Effect of Iron Ore Particle Assimilation on Sinter Structure

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The properties of the melt generated during sintering determine the structure of the bonding phases formed. Melts that do not undergo reshaping and coalescence solidify into porous structures and this could have an adverse effect on sinter properties. The properties of melts, just prior to solidification, are highly dependent on the chemical composition of the adhering fines layer in granules and the assimilation behaviour of the nuclear particles. In this study, a carefully controlled bench-scale furnace was used to manufacture analogue sinters, which were characterized using optical microscopy and image analysis. Results show that altering the lime, and silica content of the adhering fines changed the structure of the analogue sinters formed because this altered the ability of the melt generated from the adhering fines, or primary melt, to react with iron oxide. The properties of the ore nuclear particles—in particular, porosity—have a significant influence on the proportion assimilated during the sintering period. The assimilation mechanism is different for porous ores because primary melts are highly mobile and readily penetrate into pores. Results also indicate that because of differences in assimilation mechanism, there are benefits in increasing the volume of primary melt (i.e. increased level of fines) when sintering blends containing high levels of porous ores. The yield of the sinter machine (i.e. the percentage sinter yield acceptable for use in the blast furnace) governs its productivity and is closely dependent on the structure of the sintered bed. Dense regions in the bed are clearly evident and appear to have formed because of selective coalescing of highly mobile melt1). When crushed these regions will yield strong particles suitable for use in a blast furnace. This coalescing process also causes large voids to form, which are seen throughout the sintered bed.2) The dense regions, interspersed between the voids, are linked together by a network of thinly connected material, which have been termed bridges.1) A significant proportion of bridges break down into return sinter fines as the sintered bed is crushed. A closer examination of the sintered bed also indicates that where the melt formed is less mobile, there has been reduced melt coalescence, forming a sinter structure that is very porous or ‘foamy’. Such a structure is likely to be more susceptible to breakdown during crushing. A clear understanding of the factors governing the structure of a sinter cake is essential to optimizing sinter size and porosity, and sinter strand productivity.2)

Previous work1) involving carefully controlled laboratory tests has shown that maximum sintering temperature, sinter basicity, and the levels of phosphorus, silica, alumina and magnesia all influenced the structure of the analogue sinter formed. The maximum temperature controls the degree of superheat of the melt, its flowability and the extent of melt coalescence.3) This explains why increasing coke rates usually improve sinter strength and size. However, in real systems, increasing temperatures not only reduces melt viscosity, but will increase the assimilation of larger ore particles. When this happens more melt is generated and the level of relict ore in the sinter reduces.2) The chemical composition of the melt changes with assimilation, and this has an impact on its liquidus temperature, the degree of superheat and, consequently, its viscosity and coalescing behaviour.1) It is, therefore, important to understand the influence of ore particle assimilation rate on sinter structure. In earlier studies3) it has been established that different iron ore types assimilate at different rates and to a different extent during sintering.

In the previous work program1) blends of very fine laboratory grade reagents were used to generate melts of different compositions. In this study iron ore particles were added into the blends to determine their effect on sinter structure. For mixtures containing fine chemical reagents and iron ore particles, it has been proposed3) that the reagents react very early during sintering to form a primary melt which then proceeds to assimilate the large particles to form a secondary melt. It has been argued that granules in plant sinter mixes behave in a similar manner to that observed in the small-scale experiments: the adhering fines

1. Introduction

During iron ore sintering, a packed bed of uniformly distributed granules—composed of a range of iron ore types, fluxes, fuel, return sinter fines and plant dusts—is transformed into porous sintered particles of irregular shape. The yield of the sinter machine (i.e. the percentage sinter acceptable for use in the blast furnace) governs its productivity and is closely dependent on the structure of the sintered bed. Dense regions in the bed are clearly evident and appear to have formed because of selective coalescing of highly mobile melt1). When crushed these regions will yield strong particles suitable for use in a blast furnace. This coalescing process also causes large voids to form, which are seen throughout the sintered bed.2) The dense regions, interspersed between the voids, are linked together by a network of thinly connected material, which have been termed bridges.1) A significant proportion of bridges break down into return sinter fines as the sintered bed is crushed. A closer examination of the sintered bed also indicates that where the melt formed is less mobile, there has been reduced melt coalescence, forming a sinter structure that is very porous or ‘foamy’. Such a structure is likely to be more susceptible to breakdown during crushing. A clear understanding of the factors governing the structure of a sinter cake is essential to optimizing sinter size and porosity, and sinter strand productivity.2)

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react to form a primary melt first, which proceeds to assimilate the nuclear particles. Different iron ore particle types generate secondary melts of different properties, which lead to the formation of sinters with different structures.

