fig. 5, the liquidus temperature of the slag was around 1380°C (point b). The FeO content in the slag phase during the reaction process changed from 75.9 to 45.4%. Figure 6 shows that the liquidus temperature of the slag decreased from 1330 to 1250 and then to 1200°C (points a, b, and c, respectively). Most of the time during the reaction course (from point a to point b), the reaction temperature was below the liquidus temperature of the slag. Therefore, no melting occurred. However, certain softening could be anticipated. For the short period of the later stage of the reaction (from point b to point c), the reaction temperature was above the liquidus temperature of the slag. Therefore, slight melting occurred. Figure 7(b) shows the micrograph of Case A with the addition of 5% SiO₂. A large area of the continuous phase can be observed. The continuous phase in the matrix was the solidified softened slag mixed with metallic iron, which increased the crushing strength of DRI.

The crushing strength of DRI for Case A with the addition of 10% SiO₂ was 0.98 kg/mm², which is lower than that for 5% SiO₂. Slag basicity with the addition of 10% SiO₂ was 0.55 (as shown in Table 2). Figure 5 shows that the liquidus temperature of the slag was around 1320°C (point c). The FeO content in the slag phase during the reaction process changed from 70.9 to 43.8%. Figure 6 shows that the liquidus temperature of the slag decreased from 1270 to 1250 and then to 1120°C (points d, e, and f, respectively). Most of the time during the reaction course (from point e to point f), the reaction temperature was above the liquidus temperature of the slag. Therefore, melting occurred. Figure 7(c) shows that there was a number of large hole areas due to the leakage of the melted slag out of the DRI, which decreased the DRI crushing strength. It can also be observed that the melted slag seeped through the bottom of the DRI at the end of the experiment, as shown in Fig. 8. This loosened the structure of DRI and decreased the crushing strength.

As shown in Fig. 4, the crushing strength of DRI for Case A with the addition of 15% SiO₂ was 1.28 kg/mm², which is higher than that of 10% SiO₂. Slag basicity with the addition of 15% SiO₂ was 0.38. Figure 5 shows that the liquidus temperature of the slag was around 1420°C (point d). The FeO content in the slag phase during reaction process changed from 66.3 to 42.3%. Figure 6 shows that the liquidus temperature of the slag decreased from 1210 to 1120°C (points g and h, respectively). This indicates that the slag melted during the course of the reaction. However, the liquidus temperature for the slag with the addition of 15% SiO₂ without considering the effect of FeO was 1420°C, which is much higher than that for the

Fig. 8 Melted slag seeping through the bottom of DRI (Case A + 10%SiO₂).

Fig. 9 Crushing strength of DRI for various Fe₂O₃ additions in Case A (1250°C, 15 min).

slag with 10% SiO₂ (1320°C). This can be anticipated that the melting for the slag with the basicity of 0.38 at 1250°C was not as serious as that of 0.55. Figure 7(d) shows that there were fewer large hole areas in comparison to these in Fig. 7(c). Therefore, the crushing strength of DRI with a basicity of 0.38 was higher than that of DRI with a basicity of 0.55.

3.3 Fe₂O₃ addition effect

Figure 9 shows the crushing strength of DRI with the addition of various amounts of Fe₂O₃ (as listed in Table 3) and reduced at 1250°C for 15 min. The crushing strengths for additions of 10, 15, and 20% Fe₂O₃ in Case A were 2.64, 2.48, and 1.64 kg/mm², respectively. The crushing strength of DRI for Case A was 1.66 kg/mm². The crushing strengths with 10 and 15% Fe₂O₃ added were higher than that for Case A. However, the addition of 20% Fe₂O₃ did not further increase crushing strength. From Table 3, the remaining carbon content in the DRI for Case A with or without the addition of Fe₂O₃ was rather small. However, iron oxide (FeO and Fe₂O₃) content remaining in the DRI increased with increasing amount of Fe₂O₃ addition due to the exhaustion of fixed carbon. Hence, the metallization degree of DRI gradually decreased with increasing amount of Fe₂O₃ addition.

