1. Introduction

Iron ore sinter constitutes a major proportion of blast furnace burden in most countries in the Asia-Pacific region. Hence, its quality and consistency are expected to have a significant impact on blast furnace performance. The counter-current principle on which the blast furnace operates makes it reliant heavily on the quality of its burden to maintain a sufficient level of gas permeability in its upper shaft and of liquid and gas permeability in its lower part. Iron ore sinter, constituting a major proportion of blast furnace burden in most countries, particularly in the Asia-Pacific region, is therefore expected to have a significant impact on blast furnace performance.

The chemical composition of iron ore fines, together with the thermal conditions that sinter blends are subjected to, plays an important role in forming the primary melt during the sintering process and subsequently determines the sinter structure and quality. Considerable emphasis has therefore been placed on the chemical composition and consistency of iron ore fines, particularly in terms of alumina content. However, due to the limited reserves and increasing depletion of high-grade iron ore resources, the alumina content of iron ores is expected to increase gradually. While the increase in such constituents is relatively slow over a long period, it has still caused problems for blast furnace operators.

This paper attempts to clarify the role of different types of alumina present in iron ore fines and their effects on melt formation, sinter structure and sinter quality, as well as the sintering process itself. Mechanisms responsible for the deterioration of the low temperature reduction degradation characteristics (RDI) of sinter due to the increasing alumina content are also reviewed. In addition, potential measures to counter the adverse impacts of alumina on sintering performance of hematite iron ore fines are also discussed.

KEY WORDS: High alumina iron ores; kaolinite; gibbsite; melt formation; sinter structure; sintering performance, sinter quality.
alumino-silicates like kaolinite (Al₂O₃ · 2SiO₂ · 2H₂O), while the A type ores contain gibbsite (Al(OH)₃).⁹⁰ Extensive work has been conducted on the effects of alumina on sinter structure, quality and productivity.¹²,⁴–⁶,⁹–₁₄ While the results are not conclusive and sometimes contradict each other, it is generally believed that too much alumina impairs the sinter quality, particularly the low temperature reduction degradation characteristics. However, much of the previous work showing the strong adverse effects of alumina on sinter quality and the sintering process has been focused mainly on Indian ores,¹,⁴–⁶,⁹ which often belong to A type iron ores. Only limited work has been conducted on the majority of iron ores that contain alumina in the form of kaolinite.²,¹₀,¹₂ From high temperature X-ray diffraction studies on Fe₂O₃–SiO₂–CaO–Al₂O₃ ores, it has been found that kaolinite type ores generated melilite as a slag-forming mineral when heated in air, while gibbsite type ores formed calcium ferrite.⁹ It is therefore reasonable to assume that these two types of iron ores will behave differently during the sintering process, leading to different sinter structure and quality. This paper attempts to clarify the role of different types of alumina present in iron ore fines and their effects on melt formation, sinter structure, sinter quality and the sintering process. The mechanisms responsible for deterioration of sinter low temperature reduction degradation characteristics (RDI) with increasing alumina are also reviewed, and potential measures to counter the adverse impacts of alumina on the sintering performance of hematite iron ore fines are discussed.

2. Effect of Alumina on Sinter Mineralogy

Low temperature fluxed sinter mainly contains un-reacted hematite nuclei (around 30 vol%) in a matrix (about 70 vol%) consisting of silicoferrite of calcium and aluminium (SFCA), secondary hematite (H₂), secondary magnetite (M₂), silicates and glass. The results reported in the literature using different types of alumina, including chemical reagents, kaolinite, and gibbsite as the alumina source, appear to agree on the essential role of alumina in the formation of sinter structure, particularly SFCA. Generally, alumina is believed to promote and stabilize SFCA.¹,³,¹₅,¹₆ As the alumina content increases, the amount of hematite in the sinter decreases and the quantity of SFCA increases if the basicity is maintained at the same level.²,⁴,⁹ This should be advantageous as far as sinter quality is concerned, providing fine fibrous SFCA is produced in the sinter.