2. Theory: Assimilation of Nuclear Particles

A conceptual model for nuclear particle assimilation has been proposed. Assimilation of nuclear particles by primary melt involves breaking down of a solid lattice structure by a dissolution reaction. This is followed by the diffusion of species to (e.g. calcium oxide) and away from (e.g. iron oxides and silica) the interface as material is transferred into the bulk of melt (see Fig. 1). The rate of assimilation depends on the solid-melt interfacial area, temperature, and chemical composition of the primary melt. A conceptual model for the rate of solid dissolution is given by the expression:

$$\frac{dm}{dt} = K \cdot A_r \cdot D_c \cdot \Delta c^n$$

where $m$ is the mass of solid assimilated, $t$ is the reaction time, $K$ is a proportionality constant, $A_r$ is the area normal to the direction of mass transfer, $D_c$ is the concentration driving force, and $n$ is a constant. The value of $n$ is 1 if assimilation is diffusion controlled and greater than 1 when the dissolution reaction is also influential. Assimilation will terminate if the iron oxide concentration in the mass transfer zone is sufficiently high, or when the melt is too viscous to allow the diffusion of species.

When pisolite ore calcines it becomes very porous as goethite transforms into fine hematite crystallites. Goethitic ores assimilate much more readily than hematite ores because melts are very mobile and easily penetrate into porous ores, which therefore have a very high reaction surface area. Sintering temperature influences both the assimilation reaction rate and the diffusion rate of species. The degree of superheat, which is the difference between the sintering temperature and the liquidus temperature of the primary melt, has been shown to have a significant effect on the viscosity of the melt. Therefore, changes to sintering temperature or primary melt composition will alter assimilation also through changes in melt viscosity. As sintering is carried out close to the liquidus temperature of the melt, relatively small changes in sintering temperature can have a very significant influence on melt fluidity.

3. Experimental Details

3.1. Materials Used

Fine analytical grade reagents and naturally occurring iron ore particles were used to produce a cylindrical tablet with a diameter of 6.3 mm. Each pressed tablet weighed 0.8 g. The blended reagents in the tablets simulated the adhering fines layer in a granule while iron ore particles, with sizes ranging from 0.3 to 1.7 mm, were used to simulate the nuclear particles of granules. The nuclear particles were first wetted with a controlled amount of water before mixing in the adhering fines blend. The length of the tablets was varied, depending on the nuclear particle type, size and amount, to keep the inter-particle voidage unchanged. The pressure applied to produce the tablets was kept low to minimise the fracture of nuclear particles.

Table 1 shows the chemical composition of the five nuclear particle ore types used in the study. The porosity of these ores, as measured by mercury porosimetry, is shown in Table 2. Ore M is very porous while Ore I has the lowest porosity value. The porosity of ores will increase on calcination, which is an important mechanism when the ore contains a significant amount of goethite. This means that during sintering Ore Y, which has the highest LOI value, will have a very large assimilation reaction area, however, Ore I will remain very dense even after calcination. The adhering fines mix was a blend of fine analytical grade chemicals, which included Fe$_2$O$_3$, CaCO$_3$, kaolinite and MgO. For experiments with a different adhering fines mix basicity, CaCO$_3$ was used to replace iron oxide.

In this study the ore nuclear particle type will be used to denote the identity of the pressed tablets used in sintering, e.g. Tablet N denotes a tablet containing Ore N nuclear particles.

