STUDY ON FORMATION MECHANISM OF RETURN FINES IN SINTERING PROCESS[1]

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Abstract

The Formation of return fines not only reduces productivity but also affects moisture and fuel additions when they return to blending. Previous researches mainly focus on the effects of parameters, such as temperature and basicity, on the formation rate of return fines, and their size or addition on sintering. However, the formation mechanism hasn't been clearly and deeply studied. By analyzing mineralization, two main breaking forms of sintered body are summarized in this paper, then the experiments are conducted to study the effects of corresponding factors namely liquid fluidity, pore and mineral properties in bonding phase so that the formation mechanism of return fines is unveiled. The results show that: (1). Essence of failure in effective bonding is insufficient bonding interface due to low liquid fluidity, which can be ascribed to two reasons: low segregated basicity or heat shortage, and significant decrease in proper primary liquid fluidity caused by excessive assimilability of nuclei.(2)Low self-strength of bonding phase is primarily related to weak structure and high internal stress of minerals. When the pores in bonding phase matrix have macroporous and thin-walled structure, it has the most negative impact on the strength, high porosity and their uneven distributions in SFCA also reduce the strength of bonding phase. Besides, SFCA decrease or large pieces of hematite entrainment in SFCA caused by basicity segregation reduces self-strength of bonding phase.

Key words: Iron ore; Sintering; Return fines; Formation mechanism.

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1 INTRODUCTION

Return fines is generally of great importance to efficient ironmaking as it comprises 20 to 30 percent of the sintered cake, and will be recycled back to the sintering process, so the formation of return fines not only influences sintering yield and productivity, but also affects the operating parameters,[1,2] such as moisture and coke addition. Since the ratio of return fines impacts sintering efficiency and stability, its generation increases CO_2 emissions and energy consumption overall. Therefore, the formation of return fines, which is thought to be ascribed to inferior strength of sintered body, is very important to the whole sintering process.

Referring to the formation of return fines, most researchers studied the influences of parameters, such as temperature,[3,4] basicity,[5,6] ignition[7,8] and etc. With regard to lower strength leading to the return fines, Sato, Kawaguchi and Ichidate,[9] thought that sinter strength are dependent on porosity, mineral composition and melting ratio, while Oyama, Nushiro and Konishi,[10] found that the porosity and the pore size distribution are also the main factors that influence sinter cake strength besides mineral compositions such as calcium-ferrite and amorphous silicate percentage, they thought that the pore size distribution is the most important factor within whole contribution as it counts as high as 60%. Higuchi and Heerema,[11] proved the importance of pore distribution which was characterized with matrix length between the adjacent pores by carrying out experiments with hematite tablet. Kasai, Wu e Omori,[12] found that shatter strength of quasi-particles had fair linear relationship with liquid fluidity of the adhering fines, and they also pointed out that the chemical compositions of adhering layers, large pores and LOI of core particles are the dominant factors governing strength. Since the chemical composition and sintering conditions are of great significance for sinter strength, LOO and Wong[13] revealed that the factors, such as silica, alumina, magnesia, bacisity and the highest sintering temperature, affected the bonding phase structures, especially the pore structure through reshaping and coalescing of melt and bubbles.

However, previous researchers paid too much attention on the conventional sintering parameters with the aim of obtaining lower return fine ratios. Besides, available researches about the influences of pore structure on crushing strength of sintered specimen were mainly conducted with chemical reagent, which is thought to be quite different in both compositions and structures of iron-bearing or gangue minerals form actual sintering iron ore, and since the effect of melt property, pore structure and mineral property are generally unified as a whole in the sintering process, they were rarely combined in previous researches to clearly and deeply reveal the mechanism of inferior strength of sintered body. Therefore, the influences of the liquid fluidity and the pore structure as well as the mineral property on iron ore sintered specimen are investigated based on two main breaking forms summarized with bonding appearance in this paper, so that formation mechanism of return fines and the influencing factors is unveiled.

2 ANALYSIS OF TYPICAL BREAKING FORM OF SINTERED BODY

Figure 1 shows the cross section of sintered body of typical limonite. It is seen that quasi-particles mainly appear in two forms, one is inefficient bonding as sintered quasi-particles standing next to each other with thin matrix length, the other is efficient bonding as sintered particles binding as a whole. When the sintered body crushed or dropped, due to the weaker strength, the cracks would happen in locations along the marked dot lines shown in Figure 1.