Studies on SFCA morphology have further identified two different types of SFCA, i.e., SFCA and SFCA-I.³,¹₆,¹₇ While platy SFCA-I appears needle-like or fibrous in cross-section, SFCA tends to take a columnar or blocky form. Previous work has demonstrated that the SFCA-I phase is the most desirable bonding phase in iron ore sinter, since it results in higher sinter strength and better reducibility.²,³,¹₈,¹₉ The effect of alumina on SFCA morphology is summarized in Fig. 1,³ showing that SFCA-I is favoured when the total alumina and silicate content in the bonding phase is low and the hematite content is high. Therefore, although alumina tends to stabilize and promote the SFCA phase, it may actually reduce the amount of SFCA-I produced by forming more SFCA.

In terms of the distribution and occurrence of alumina in the sinter, electron probe microanalysis (EPMA) results have shown that it can dissolve in all major mineral phases in sinter except the un-reacted hematite. There is only a very limited amount of alumina in the un-reacted hematite. The distribution of alumina in major sinter mineral phases reported in the literature is summarized in Table 1, which shows that the majority of the alumina is present in SFCA.

![Fig. 1. Ternary plot showing the approximate compositional break between columnar SFCA (labelled as Pr in the plot) and platy SFCA-I (labelled as P in the plot) measured from pot-grate sinters fired at 1 543 K.³¹](image)

<table>
<thead>
<tr>
<th>Researchers</th>
<th>Type of alumina used</th>
<th>SFCA (%)</th>
<th>Secondary Hematite (%)</th>
<th>Secondary Magnesite (%)</th>
<th>Glass (%)</th>
<th>Unreacted Hematite (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ostwald, J. et al. [10, 12]</td>
<td>Kaolinite type ore fines: Al₂O₃: 2.28, SiO₂: 6.5%</td>
<td>4.84-9.49</td>
<td>1.17-2.37</td>
<td>1.28-2.17</td>
<td>3.72-10.57</td>
<td>&lt;0.15</td>
</tr>
<tr>
<td>Dawson, P. et al. [2, 20]</td>
<td>Chemical reagents: Al₂O₃: 2.5-8.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Yamaoka, Y. et al. [9]</td>
<td>Gibbsite type ore fines and gibbsite reagent: Al₂O₃: 4.6%, SiO₂: 5.5% and a basicity of 0.8-1.8 in sinter</td>
<td>4.02-12.03</td>
<td>1.61-3.01</td>
<td>2.75-3.06</td>
<td>11.05</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Standard sinter blend: Al₂O₃: 1.5%, SiO₂: 5.5% and a basicity of 0.8-1.8 in sinter</td>
<td>3.24</td>
<td>0.75-1.49</td>
<td>0.63-1.61</td>
<td>7.95</td>
<td>-</td>
</tr>
<tr>
<td>Mukherjee, T. et al. [1]</td>
<td>Mean analysis of industrial sinters</td>
<td>4.87</td>
<td>0.71</td>
<td>1.13</td>
<td>5</td>
<td>0.17</td>
</tr>
<tr>
<td>Kim H. S. et al. [21]</td>
<td>Chemical reagents</td>
<td>&lt;=7%</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 1. Summary of alumina distribution in major sinter minerals reported in the literature.
and glass, and the remainder enters the secondary hematite and magnetite. The distribution of alumina amongst the minerals does not appear to be affected by the type of alumina used. This is understandable, since all these mineral phases are precipitated from the primary sinter melt during the cooling cycle. The difference between different types of alumina completely disappears upon dissolution into the primary melt. However as discussed later, different types of alumina are expected to show different reactivities toward the primary melt. This will affect the amount of alumina that the primary melt eventually carries.

3. Effect of Alumina on the Physicochemical Properties of Primary Melts

Figure 2 shows a typical texture of self fluxed iron ore sinter produced in a pilot-scale pot-grate sinter rig. In addition to mineral phases, it consists of many pores of varying shapes and sizes. It is believed that the strength, reducibility and size distribution of sinter particles and the yield from a sinter strand are determined by the inherent strength of the bonding phases present and the structure of the pores. Furthermore, different pore sizes seem to have different effects on sinter strength, reducibility and other properties: the high temperature reducing property is controlled by the micro-pore sinter structure, while the sinter strength is determined by the macro-pore sinter structure. It is therefore important to optimise the pore structure in sinter to improve its reducibility, while maintaining the cold strength, reduction degradation and load softening properties.