3.2. Experimental Technique

Sintering was performed in an Infra-red image furnace. Details of this technique have been discussed elsewhere. For all experiments except for the runs investigating calcination, the heat treatment was similar to the ther-

![Conceptual model for solid dissolution.](image1)

Table 1. Chemical analysis of ores.

| Component | Ore Y (%) | Ore M (%) | Ore N (%) | Ore B (%) | Ore I (%) |
|-----------|-----------|-----------|-----------|-----------|-----------|
| Fe (total) | 58.5      | 62.7      | 6.8       | 66.6      | 67.2      |
| SO$_2$    | 4.6       | 3.0       | 3.9       | 2.0       | 2.9       |
| Al$_2$O$_3$ | 1.5    | 1.9       | 1.7       | 1.0       | 2.0       |
| CaO       | 0.04      | 0.01      | 0.05      | 0.01      | 0.07      |

| Total LOI (%) | Yellow (%) | Black (%) |
|---------------|------------|-----------|
| 0.199| 0.186 | 0.197 |

Table 2. Pre-calcination porosity of ores.
mal profile in sintering. The sample starts off ambient and is heated to 800°C at 5°C/s and is held at this temperature for 1 min. Then the temperature is increased to 20°C/s to the maximum temperature and held for 2 min. For cooling, the sample is cooled to 400°C at 2°C/s. The sintered tablets or analogue sinters were then mounted in a low reflectance resin and polished to a constant depth with a 0.5 μm alum paste.

Images of polished analogue sinters were obtained using a Zeiss Axioskop optical microscope at magnifications of 2.5× and 10×. The images were captured using a black and white digital camera mounted on the microscope. To analyse pore structure the lighting conditions of the microscope were set for best image quality and standardised. Commercially produced software by Kontron called KS400 was used for processing the images taken with 10× magnification. The first step to differentiate pores and solid involved the application of an appropriate greyscale threshold value. Care was taken when differentiating between pores filled with resin and glassy phases in the sinter because of their very similar grey scale values. Additional processing steps included eroding and dilating the image and setting minimum size limits.

The extent of coalescing and reshaping of melts during sintering can be quantified by measuring the pore properties in sinter. The images shown in this paper were taken using a magnification of 2.5× and the actual dimensions of the frames shown are 5.26×4.17 mm. For the magnification used in this study, there is a minimum pore size measurable because of the difficulty differentiating small glassy phases from small pores. For pores 50 μm and greater, reliable results could be obtained for all the pore properties. The area fraction of pores between 8 and 50 μm was also estimated to show how the quantity of small pores in sinter changes under different conditions, but the reliability of these results was not as good.

Image analysis software was used to measure the equivalent circle diameter and the circular shape factor (circular shape factor = 4π multiplied by the ratio of the crofton area and perimeter) of pores, and the percentage pore area. The equivalent circle diameter was used as an indicator of pore size and the circle factor was a measure of how different in shape the pores deviated from a circle. These results were obtained only for pores 50 μm and greater. The fraction of 50 μm and greater pores was calculated using the total area of pores measured, which excluded area of pores touching the border of images. Throughout the paper the terms macro-pores and micro-pores are used—macro-pores refer to the larger pores generally formed in regions between nuclear particles as the primary melt coalesces; micro-pores refer to the smaller pores captured in the melt.

### 3.3. Experimental Program

Table 3 provides a summary of all the tests carried out. Six sets of experiments were carried out and the variables studied were:

- Set 1 – ore nuclear particle types;
- Set 2 – temperature and basicity of adhering fines;
- Set 3 – combination of fines basicity, alumina and silica levels;
- Set 4 – nuclear particle size and level;
- Set 5 – holding time at maximum temperature; and
- Set 6 – fines silica levels.

Only two ores—a porous (Ore Y) and a dense ore (Ore I)—were considered in Sets 2 to 6. Three repeat runs were carried out under each condition, to generate an acceptable sample size and increase the confidence level of the test results obtained. All the experimental results are given in Figs. 2, 4, 8, 11 and 12 as binary images, where white regions are solid and black regions are pores.

Except for experiments aimed at understanding the effect of nuclear particle type (Set 1 in Table 3) and silica level (Set 6 in Table 3), conditions used were selected using a fractional factorial design, which allowed the interaction between variables to be considered. The basicity (ratio of CaO to SiO₂) and the alumina and silica levels shown are for the adhering fines.