On the one hand, as the liquid phase generated at high temperature acts as the bridges connecting neighboring particles, so the matrix thickness of the connecting bridge is dependent on the liquid property, especially the liquid fluidity. On the other hand, even if the particles were efficiently bonded with thick matrix length, they would broke up when the self-strength of the bonding phase was low, so the self-strength of bonding phase is the other factor that determines the strength of the sintered body. Generally speaking, cracks usually happened around pores or minerals of inferior intensities. Hence, the influence of factors named liquid fluidity, pore structure and mineral property would be discussed in this paper.

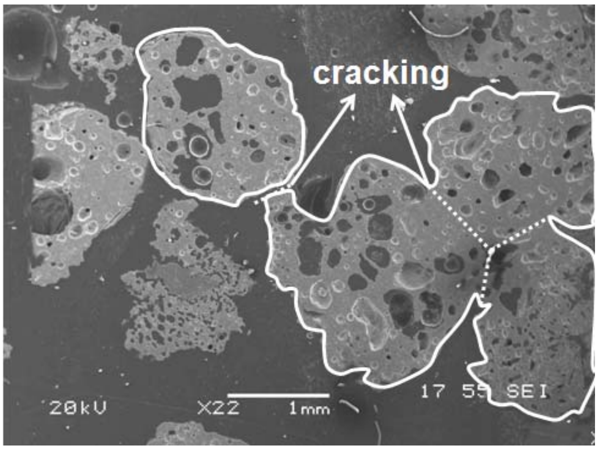

Figure 1 Schematic diagram of breaking forms of sintered body

3 MATERIALS AND METHODS

3.1 Sample Materials

Chemical Compositions of the materials used in the experiments are listed in Table 1. They are Australian limonite Ore A, marra mamba pisolite Ore B, Australian hematite Ore C, Brazilian hematite Ore D, Ore E, and sintering blend Ore F from some sintering plants in China. Ore A is characterized by its porous structure and the highest combined water amount, while Ore B and C are featured by high alumina content. Ore F is a typical iron ore with low silica content.

Table.1 Chemical compositions of raw materials (mass%)

Material	T.Fe	FeO	SiO_2	CaO	Al_2O_3	MgO	LOI	CW	Ore type	District
Ore A	57.99	0.19	5.40	0.04	1.61	0.05	10.17	9.08	Limonite	Australia
Ore B	61.07	0.30	3.70	0.03	2.20	0.05	6.24	5.81	Marra mamba	Australia
Ore C	62.46	0.28	4.41	0.03	2.35	0.04	3.29	3.05	Hematite	Australia
Ore D	64.89	0.55	4.55	0.02	0.73	0.07	1.36	1.26	Hematite	Brazil
Ore E	65.36	0.17	1.78	0.02	1.31	0.03	2.09	1.59	Hematite	Brazil
Ore F	60.93	1.27	3.98	1.25	1.45	0.34	5.55	4.47	Sintering Blend	China

3.2 Experimental Method

3.2.1 Preparation of iron ore compacts

To focus on the influence of the pore structure and the mineral properties on the self-strength of boding phase, analytical grade reagent CaO and iron ores (Ore A to Ore F) are mixed with CaO/Ore equals to 0.1, then, then take Ore F as an example, change the ratio of CaO/Ore to 0.075 and 0.125. The cylinder tablet is pressed with the mixed powder, and sintered in an infrared image furnace using a simulated sintering temperature profile as shown in Figure 2.

After the compact is sintered, it is embedded in epoxy resin and polished for pore structure observation and mineral property evaluation. In addition, the self-strength of bonding phase of sintered sample is measured by crush method [14] as well.