The physicochemical properties of the primary melt become increasingly important as the amount of slag in sinter decreases. Loo and Leung discussed the effect of the physicochemical properties of the primary melt on the reshaping and coalescing process of the primary melt and bubbles formed in the flame front during sintering and therefore on the resulting pore structure of the sinter. Melt with good fluidity and a low melting temperature is generally desirable to obtain a favourable sinter pore structure. By changing the physicochemical properties of the primary melt, alumina is believed to play an important role in the reshaping and coalescing process during sintering.

From the data published the chemical composition of primary melts formed during iron ore sintering is believed to fall within the range of the ferrous calcium silicate slag system. There has been a considerable amount of work on the physicochemical properties of different oxide melts based on the FeO–CaO–SiO2 ternary system. However, while significant impacts of alumina on the properties of oxide melts have been reported, unfortunately most of the data reported in the literature to date have been conducted at compositions, thermal conditions or oxygen partial pressures not relevant to the conditions encountered during normal sintering processes. According to Tsukihashi and coworkers, the addition of alumina up to 5% under oxygen partial pressures ranging from 1.8×10⁻³ to 10⁻¹ Pa at 1 573 K, enlarges the liquid phase field slightly, which is particularly important for keeping the sinter mixture molten over a wide range (Fig. 3(a)). This agrees with the results reported by other authors that alumina in the ore lowers the temperature at which primary melt forms in sinter, but contrasts with the general belief that alumina is not a good flux, based on the rationale that alumina behaves like a kind of refractory material with a high melting temperature. By using the computer package FLOGEN, Kongoli et al. tried to quantify the effect of alumina on the same system at 1 523 K and 10⁻³ Pa, with alumina varying from 0 to 7%. As shown in Fig. 3(b), their results agree with the

![Fig. 2. Typical texture of self fluxed iron ore sinter produced in a pilot scale pot-grate sinter rig. M: matrix, P: pore, N: unreacted nucleus, aN=assimilated nucleus.](image)

![Fig. 3. (a) Effect of alumina addition on the liquid field of the CaO–SiO2–FeOx system under P02=1.8×10⁻³ Pa at 1 573 K, (b) comparison of observed (5% Al2O3, P02=1.8×10⁻³ Pa, 1 573 K) and calculated (3% Al2O3, P02=10⁻³ Pa, 1 523 K) liquidus for the CaO–SiO2–FeOx–Al2O3 system, (c) effect of alumina addition on the viscosity of the Fe2O3–CaO system, x: 1 250°C, ◆: 1 300°C, □: 1 350°C and Δ: 1 400°C.](image)
work conducted by Kimura and coworkers reasonably well.8,25)

Little research has been conducted on the effect of gangue such as Al₂O₃ on the viscosity and fluidity of the molten FeOₓ-CaO-SiO₂ system, which is believed to play a crucial role in the reshaping and coalescing process during sintering. Saito and co-workers28) and Machida and coworkers27) measured the effect of alumina on the viscosity of calcium ferrite slags separately. As shown in Fig. 3(c), alumina is very effective in increasing the viscosity of calcium ferrite slags, particularly at temperatures below 1 573 K. However it is worth mentioning that all the work was conducted in air. It is well known that oxygen partial pressure at the flame front in the actual sintering process is much lower. It is therefore necessary to quantify the effect of alumina on the viscosity and fluidity of the sinter primary melts in a reducing atmosphere.

The observed effects of alumina on the physicochemical properties of the primary melts are expected to have a great impact on the reshaping and coalescing process of primary melt and bubbles during the sintering process, eventually leading to a unique sinter pore structure. Experimental results in Fig. 422) showed that the pore area increases drastically, and the pore shape becomes more irregular as alumina increases from 1.6 to 2.4%. Okazaki and coworkers11) further suggested that, for a desirable pore structure, the alumina content in the adhering fines is required to be below 1.5%. This is believed to be due to the significant increase in melt viscosity as a result of increasing alumina content in the adhering fines.