A modelling package FactSage 5.1 (2002, C. W. Bale et al.) was used to calculate the melting point of primary melts. Since the adhering fine mixes used were composed of very fine and highly reactive particles, the predicted melting points were indicative of liquidus temperature of

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**Table 3. Summary table of experimental program.**

| Set | Variables Studied | Experimental Conditions |
|-----|-------------------|-------------------------|
| 1   | NP               | Ore Y/ Ore M/ Ore N/ Ore I | 1360 | 2 | 2.0 | 2.0 | 5.5 | 0.71-1.0 | 60 |
| 2   | NP/Temp/Basicity | Ore Y/ Ore Y | 1320/1400 | 2 | 1.5/2.5 | 2.0 | 5.5 | 0.71-1.0 | 60 |
| 3   | NP/Basicity/Alumina/Silica | Ore Y/ Ore Y | 1360 | 2 | 1.5/2.5 | 1.6/2.4 | 4.5/6.5 | 0.71-1.0 | 60 |
| 4   | NP/NP size/NP amount | Ore Y/ Ore Y | 1360 | 2 | 2.0 | 2.0 | 5.5 | 0.30-0.43/14.1-17 | 50/70 |
| 5   | NP/Temp/profile | Ore Y/ Ore Y | 1320/1400 | 5 | 2.0 | 2.0 | 5.5 | 0.71-1.0 | 60 |
| 6   | NP/Silica | Ore Y/ Ore Y | 1360 | 2 | 2.0 | 2.0 | 4.0/7.0 | 0.71-1.0 | 60 |

*NP is nuclear particle.*
the primary melt. These values, used to estimate the degree of superheat and changes to melt viscosity, are shown in Table 4. Results indicate that increasing the basicity and increasing the silica level at constant basicity decreased the melting point, while increasing the alumina level had a negligible influence on melting point. It is acknowledged that using the melting point is not a completely valid concept when considering the assimilation process because of the solids present in melt.

4. Results and Discussion

4.1. Effect of Nuclear Particle Type on Sinter Structure

The ore nuclear particle types (Table 1) were investigated using a standard condition: 1 360°C for 2 min, basicity of 2, alumina level of 2%, silica level of 5.5% and 0.71–1.0 mm nuclear particles. The final structure of sinter was used as an indicator of melt flow and penetration. The pores between nuclear particles and within nuclear particles show clearly where the primary melt has flowed and reacted. Results shown in Fig. 2 indicate that sinters formed with dense ores B and I have dense regions, indicating that not all the nuclear particles have assimilated. When porous Ores Y and M were used, the sinter structures indicate that primary melt had penetrated completely into nuclear particles. Ore N has porosity and LOI values in between those of the dense and porous ores; it is, therefore, not surprising the sinter contained structures similar to that found in both Tablets M and Y. As for Ores Y and M, there was penetration of melt into Ore N but the sintered tablets also had a significant amount of unreacted ore particles. Set 1 results show that the nuclear particle type had a very significant influence on sinter structure. To understand factors causing the changes in sinter structure, the following areas were considered in greater detail: calcination behaviour, melt coalescence and reshaping, and sinter pore properties.

4.1.1. Calcination of Nuclear Particles

For pisolite ores, the structure of the ore presented to the primary melt is quite different to that of the original ore. It is this structure that determines assimilation behaviour, thus further understanding of the effect of calcination is warranted. Tablet Y and I were heated up to 1 100°C, which is before sintering reactions initiate but after calcination. The heating profile for calcination was like all other experiments, the difference being the maximum temperature was 1100°C which was not held but cooled instantaneously at a rate of 2°C/s. The structures formed are shown in Fig. 3. In Tablet Y (Fig. 3(a)), large cracks and pores and, in some cases, regions with severe cracking were observed throughout the nuclear particles. When tablet Y was subjected to the full thermal cycle it no longer contained such pores and cracks because the primary melt has assimilated the walls of nuclear particles—see Figs. 2(a), 2(b), 2(c). The penetration of melt into pores and cracks prior to assimilation has been very effective. Past work has indicated that primary melts have good wetting properties, and the capillary forces causing penetration into pores are large. For Tablet I a negligible change in the structure of the nuclear particles was observed on heating to 1 100°C, because of the low LOI value of the nuclear particles.