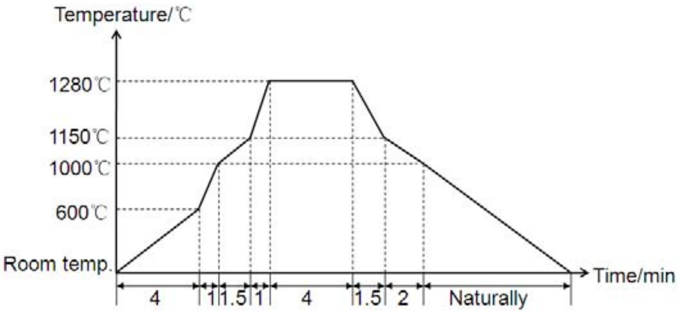

Figure 2 Experimental sintering tempersature profile.

3.2.2Preparation of quasi-particles

In order to clarify the effect of liquid fluidity on the bonding efficiency of quasi-particles, the experiments are conducted. In this experiment, iron ores are crushed into sizes ranged in 1.8-2.0mm to be cores, and the sintering blend is grinded into fines smaller than 0.25mm to be adhering fines, then add CaO reagent into the grinded fines with CaO/Ore ratio equals to 0.2, 0.15 or 0.25. After that, the quasi-particles are made with 60 mass% cores and 40 mass% adhering fines under the effect of moisture in a balling disc, and dried at 105℃ for 5 hours afterwards. Then they are charged into a transparent quartz tube (φ16mm×20mm) and sintered in the infrared furnace following the same sintering temperature profile as iron ore compact. After being sintered, the specimen is dropped from the height of 2m onto iron plate with thickness of 5mm for five times. The bonding strength of quasi-particles is evaluated by the percentage of samples larger than 5mm. Detailed information of experiments is listed in Table 2.

Table.2 Detailed information of the experiments

Number	Iron ore Compact		Quasi-particles		
	Ore	CaO/Ore*	Nuclei core	Adhering fines	CaO/Ore**
A	Ore A	0.100	Ore A	Ore F	0.20
B	Ore B		Ore B	Ore F	0.20
C	Ore C		Ore C	Ore F	0.20
D	Ore D		Ore D	Ore F	0.20
E	Ore E		Ore E	Ore F	0.20
F	Ore F		Ore A	Ore F	0.15
G	Ore F	0.075	Ore A	Ore F	0.25
H	Ore F	0.125	——	——	——

CaO/Ore for pore structure and mineral property investigation, and CaO/Ore** for investigation of influence of liquid fluidity.*

3 RESULTS AND DISCUSSION

3.1 Influence of Liquid Fluidity on Bonding Strength of Quasi-particles

The liquid generated in the adhering layer at the high temperatures acts as the binder to connect the un-melted ores. Liquid fluidity is believed to act efficiently in obtaining high bonding strength and good permeability in mediate range. Since liquid phase in sintering is influenced not only by the compositions in adhering layer, but also by nuclei cores in quasi-particles, fluidity of liquid changes all the time at the high temperatures, so the bonding effect of liquid phase varied.

Figure 3 shows the macroscopic image of sintered quasi-particles with different CaO/Ore in adhering layer but the same nuclei of limonite Ore A. Figure 4 shows macroscopic image of sintered quasi-particles with different nuclei when CaO/Ore is fixed at 0.20 in adhering layer.

It is seen from Figure 3 that the bonding phase appears to fill the gaps among quasi-particles with the increasing CaO/Ore, and too much bonding phase form to wrap gaps and surface of sintered sample in samples G. Furthermore, the macroscopic images are quite different from each other with different nuclei. Since the limonite has strong assimilation ability,[15] the porous nuclei are thought to easily react with melt surrounded, so the acid ore dissolves into the molten layer, fluidity of secondary liquid drops, and the bonding ability weakens, consequently, more porous morphology is observed with sample A in Figure 4. On the contrary, as Brazilian hematite usually has weaker assimilation ability,[15] better bonding effects present with large amounts of bonding phase on the surface.

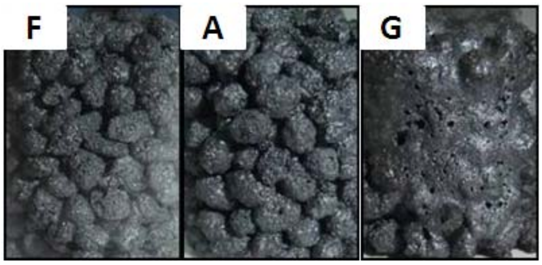

Figure 3 Macroscopic image of sintered quasi-particles with different CaO/Ore, nuclei A.