Furthermore, the time for which the melt is kept above its liquidus temperature during the sintering process is extremely short. The assimilation behaviour of primary melts towards the adhering fines and nuclei is therefore extremely important for generating sufficient melt of appropriate composition. Addition of alumina is found to increase the melt viscosity and is therefore expected to inhibit further assimilation of adhering fines and nuclei into the melt. In addition, the reactivity of mineral components in the adhering fines and nuclei is also believed to play an important role in determining the assimilation process. The reactivity of different types of alumina to the primary melt was found to be quite different. Experimental results22) showed that the use of chemical reagents as the source of alumina resulted in areas of un-reacted alumina in the sinter structure, which is similar to the aluminous relics reported in the literature29) using bauxite as the source of alumina. This is because different aluminous materials have varying reactivities to the primary melts during the sintering process. As a result, more SFCA may be produced when alumina presents in the form of kaolinite. Therefore, from this point of view, iron ores containing kaolinite are superior to these containing gibbsite of low reactivity. Recent results on pisolitic ore have also shown that it is more reactive compared to denser hematite ores.30) Therefore, addition of low alumina, reactive pisolitic ore, such as Yandi, into sinter blends may help to generate more fluid melt at relatively low temperatures to dilute the negative effect of alumina, which will be discussed in detail later.

4. Effects of Alumina on Sinter Quality and Sintering Process

4.1. Sinter Quality

While the results from mineralogical studies of high alumina sinters are generally consistent, the effect of alumina on sinter quality varies, depending heavily on the type of alumina present in iron ores. Previous studies on the effect of alumina in the form of gibbsite on sinter quality4–6,9,11) are quite conclusive. As shown in Fig. 5(a), sinter strength deteriorates as the alumina content increases. As mentioned earlier, alumina promotes the formation of SFCA, which should be beneficial to sinter strength, but lower strength of the mineral constituents in the sinter due to the presence of high alumina in their lattices has been quoted as the main cause responsible for the lower sinter strength observed.9) Alumina is also expected to increase the viscosity of the primary melt formed during the sintering process, leading to a weaker sinter structure with more irregular interconnected pores.11,22) Furthermore, un-reacted gibbsite powders in the sinter may form centers of weakness and result in weaker sinter. While extensive studies have been conducted on iron ores of the gibbsite type, very limited work has been reported on the SA type iron ores. From limited data available (squares in Fig. 5(a)), it appears that alumina in the form of kaolinite is less detrimental to sinter strength compared to gibbsite type alumina (circles and triangles).10,20) As shown in Fig. 5(a), there is no adverse effect of alumina in the form of kaolinite in the range of 2.0–2.8% on sinter strength at a constant coke rate. However, it is worthwhile emphasizing that these results reported by Stenlake and coworkers10) were achieved at a relatively high fuel rate of about 65 kg/t. It has been reported that by increasing heat input into the sinter bed, it is possible to produce a sinter with reasonable quality even at high gibbsite contents in the sinter blend.4,5) However, this will increase the fuel consumption, leading to serious environmental and economical concerns. Therefore it is necessary
to clarify this effect using kaolinite as a source of Al₂O₃, particularly at normal fuel rates.

Probably the most significant adverse effect of alumina reported to date is on the low temperature reduction degradation characteristics (RDI) of sinter. With enormous effort being made to reduce coke consumption while increasing productivity of the blast furnace, the sinter RDI characteristics become increasingly important to maintain the furnace permeability. As indicated in Fig. 5(b) (triangles and circles), RDI is reported to deteriorate markedly as the alumina content increases. Industrial experience suggests that, in the CaO range of 10 to 10.5%, a 0.1% rise in sinter alumina will increase RDI by 2 points. Again, as indicated in Fig. 5(b) (squares), there is only a marginal and manageable deterioration in RDI as the alumina content, in the form of kaolinite, increases. The possible mechanisms responsible are not yet clear, and are discussed in detail below.

While maintaining RDI, sinter needs to have sufficient reducibility to promote indirect reduction in the blast furnace to reduce coke consumption. Sinter reducibility is primarily determined by the sinter chemistry, pore structure and mineralogy, which are often interrelated and determined by raw material and operational conditions. Due to the complexity of the effects of alumina on each of these factors, studies of the effect of alumina on sinter reducibility have shown mixed results. Mineralogically, lowering sinter alumina content would increase hematite and promote the SFCA-I bonding phase, leading to a sinter with improved reducibility. Furthermore, the fact that alumina lowers the liquidus and increases the viscosity of the melt during reduction is of concern. This may result in a harmful effect on the permeability within the sinter in the lower part of the blast furnace, which further inhibits indirect reduction.