A close study of Fig. 3 also shows another phenomenon, which could be important in considering assimilation rates. The nuclear particles in Tablet I are in contact with the adhering fines layer, but in Tablet Y a gap has formed between the nuclear particles and the adhering fines. This has also been observed in a previous study and is most likely a direct result of nuclear particle shrinkage during calcination. Figures 4(a) and 4(b) shows that in both Tablets I and Y, all the nuclear particles were connected by a very irregular and branched solidified melt, which indicates that the primary melt was capable of bridging the gap to pene-

| Table 4. Melting points of the primary melt for each experiment set predicted by the modelling package FactSage. |

| Set | 1–A | 1–B | 1–C | 1–D | 1–E | 1–F | 1–G | 1–H | 1–I | 1–J | 1–K | 1–L |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Basicity | 0.5 | 1.0 | 1.5 | 2.0 | 2.5 | 3.0 | 3.5 | 4.0 | 4.5 | 5.0 | 5.5 | 6.0 |
| SiO₂ (%) | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 |
| Al₂O₃ (%) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Melt Temp. [°C] | 1409 | 1457 | 1353 | 1480 | 1395 | 1482 | 1399 | 1432 | 1335 | 1436 | 1325 | 1401 | 1414 | 1506 |

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trate into pores and cracks of calcined nuclear particles. In tests which had a high melting point primary melt, there was evidence of reduced effectiveness in bridging the gap (Fig. 4(a)). When this happens the time available for assimilation is shortened.

4.1.2. Melt Coalescence and Reshaping

The structure of sinters formed in this study was quite different to those formed in the earlier program. The presence of nuclear particles greatly restricted the ability of melt to coalesce, reshape and alter the sintered tablet structure. With reduced levels of primary melt compared to the previous program, the surface forces acting in the tablets were lower. The presence of nuclear particles in the melt would increase its resistance to flow, which is similar to increasing the effective viscosity of the melt. This change reduces the degree of melt coalescence and reshaping, which depends on the ratio of surface forces to viscous forces.

The large dense regions in the optical micrographs are either nuclear particles or solidified melts that have undergone significant coalescing. Mineralogical differences make it possible to distinguish between the two to draw conclusions about the assimilation mechanism and the properties of the melts formed.

For Tablets Y and M, the primary melts have penetrated the nuclear particles, leaving behind large voids between the nuclear particles. Therefore, the voidage of the pre-sintered tablet and the mass ratio of adhering fines to nuclear particle will influence the volume of macro-pores in the sinter. When primary melt was drawn into nuclear particles very little movement of nuclear particles occurred because of the limited surface forces. Thus, the size and shape of the tablets did not undergo much change.

The ability to penetrate effectively into the cracks and pores of calcined nuclear particle meant that the primary melt in Tablets Y and M had been spread thinly across a very large area. The high assimilation reaction area causes the composition of the primary melt to alter very rapidly, in particular its iron oxide and silica contents. As indicated by the FactSage model and shown in Table 4, increasing the iron oxide content of the primary melt raises its melting point, which translates into a more viscous melt at the same temperature. According to the absolute rate theory approach the diffusion coefficient of a species is inversely related to the viscosity of melt. In a relatively short time, the melt would be too viscous to accommodate any more iron oxide and the assimilation reaction terminates. Because the melt is spread thinly over a large area, assimilation rate is likely to depend on the dissolution rate of the ore i.e. reaction controlled. For Tablet I, the melt is confined to the outer surface of nuclear particles and the diffusion of oxides to and from the nuclear particles is expected to become significant during assimilation.

4.1.3. Pore Properties

The differences in assimilation mechanism described above, which result in melts of different properties, have a direct effect on pore properties. Figures 2(a), 2(b), 2(d) and 2(e) shows that the macro-pores in Tablets I and B are less branched and are wider than those found in Tablets Y and M. Figure 5(a) showed that sintered Tablets I and B had larger pore sizes than those found in Tablets Y, M and N. Furthermore, the proportion of pores greater than 50 μm for Tablets I and B (79% for both, Table 5) was greater than for Tablets Y, M and N (64%, 65% and 56% respectively, Table 5). Differences in pore size can also be ex-
explained by differences in melt properties.