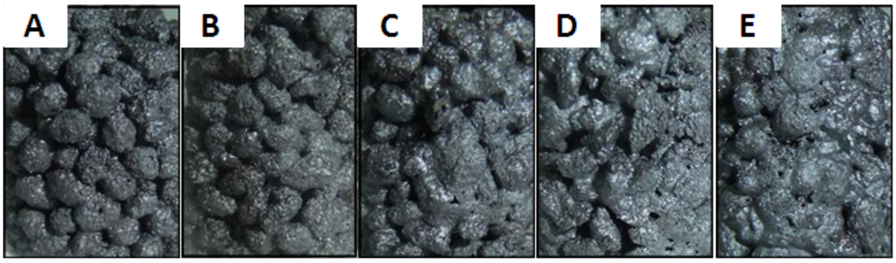

Figure 4 Macroscopic image of sintered quasi-particles with different nuclei, CaO/Ore=0.20.

The shatter strength of sintered quasi-particles under different nuclei and adhering layer conditions are shown in Figure 5. When the nuclei are the same as Ore A, the shatter strength or bonding strength was improved with increased CaO/Ore ratio, because the bonding liquid property, especially the liquid fluidity improved as shown in Figure 6, measured with projection area method.[16] Moreover, when the properties of adhering layer are the same, the shatter strength of sintered quasi-particles with hematite nuclei seems to be higher, for the bonding phase observed to be sufficient and efficient in bonding after the liquid phase condensed and consolidated.

As summarized from macroscopic image of sintered quasi-particles and the shatter strength, the bonding interface is a significant factor for efficient bonding, which is mainly determined by the fluidity of secondary liquid. As shown in this paper, both the primary liquid generated in adhering layer and the assimilation ability of the nuclei affect the fluidity of secondary liquid. Hence, segregated basicity or heat shortage that may cause lower primary liquid fluidity would result in insufficient interface, leading to inferior bonding strength. Besides, high assimilation ability of nuclei would cause decrement in liquid fluidity, resulting in weaker bonding strength, so the return fines are formed.

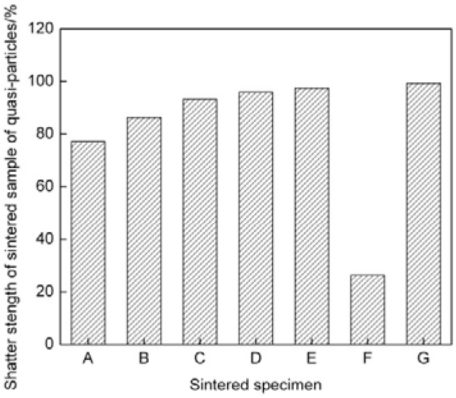

Figure 5 Shatter strength of sintered quasi-particles under different conditions.

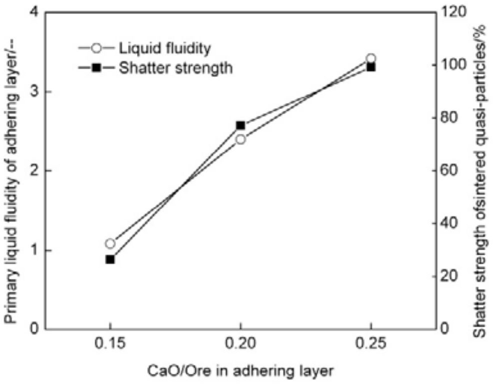

Figure 6 Primary liquid fluidity of adhering layer and shatter strength of sintered quasi-particles.

3.2 Influence of pore structure on crushing strength of iron ore compact

Figure 7 shows the macro image the cross section of iron ore compact after sintered at 1280℃.It is seen that pores take on different appearances with irregular shapes and heterogeneous distributions. Figure 8 shows measurement of total porosity of sintered specimen with image analysis. Sintered specimen of hematite contains many pores and the porosity is approximately 40%, while the limonite and marra mamba ore contain only about 25% pores. With regard to sintering blend Ore F, the porosity firstly drops when CaO/Ore is raised from 0.075 to 0.100, then increases when CaO/Ore is further raised. The reason accounting for the phenomenon might be lots of gaps, which are caused by sample shrinkage when the melt generation is low with less CaO content in sample F. As CaO content increases, the flowing liquid fills gaps so that the porosity of sample G decreases. But when CaO content surpasses certain value, melt of high fluidity flows away and pores are residue.