Historically blast furnace operators have focused more on sinter size, cold strength, and then reduction degradation. However, studies on quenched and dissected blast furnaces in Japan and Germany have revealed the importance of softening and melting behaviour of sinter for stable blast furnace operation. This determines the position and shape of the blast furnace cohesive zone. A low, narrow inverted “V” shaped cohesive zone is generally desirable to improve blast furnace performance. While extensive effort has been made to measure the softening and melting behaviour of blast furnace ferrous burdens, information on the influence of alumina on such behaviour is very limited. It is expected that the effects of alumina on the physicochemical properties of the primary melt during sintering and the mineralogy of sinter will play an important role in determining the softening and melting behaviour. After measuring the dripping and softening behaviour of a variety of sinter and pellets, Higuchi and coworkers concluded that while the effect of alumina on the dripping temperature of molten iron varies depending on basicity, alumina lowers the softening temperature, as shown in Fig. 6. This is not desirable from the blast furnace operation point of view.

4.2. Sintering Process

High gibbsite type iron ores are expected to demand a high sintering temperature and a longer sintering time to promote melt formation. This is due to the poor reactivity of this type of alumina and the high viscosity of the primary melt formed. As a result, the fuel rate is reported to increase and the sintering productivity to decrease as the
alumina content increases. Industrial experience has also suggested that for every 1% increase in alumina content in sinter, the coke breeze consumption increases by 5–10 kg/t-sinter in order to raise the sintering temperature by about 30°C. A similar conclusion on the effect of alumina on sintering productivity has also been reported, which was further confirmed by Yamaoka and coworkers, as shown in Fig. 7. In addition to the observed increase in fuel rate and drop in sintering productivity, a high sintering temperature is expected to cause other adverse impacts on sinter quality due to the formation of an unfavourable sinter structure of poor reducibility and strength. High temperature sinter is usually characterized by a high FeO content and a large volume of bonding phases consisting of coarse columnar SFCA and glassy silicates. Research on the influence of the kaolinite-type alumina on sintering process is limited and the only results available (squares shown in Fig. 7) show no clear trend.

It has to be emphasized that factors like ore types will also affect sinter quality and sintering performance. Unfortunately information on ore type is not always readily available in the literature. Therefore it is quite possible that some of the relationships above may include the possible effects of ore type. Furthermore, this paper largely focuses on the effect of alumina in the form of gangue minerals. However it was found that for some Indian ores, alumina sometimes presents in the hematite crystals. This type of alumina will behave differently depending on the reactivity and size distribution of the hematite particles. Coarse dense hematite particles will have less negative effects as the alumina will not enter the melt phase.

5. Mechanisms Responsible for RDI Deterioration

The mechanisms responsible for RDI deterioration with increasing alumina are not yet fully understood. Historically, particularly in Japan, it is strongly believed that the secondary hematite, also known as skeletal rhombohedral hematite, is the major cause of poor reduction degradation resistance of sinter. This is based on frequent observations of cracks around the narrow neck regions of such hematite. However, low to intermediate levels of alumina have been reported to reduce the amount of secondary hematite and increase SFCA in the sinter structure, both of which should be advantageous to RDI. On the other hand, a number of other researchers suggested that the cracks resulting from a volumetric change accompanying the phase transformation of crystalline hematite to magnetite are mainly responsible for the reduction degradation of sinter. However, once again this mechanism cannot explain the favourable effect of alumina on the sinter structure.

In order to explain the role of alumina, some studies suggested that the presence of alumina as a solute in hematite is responsible for the adverse effect of alumina on RDI. According to Sasaki and co-workers, a solid solution of alumina in hematite could induce the formation of multi-component hematite, leading to increased strain in the resultant magnetite during reduction. However, scanning electron microscope observations at a magnification of up to 15 K failed to confirm the presence of any fine components in hematite. After measuring the crystal lattice distortions of hematite and magnetite due to alumina in solid solution using X-ray diffraction (XRD), Yamaoka et al. suggested that the decrease in natural strength of mineral components in sinter, including hematite and magnetite, due to addition of alumina was responsible for the deterioration of the reduction degradation resistance of sinter. While similar observations were made in their XRD work on the lattice parameters of hematite and magnetite, Pimenta and Seshadri arrived at a different explanation concluding that hematite containing alumina generated a magnetite phase with a distorted structure during low temperature reduction, which, together with the structural deformation resulting from the volumetric change of the hematite crystal, can promote crack initiation and propagation in the sinter, leading to disintegration.