The micrographs in Fig. 2 indicate that when the melt penetrates effectively into nuclear particles, there is limited coalescence and the solidified melt contains a high level of micro-pores. This is consistent with the formation of a viscous melt, where bubbles do not coalesce and cannot be expelled from the melt.1 When good penetration into the nuclear particles takes place the chemical composition of the primary melt has a limited influence on the level of micro-pores. For dense Ores I and B, the pores in the solidified melt would be strongly dependent on the primary melt chemical composition, which changes more gradually during the sintering process. During this period, the melt and pores can coalesce and reshape, and the larger bubbles are expelled from the melt. Figure 2(c) shows that the unreacted particles in sintered Tablet N are still quite dense even though there has been penetration by the primary melt. A possible explanation for this is that the pores and channels formed as a result of calcination are relatively small compared to those formed in Tablet Y.

For the Tablet I, Figs. 4(b), 4(d), 4(f) and 4(h) shows that increasing basicity and temperature increased the level of micro-pores in the sinter. Increasing basicity and temperature increased the volume of nuclear particles assimilated, and also increases the fluidity of the melt, which enhances the bubble and melt reshaping/coalescing processes. Figures 4(a) and 4(g), 4(b) and 4(h), shows that there is a reduced distinction between macro and micro-pores in the sinter indicating that significant bubble coalescence has occurred. The increase in fluidity is also confirmed by the increased roundness of the macro-pores.

As shown in Fig. 5(b) it was generally observed that the circle factor of pores decreased as pore size increased, the only exception being Tablet M. Tablet M had a comparatively small number of large pores, and the observed discrepancy could be explained by the small sample size and, therefore, reduced accuracy in the average circle factor values. Overall the roundness of pores tended to be inversely related to pore size. This phenomenon has been discussed in an earlier paper.1 The magnitude of the surface forces acting on a bubble is 2γ/r, where r is the bubble radius and γ is the surface tension of the melt. This relationship indicates that surface forces increase with decreasing pore size.

### 4.2. Influence of Maximum Temperature and Temperature Profile

When temperature was increased more Ore I nuclear particles dissolved and the structure of Tablet I became more homogeneous as dense ores were replaced by more uniform porous solidified melts (Figs. 4(f) and 4(h)). Changes were also observed in Tablet Y at increased temperature because of the higher degree of superheat and melt mobility. The smaller pores coalesced to form larger ones, the solids surrounding the pores became thicker and the distinction between macro-pores and micro-pores reduced.

Table 6 shows that for Tablets Y and I, increasing the temperature at both low and high basicity increased the amount of pores greater than 50 μm. For Tablet Y, increasing temperature increased the percentage of pores greater than and equal to 50 μm from 0.55 to 0.60 for the low basicity case, and from 0.73 to 0.83 for the high basicity case.

| Table 6. Proportion of pores ≥50 μm for different experimental sets. |
|--------------------------|--------|--------|
| **Ore**                  | **% area pore ≥50 μm** |
| Set 2: Basicity=1.5, 1320 C | 0.55   | 0.68   |
| Set 2: Basicity=2.5, 1320 C | 0.73   | 0.87   |
| Set 2: Basicity=1.5, 1400 C | 0.60   | 0.77   |
| Set 2: Basicity=2.5, 1400 C | 0.83   | 0.89   |
| Set 4: 0.30~0.36 mm, 30% af | 0.57   | 0.70   |
| Set 4: 0.30~0.36 mm, 50% af | 0.83   | 0.80   |
| Set 4: 1.4~1.7 mm, 30% af | 0.59   | 0.73   |
| Set 4: 1.4~1.7 mm, 50% af | 0.72   | 0.80   |
| Set 5: 1320 C, 2 min | 0.65   | 0.71   |
| Set 5: 1320 C, 5 min | 0.58   | 0.65   |
| Set 5: 1400 C, 2 min | 0.73   | 0.81   |
| Set 5: 1400 C, 5 min | 0.81   | 0.83   |
| Set 6: 4% silica | 66     | 84     |
| Set 6: 7% silica | 71     | 81     |

* af is adhering fines.

For Tablet I equivalent values are from 0.68 to 0.77 and from 0.87 to 0.89 respectively, and they indicate similar trends. However, the size distribution of these pores in Tablets Y and I moved in opposite directions as temperature was increased (Fig. 6(a), since a 10X magnification was used which excluded many of the larger pores from the size distribution, the influence of macro-pores on the size distribution was not taken into account). The size distribution of pores greater than 50 μm for both Tablets Y and I shifted toward larger sizes as temperature was increased for high
basicity (Fig. 7(a)). This observation confirms that bubbles were coalescing to form larger bubbles as the sintering temperature increased, even though the increased assimilation of ores forms a secondary melt with higher viscosity.