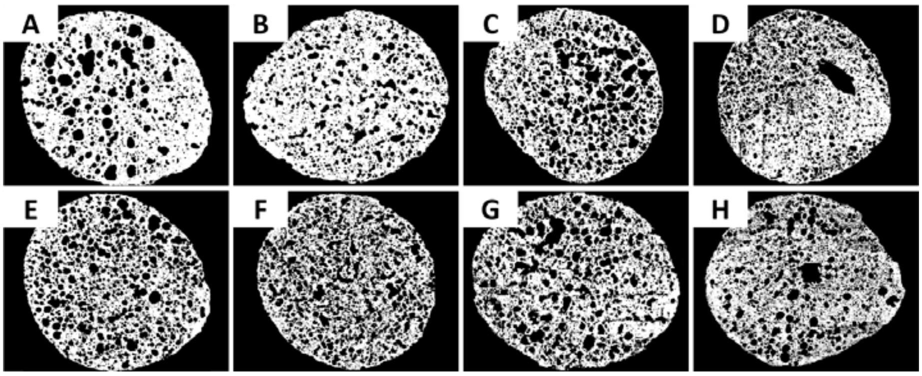

Figure 7 Cross section of iron ore compact after sintered at 1280℃.

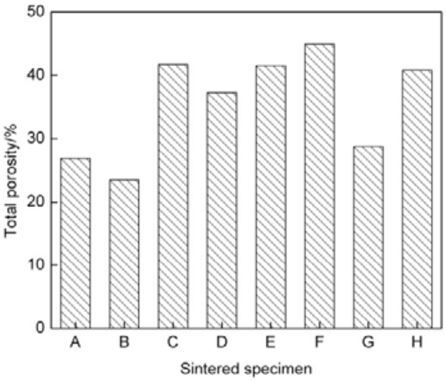

Figure 8 Measurement result of total porosity of sintered specimen.

Figure 9 shows the result of porosity composition with different pore diameters in sintered specimen. Figure 10 shows the number of pores within certain diameter ranges. The results reveal that both the volume and the number of pores larger than 400 μ m and smaller than 100 μ m increased with increasing CaO content in Ore F. Besides, the hematite seemes to contain more large pores than limonite, marra mamba ore has the least large pore volume and total pore number.

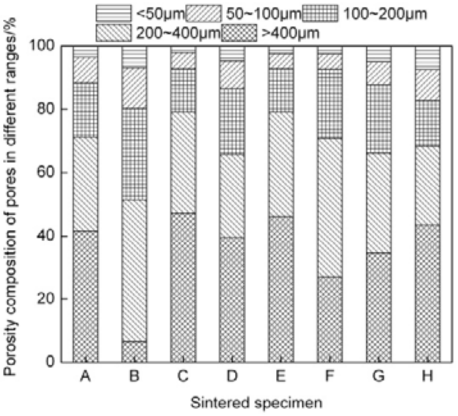

Figure 9 Measurement of porosity composition of pores in different ranges.

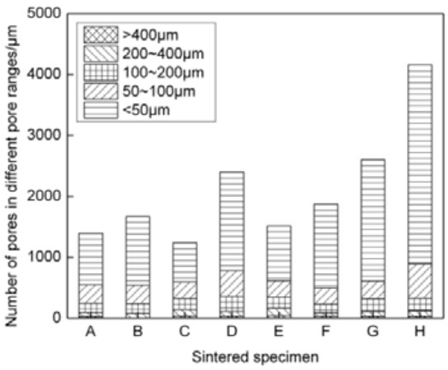

Figure 10 Measurement of the number of pores in different ranges.

Since previous researchers point out that porosity and pore distribution are important factors that contribute to sample intensity, pore diameter together with pore number, porosity and distance between pores are used to evaluate pore structure of sintered specimen in this paper. Among the four indexes, the distance between pores is distilled to characterize the thickness of mineral matrix by calculating sum of length between some pore and all the other pores. The smaller the value of distances between pores is, the more homogeneous the pores distribute.