On the other hand, Matsuno et al. found that RDI was related neither to the amount of hematite nor to multi-component hematite. Instead they suggested that the ability of the mineral phases in sinter to resist crack initiation and propagation determined the extent of disintegration during low temperature reduction, or RDI. They further suggested that alumina weakened the strength of the glassy silicates and promoted large columnar SFCA, both of which are detrimental to crack propagation resistance. This was further supported by Bristow and Loo’s work.

While extensive work has been conducted to understand the mechanisms responsible for RDI deterioration, no consensus has been reached. It is believed that crack initiation/propagation and lattice distortion are the important factors to understanding RDI. If fewer cracks and less distortion are present in the mineral phases, or the cracks are easily arrested during the low temperature reduction, a better RDI is expected.

6. Potential Measures to Improve Sintering Performance of High Alumina Hematite Iron Ores

While its cause and severity are still subjected to considerable debate, the adverse impacts of alumina, particularly the gibbsite type, on sinter quality and the sintering process are clear. It is not difficult to propose that the most effective way to avoid these detrimental effects is to reduce the alumina content of iron ores. However, earlier efforts in this regard, mainly focussed on selective flocculation techniques, had limited success. The fine grain size, occurrence of clay minerals and poor liberation of hematite iron ore slimes are believed to be the major reasons for the limited
success of these earlier researchers. New strategies, including multi-gravity separation and bio-beneficiation have recently been proposed to separate alumina from hematite iron ores. However this is outside the scope of this paper. While some of them look promising, these alumina reduction technologies are currently limited to laboratory tests only. Furthermore, the technologies under development are generally aimed at processing Indian iron ore slimes containing extremely high alumina and are not necessarily applicable to counteracting smaller incremental increases in the alumina content of iron ores. Therefore, sinter plants are still facing the challenge of finding effective solutions for dealing with the gradual increase in alumina in their ores. Based on the discussion above, the sintering performance of high alumina hematite iron ores may be improved by one of the following measures or in combination.

### 6.1. Neutralisation of the Effects of Alumina

Undoubtedly the most significant adverse effect of alumina is on the low temperature reduction degradation characteristics (RDI) of sinter. While the mechanism responsible for RDI deterioration is still debatable, it appears to be partially related to the amount and type of hematite in the sinter structure. Therefore, reducing secondary hematite in the sinter structure may lead to an improved sinter quality, particularly RDI. Addition of magnetite, MgO and CaO in sinter blends has been reported to be effective in neutralising the adverse effects of alumina and improving the RDI characteristics of sinter.

As the FeO content in sinter increases, the hematite content in sinter is expected to decrease, which in turn can reduce the volumetric change associated with the transformation of hematite to magnetite in the upper part of the blast furnace. The effect of sinter FeO content on RDI performance has been clearly demonstrated in Fig. 8. It was found that not only was the RDI index reduced by about 8 points for a 2% increase in sinter FeO content, but also the sensitivity of RDI to alumina was lowered. It is well known that the FeO content of sinter can be adjusted by changing the coke rate in sinter blends. However, it may be cheaper to do so through addition of an appropriate type and amount of magnetite to sinter blends. It is true that, in countries like China, magnetite concentrates constitute a considerable proportion of sinter blends. Yamaoka and co-workers found that both sinter strength and RDI improved as the addition of magnetite in sinter blends increased. This trend continues until the magnetite content in the blends reaches about 50%. The type of magnetite mineral was also found to play a role in determining the effectiveness of magnetite addition. However, since the FeO content of sinter affects the reducibility of sinter adversely and addition of magnetite concentrate to hematite sinter blends will also have negative effects on sintering productivity due to the low reactivity of magnetite, it is important to find an optimum FeO level to improve RDI without compromising the other sinter properties.