At a basicity of 1.5 Fig. 6(b) shows that, for a given pore size, increasing temperature caused the average circle factor in both Tablets Y and I to increase. Figure 7(b) suggests that at a higher basicity of 2.5, increasing temperature also increased the average circle factor of a given pore size, but to a lesser extent than at a basicity of 1.5. Therefore, it appears for both Tablets Y and I that increasing temperature increased the roundness of a given sized pore, although this effect appears to diminish as basicity increases. This could be expected since a low basicity melt is quite viscous at a low temperature.

At 1 400°C the pore size distribution of Tablet Y is shown in Table 6. At increased holding time at maximum temperature, there is an increase in pore size and the fraction of pores greater or equal to 50 μm also increased from 73 % to 81 %. Figures 8(f) and 8(h) shows that increasing the holding time for Tablet I caused extensive pore coalescence and increased ore assimilation. These results show that increasing the length of time at maximum temperature influenced sinter structure, presumably through enhancing the reshaping and coalescence of melts and bubbles in melts.

4.3. Role of Primary Melt Composition

The three aspects of chemical composition considered in the current work were basicity, silica content and alumina content of the adhering fines.

4.3.1. Basicity

It is apparent from the images shown in Fig. 4 that increasing basicity resulted in greater melt coalescence and reshaping of bubbles for both Tablets I and Y. These observations can be explained by the predictions of FactSage, which indicated a decrease in the melting point of approximately 100°C as basicity was increased from 1.5 to 2.5 (Table 4). As sintering temperatures were kept unchanged, melts of high basicity will have significantly higher fluidity. Changes in basicity were considered at two different temperatures.

At the lower temperature of 1 320°C, increasing basicity increased the degree of reaction in Tablet I, (Figs. 4(b) and 4(d)), probably because the primary melt could accommodate more iron oxide before reaching solidification temperature (i.e. the appetite of the melt for iron oxide has increased). Assimilation was also enhanced because of higher diffusion rates of the oxides in the melt. Increasing the basicity of Tablet Y enhanced melt penetration into the nuclear particles and also increased the appetite of the melt (Figs. 4(a) and 4(c)). Table 6 shows that at increasing basicity, the fraction of pores greater than or equal to 50 μm for Tablet Y increased from 55 % to 73 %, while for Tablet I the same fraction increased from 68 % to 87 %. Figure 9(a) shows the pore size distribution for Tablet I. Results indicate that there has been a clear shift towards the larger pore size at increasing basicity. For Tablet Y the shift is not as evident simply because many large pores, outside the measurement range of the technique, were not included. The pores, as indicated in Fig. 4, also appear to be more circular at increasing basicity. Circle factor results confirming this observation are shown in Fig. 9(b). The transformation of bubbles into rounder shapes is another confirmation that the formed melt had been more fluid.

At the higher temperature of 1 400°C, Fig. 4 shows that increasing basicity gave very similar trends. It is clear that increasing temperature results in more profound changes because the melt was more fluid and more of the nuclear particles were assimilated. Analysis of the structures for...
both ore types show that pore size distributions moved toward larger sizes as basicity was increased at the higher temperature as seen in Fig. 10(a). Also the fraction of pores greater than or equal to 50 μm increased from 60% to 83% for ore Y, and from 77% to 89% for ore I as basicity was increased (Table 6). Again the pores looked rounder for both ore types as basicity was increased, which was confirmed by image analysis, as shown by the results in Fig. 10(b).

At a fixed basicity, increasing melt silica also increased its CaO content. For the increases in silica considered in sets 3B and 3F, predicted melting point decreased by 65 degrees (Table 4), mainly because of higher CaO levels. It appears that sinter structure is more dependent on CaO content rather than on basicity. The phase diagram for a Fe₂O₃–CaO–SiO₂ system suggests that increasing the level of CaO in the mix beyond a point (approximately 30% level) will cause the liquidus temperature to increase. Thus, it is to be expected that there is a point where further increases in CaO will lead to reduced coalescence and reshaping.