In order to unveil the influence of pore structure on self-strength of the bonding phase, the relations of pore structure evaluating indexes and crushing strength are analyzed with the same CaO/Ore ratio, avoiding obvious interaction of mineralogy.

Figure 11 shows the linear fitting result of pore number, porosity and pore distance in the range that pore diameter larger than 400 μm. Figure 12 shows the analysis result in the mediate range of the pores lying in 200 to 400 μm. Figure13, Figure 14 and Figure 15 show the results of pores with diameter of 100 to 200 μm , 50 to 100 μm and smaller than 50 μm respectively.

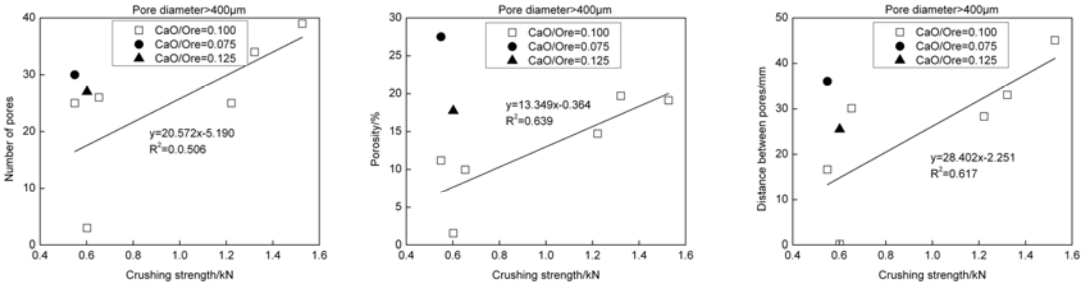

Figure 11 Relations of crushing strength and structural properties of pores bigger than 400 μm.

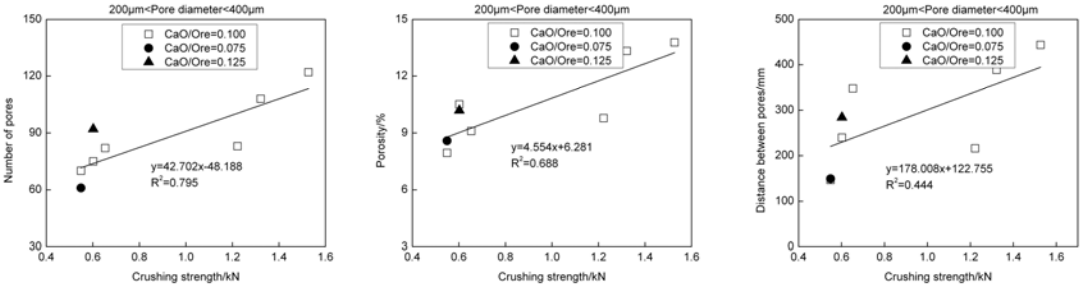

Figure 12 Relations of crushing strength and structural properties of pores of 200~ 400 μm.

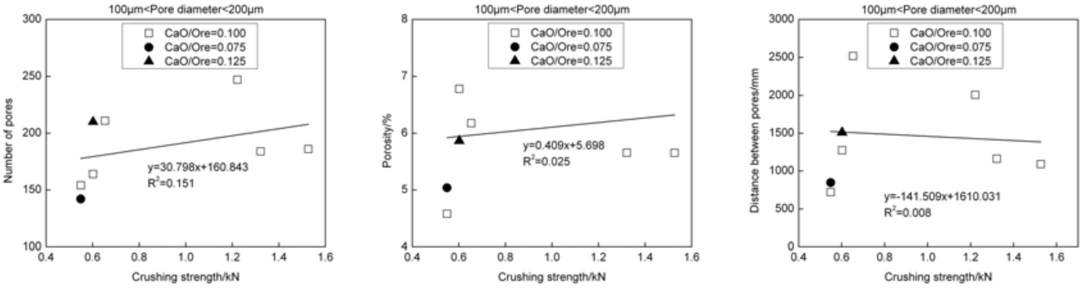

Figure 13 Relations of crushing strength and structural properties of pores of 100~200 μm.