In addition to FeO, addition of MgO in sinter blends has also been proposed to improve the RDI characteristics of sinter. Detailed studies showed that increased replacement of CaO with MgO in the form of dolomite at a basicity of 1.6–1.9 leads to a slight decrease in sinter strength, reducibility and productivity, but the reduction degradation and the softening and melting properties of sinter are significantly improved. A slight decrease in cold strength and reducibility may be justified as more and more emphasis is being shifted towards the low and high temperature properties of sinter. The beneficial effect of MgO on RDI may be attributed to the role of MgO in stabilizing magnetite. Increasing MgO content leads to more magnetite and therefore less hematite in sinter, causing less strain in the sinter during reduction. The beneficial effects of MgO have also been observed when magnesium silicates are used. However, this can be applied only when the silica content in the iron ore fines is low. On the other hand, MgO increases melting temperature and viscosity, which limits the amount of MgO in the sinter.

While sinter basicity is usually fixed by plant requirements/practice, it may still be possible to adjust the CaO content in the sinter if its positive role in counteracting the alumina effects is confirmed. As shown in Fig. 9, the effect of alumina on RDI is not uniform but a function of the CaO content of the sinter. A higher CaO content is beneficial to sinter RDI and also to RI. A similar approach was also suggested by Yamaoka and co-workers to improve the sintering performance of sinter blends with higher gibbsite contents. It was found that the cracking tendency during reduction of high basicity sinter was negligible compared with that observed in the natural iron ore particles. When sinter basicity increases, the SFCA bonding phase is expected to increase in abundance. Microstructure observa-
tions suggest that the SFCA bonding phase is very effective at arresting the propagation of cracks. Increasing sinter basicity can also improve the fluidity of the primary melt formed during sintering, leading to a more favourable pore shape and size distribution and a decrease in total pore area. However, sinters of basicity higher than 2.0–2.2 are not desirable from the blast furnace operation point of view. Higher basicity leads to a sinter having a broad softening and melting range, leaving refractory residue on the coke bed, and generating a slag with high viscosity. All this affects the permeability in the lower part of blast furnace. Nevertheless, it is an effective measure to counter the adverse effect of alumina on RDI.

6.2. Dilution of the Effects of Alumina

Due to the low reactivity of alumina bearing minerals and the high viscosity of primary melts with high alumina content, ores with high alumina content are usually believed not to be good in forming sinter matrix if sintered alone. However it is possible to improve the reactivity of alumina bearing materials and dilute the adverse effects of alumina by adding other more reactive components in the sinter blends. Recent results on pisolitic ore showed that it more readily forms a melt than dense hematite ores. Therefore, addition of low alumina pisolitic ore, such as Yandi, to high alumina sinter blends may help to produce more melt and dilute the effect of alumina on sinter quality. On the other hand, dissolution of alumina is expected to assist in the formation of a viscous primary melt to hinder excessive assimilation of pisolitic ore particles into the melt. As illustrated in Fig. 10, the concept of using highly reactive components to support high alumina ores sounds very attractive. However, tests are needed to determine the assimilation kinetics of alumina bearing ores towards various reactive components before practical application. Hence, appropriate reactive components can be selected to ensure enough melt is generated during the sintering process that is more reactive to alumina and less viscous.

6.3. Localization of the Effects of Alumina

Depending on the abundance of alumina in different size fractions, opposite strategies may need to be used to either dissolve or localize the alumina minerals. For fine alumina bearing minerals, it may be possible to dissolve them completely in the primary melt to avoid any unreacted alumina, which has been reported to form weak centers in sinter. With the coarse alumina bearing minerals, it may be better to keep them un-reacted and therefore to localize their effect.

A selective granulation technique has recently been proposed as one of the most promising measures to control melting reactions during the sintering process. It was found to effectively promote melt formation in sinter products, as evidenced by the increase in open pore ratio and pore size. As a result, the coke consumption was reduced and the permeability and reducibility of sinter were significantly improved. Due to its role in controlling melt formation, this technique may be useful in counteracting the incremental increase in ore alumina content. As illustrated in Fig. 11, unlike conventional granulation, high alumina ores are pre-granulated to form numerous small alumina-rich granules, which act as nuclei in the subsequent granulation stage. Figure 11 compares the structure of the granule produced using selective granulation with that for conventional granulation. Alumina is clearly segregated in the centre of granules as a result of selective granulation. However, it has to be emphasized that the nuclei in selective granulation are actually small granules, compared with coarse particles in conventional granulation. These small granules have to be strong enough to survive the subsequent granulation stage. Furthermore, good bonding at the interface between these small granules and the adhering layer is key in applying this technique.