The slag basicity of Case A with or without the addition of Fe₂O₃ was 2.05 (as shown in Table 2). No reports could be found on the softening and melting temperatures of slag with FeO content and a basicity of 2.05. Therefore, the phase diagram of ternary slag (CaO-SiO₂-FeO) in Fig. 6 was again employed to examine the softening and melting temperatures of the slag. The liquidus temperature of the slag with a basicity of 2.05 significantly decreased with increasing FeO content. During the reduction process, Fe₂O₃ is reduced by carbon to FeO and then to metallic iron. The amount of iron oxide in a pellet during the reaction gradually decreases over time, which gradually increases the liquidus temperature of the slag.

As shown in Table 3, FeO content in the DRI for Case A was 23.55%. Adding 10, 15, and 20% Fe₂O₃ in Case A resulted in 31.07, 39.51, and 42.97% of FeO content remaining in the DRI, respectively. This reveals that the FeO content for these samples was higher than that for Case A during the reaction process. A proper amount of FeO decreased the softening temperature to below the reaction temperature (1250°C), at which point part of the slag started to soften. Figures 10(a) and (b) show the cross sectional micrographs of Case A and the sample with the addition of 10% Fe₂O₃, respectively. Figure 10(a) shows that the continuous phase in the matrix for Case A was metal iron. The continuous phase in the matrix in Fig. 10(b) is solidified softened slag mixed with metallic iron. The solidified softened slag then formed slag bonds while metallic iron formed metallic bonds, which significantly strengthens the DRI crushing strength in comparison to Case A.

From Fig. 9, further increasing the Fe₂O₃ content to 15 and 20% decreases the crushing strength of DRI. This can be explained using Fig. 6; an excessive amount of FeO decreases the melting temperature of the slag to below the reaction temperature (1250°C). Therefore, part of the softening slag started to melt and seep through the bottom of the DRI sample. Figures 10(c) and (d) show the additions of 15 and 20% Fe₂O₃ increased the number of holes in the matrix. For this reason, adding more than 10% Fe₂O₃ decreases the crushing strength of DRI.

4. Conclusion

A pellet with the mixture of nine kinds of residual material from an integrated steel mill was composed of 28.82% oily dewatered sludge, 19.15% blast furnace sludge, 17.05% basic oxygen furnace slurry, and 13.55% oily mill scale (Case A). The basicity of Case A was 2.05 and the total iron content was 46.91%. The effects of various additives (Fe₂O₃, SiO₂, graphite) on the crushing strength of direct reduced iron (DRI) were investigated. The following conclusions can be drawn.

- (1) Adding graphite to residual materials resulted in more carbon remaining in the DRI after the reduction reaction. Although the metallization degree of DRI was increased, the crushing strength decreased with increasing residual carbon content. The discontinuous phase of metallic bonding was broken up by carbon granules, which decreased the crushing strength of DRI.

Fig. 10 Cross sectional photographs of metallographic observation (OM $\times 50$) for (a) Case A; (b) 10% Fe₂O₃; (c) 15% Fe₂O₃; and (d) 20% Fe₂O₃.

- (2) Adding a proper amount of SiO₂ (5% in this study) increases the crushing strength of DRI as the reaction temperature is between the softening temperature and melting temperature. Slag can be softened and form slag bonds along with metallic bonds. Further addition of SiO₂ (10 and 15% in this study) decreased the crushing strength since the reaction temperature became higher than the melting temperature, making the slag melt and drain from the DRI.
- (3) Adding up to 20% Fe₂O₃ can increase the crushing strength of DRI. However, 10% Fe₂O₃ has the maximum effect. Further addition of Fe₂O₃ gradually decreases the crushing strength. This trend is similar to that for the addition of SiO₂. Mechanisms similar to those for the SiO₂ case can be used to understand the effects of Fe₂O₃ addition on the crushing strength of DRI.

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