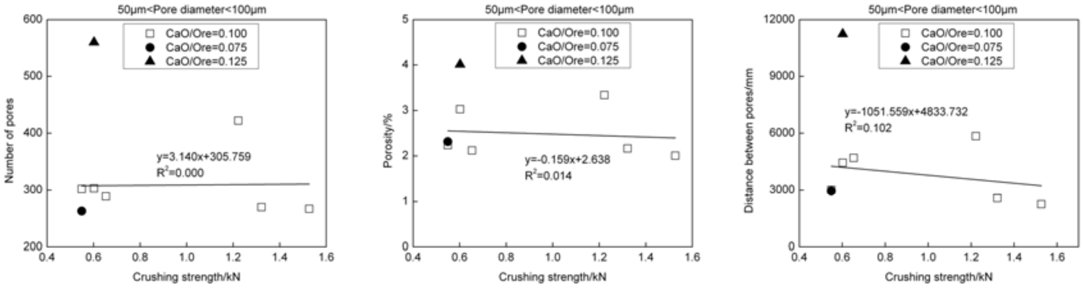

Figure 14 Relations of crushing strength and structural properties of pores of 50~ 100 μm.

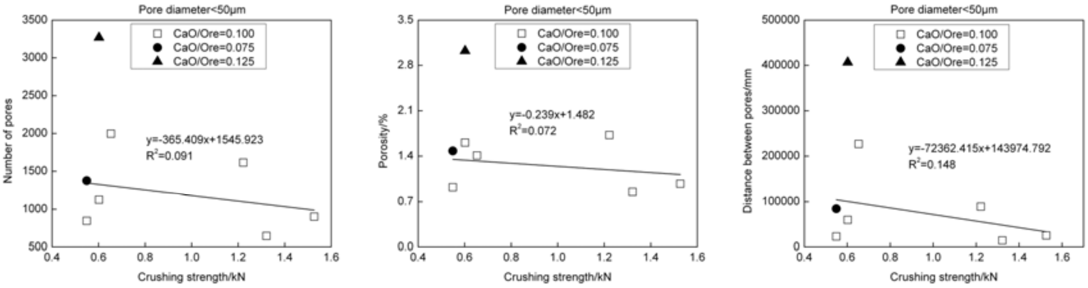

Figure 15 Relations of crushing strength and structural properties of pores smaller than 50 μm.

It is indicated that positive correlation is found between the crushing strength of iron ore compacts and the structural indexes such as numbers, porosity and matrix thickness with pores larger than 200 μm, while no linear relations are found with smaller pores. It is generally considered that the cracks are virtually formed with larger pores and will propagate from pore to pore throughout the mineral matrix,[11] resulting in inferior strength. However, the crushing strength of iron ore compact adversely improves with increased pore number or porosity in this paper. To further analyze the crushing strength with the matrix thickness, the matrix thickness between larger pores (with diameter larger than 200 μm) proves to be more important in comparison with pore number or porosity, and there might be mineralogical reasons accounting for the findings.

By comparing the fitting coefficient of crushing strength and matrix thickness with pores larger than 400 μm and within 200 to 400 μm, it comes to the understandings that the homogeneous distribution of pores with diameter larger than 400 μm are more contributive in gaining high strength with bonding phase. Therefore, if the pores in bonding phase matrix have macroporous and thin-walled structure, it has the most negative impact on strength. Besides, as shown in Figure 10 and Figure 11 to 15 with G and H, the high porosity and their uneven distributions may also lead to weaker strength that exacerbates formation of return fines.

3.1 Influence of Mineral Property on Self-strength of Boding Phase

Figure 16 shows the compositions of minerals such as hematite, magnetite, calcium ferrite and calcium silicate in the sintered specimen. It is seen that there are more hematite in sintered samples with Brazilian hematite D and E, more magnetite with hematite C, D and limonite A. Calcium ferrite content increases with CaO/Ore increment for Ore F. When CaO/Ore is set at 0.100, Australian limonite and marra mamba ore, together with Brazilian hematite Ore E form more calcium ferrite. Sample D has the least calcium ferrite. According to previous researches, sinter strength can be improved with more calcium ferrite[17] as it has higher resistance towards internal stress. However, by combining crushing strength with mineral compositions gained, there are cases that do not confirm to the very understanding mentioned above. Since the crushing strength of sintered specimen is determined under comprehensive effect of pore structure and mineral property, both the composition and mineral morphology are important.