6.4. Other Possible Measures

6.4.1. Optimisation of Raw Materials

In addition to iron ore fines, coke breeze and other raw materials contribute about 30% of the alumina in sinter. Therefore substitution of raw materials containing lower alumina in sinter blends should reduce the overall alumina level in sinter. Partial replacement of coke breeze by petroleum coke, anthracite coal and other fuels including biomass has been tried and remains a distinct opportunity to lower the total alumina content of sinter blends. Alternately high alumina ores can always be blended with those containing low alumina to keep the alumina level in sinter blends under control. While this method is currently being practised widely, it will inevitably increase ironmaking costs and is also limited by the availability of low alumina ores.

The particle size distribution of raw materials is also important, and will not only affect the granulation behaviour of sinter blends, but the sintering performance as well. While this may have no direct impact on the sintering performance of high alumina ores, improving the overall performance of the sinter blend may make it less sensitive and more tolerant to alumina. The nuclei and adhering fines
should be in the correct proportion and the proportion of intermediate particles should be low to achieve optimum granulation performance. Recent results suggested that it is possible to further improve the permeability of a sinter blend, and therefore control the pore size distribution of the sinter product, by adjusting the particle sizes of both limestone and coke breeze simultaneously.

6.4.2. Optimisation of Sintering Process

Due to the low reactivity of some alumina bearing minerals and the high viscosity of primary melts with high alumina content, sinter blends with high alumina content are expected to take a longer time to sinter. It is common industrial practice to raise the fuel rate as alumina increases. Alternatively, deep bed sintering may be used. Compared with the temperature profile of conventional sintering, deep bed sintering allows the sinter bed to be kept at elevated temperatures for a longer time. This may eventually allow alumina minerals extra time to react and assimilate with the primary melt. Increasing the time spent at temperatures above 1100°C has been previously reported to be an effective way to improve the inherent strength of sinter and therefore enhance its resistance to degradation. Deep bed sintering has been made possible by improved feed preparation, in particular better granulation.

After comparing sinters produced by different operating practices, it was found that sinter is more prone to degradation at higher sintering temperatures. Hence efficient cooling is believed to be necessary to reduce the exposure of sinter to high temperatures. Furthermore, enhanced cooling during the cooling cycle of sintering is also expected to promote fine fibrous SFCA-I and refine other secondary phases in sinter, which is believed to be beneficial to sinter strength. In Fig. 12, recent electron back-scattered diffraction (EBSD) results on the local strains in the sinter minerals, particularly FeO, found that a local strain distribution usually exists in the region within 20 μm from the grain boundary of sinter crystals. Formation of localised stresses and strains in sinter crystal grains is extremely important to the strength of sinter, because it makes the grains prone to fracture when subjected to external stress.

7. Closing Remarks

Iron ore sinter constitutes a major proportion of blast furnace burden in most countries in the Asia-Pacific region and is expected to have a significant impact on blast furnace performance. Sinter with good strength and reducibility, which is able to maintain these properties as long as possible in the blast furnace, is desirable. However, due to the increasing depletion of high-grade iron ore resources, the alumina and other gangue contents of iron ores are expected to increase gradually. The effects of alumina on the sintering performance and sinter quality for hematite iron ores have been reviewed. In general, as the alumina content of iron ores increases, both the sintering performance and the resultant sinter quality deteriorate. Hence, it is imperative for steel producers to develop strategies to maintain sinter quality with high alumina iron ores in their sinter blends. While the effects of alumina are very complex and the mechanisms responsible are not yet fully understood, extensive research suggests they should be associated with changes in the mineralogical texture and physical structure of sinter, which are largely dependent on the behaviour of primary melts formed during the sintering process. Measures which can neutralize, dilute and localize the effects of alumina on the sinter texture and promote and control the physicochemical properties of primary sinter melts will therefore be beneficial. Various methods to achieve these purposes have been discussed.

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