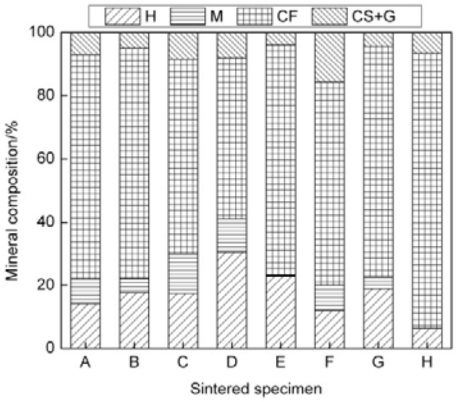

Figure 16 Compositions of different minerals in sintered specimen.

Figure 17 shows typical mineral morphology on cross section of sintered specimen. It is seen that large pieces of hematite entrainment are observed in SFCA with sample A, sample B and sample F, the crushing strength of which are in the lowest level. Comparatively, hematite C, D and E have small entrainment in denser SFCA basement with smaller pores and larger matrix thickness, and they can obtain high crushing strength. Therefore, it is indicated that SFCA decrease or large pieces of hematite entrainment in SFCA caused by basicity segregation reduce the self-strength of bonding phase as well.

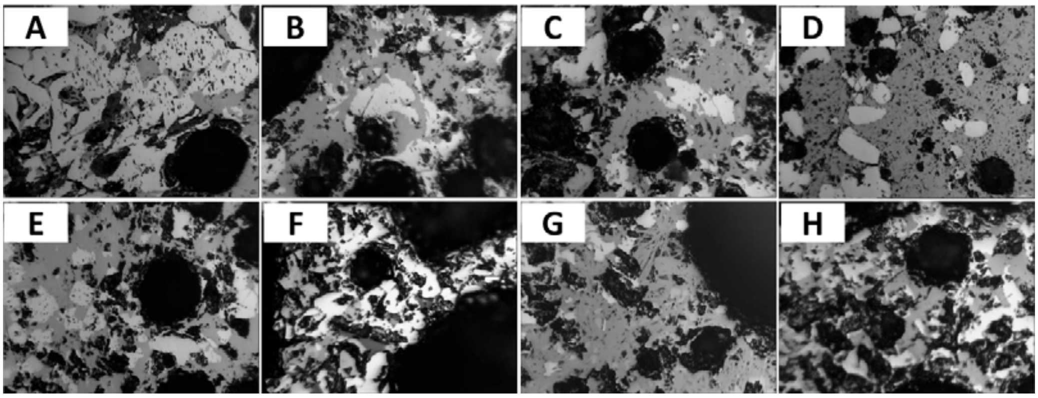

Figure 17 Typical mineralogical appearance of sintered specimen(×300).

4 CONCLUSIONS

As the return fines generally formes as a result of inferior strength in sintering process, the formation mechanism is studied by carrying out experiments on weak bonding with both bonding phase and sintered quasi-particles. Main factors such as pore structure, mineral property, and liquid fluidity are discussed. The results obtained are summarized as follows.

(1) There are two main breaking forms of sintered body, named crushes or cracks in sintered quasi-particles and bonding phase respectively, and the former form is affected by liquid fluidity, while the later one is contributed mainly by the pore structure and mineral property.

(2) Secondary liquid fluidity is the main factor accounting for bonding efficiency of sintered quasi-particles. Low liquid fluidity caused by segregated basicity or heat shortage as well as excessive assimilability of nuclei, will lead to deterioration in bonding interface and formation of return fines.

(3) The matrix thickness among the large pores that characterize homogeneous distribution of pores with diameter larger than 200 μm are the most important property of pore structure, the results indicate that even if the porosity or the number of large pores are higher, it wouldn't affect the crushing strength by homogeneous distribution. Structure of small pores has relatively small impact on strength of bonding phase.

(4) The SFCA compositions appear to be higher with limonite and marra mamba ores, but the crushing strength isn't strong possibly because of the large pieces of hematite entrainment, so the sintered specimen with more and denser SFCA basement, smaller pores and larger matrix thickness will obtain higher crushing strength.

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