4.3.2. Silica and Alumina Content

An overview of the results indicate that changing silica level had a greater influence on the sintered structure of Tablet 1 than that of Tablet Y. Figure 11 shows that at lower silica levels the Ore I nuclear particles were better connected, suggesting that there had been greater coalescence of bubbles and reshaping of the melt. Quantitative image analysis results show that the pore size distribution shifted towards finer sizes as silica level was increased, which is consistent with observations. However, for Tablet Y the opposite trend was obtained, even though the changes were not as significant. Table 6 shows that the measured area of pores greater or equal to 50 μm decreased slightly for Tablet I and increased for Tablet Y at increasing silica level, and this is consistent with the shifts in pore size distribution. For Tablet Y, the melt was capable of fully penetrating the nuclear particles irrespective of its silica content, and this could explain the small change observed in pore structure. The predicted increase in melting point with increased silica (Table 4) could explain the Tablet I results.

Changing the alumina level of the primary melt appeared to have only a small effect on the pore structure of both Tablets Y and I. These observations were confirmed by quantitative image analysis results. This finding appears to be very different to results from an earlier research program, using samples with no nuclear particles,11 which showed that alumina had a very significant effect on sinter structure. The reason for the differences is not clear. Future work will examine in greater detail the effect of alumina on sinter structure.

4.4. Role of Nuclear Particle Properties

4.4.1. Size

The effect of changing nuclear particle size is shown in Fig. 12. For Tablet Y, Figs. 12(a) and 12(c) shows that the greater degree of assimilation obtained using smaller nuclear particles led to increased melt viscosity and reduced the large-scale movements of the melt. For Tablet I, with reduced assimilation levels the melt remains fairly mobile regardless of nuclear particle size which allowed some large-scale movements of the melt and nuclear particles. The
4.4.2. Proportion

From discussions so far, it is not surprising that increasing the ratio of adhering fines mass to nuclear particle mass enhanced bubble coalescence, increased wall thickness and increased the roundness of the macro-pores (Figs. 12(a) and 12(c)). Increasing the fraction of adhering fines from 30% to 50%, raised the proportion of pores greater than 50 μm from 57% to 83% (Table 6). When smaller Ore Y nuclear particles were used, increasing the volume of primary melt increased assimilation because of increased melt penetration. Also, more adhering fines allowed for more bridging of nuclear particles, thus macro-pores become smaller and less prevalent. This was more evident for porous ores, especially for larger nuclear particles.

With larger nuclear particles, results in Table 6 show that as the adhering fines content in the tablet increased from 30% to 50%, the area of pores greater than 50 μm increased from 59% to 72%. Figures 12(e) and 12(g) also suggests that when the adhering fines level was high, primary melt remained outside the nuclear particles and assisted in the formation of a well-connected sintered structure. It is also not surprising that Figs. 12(b) and 12(d), 12(f) and 12(h) indicates that the bonding together of unreacted nuclear particles in Tablet I was less sensitive to the level of adhering fines than for the case of Tablet Y.

Overall, the results confirm the validity of the assimilation model presented in Sec. 2. When the level of adhering fines is increased, more primary melt is formed and a greater amount of iron oxide can be dissolved by the melt before it reaches the point where the melt becomes very viscous.

5. Conclusions

Bench-scale experiments were carried out to investigate how different types of nuclear particles assimilate under a range of conditions, and the effect of this on pore structure. Conclusions drawn from this work are:

(1) The properties of ore and primary melt, formed from the adhering fines layer, have been shown to influence the assimilation process. This process causes the chemical composition of the primary melt to change and the properties of the bonding phases in sinter is determined by melt properties prior to its solidification. Assimilation, therefore, has a large influence on sinter properties such as strength and reducibility.

(2) A conceptual model of the assimilation, given in an earlier paper, has been used successfully to explain how variables such as maximum temperature, adhering fines chemical composition, and nuclear particle type influenced the properties of the bonding phases. The model explains the assimilation process in terms of: reaction area, the dissolution of iron oxide in melt, sintering temperatures and the fluidity of the melt, which influences the diffusion rate of iron oxide from the solid-liquid interface. The assimilation of nuclear particles and the fluidity of melt are dependent on melt chemical composition.

(3) The assimilation of dense and porous nuclear particles occurs through quite different mechanisms. Primary melts penetrate easily into porous particles, and assimilation rates are high because of the large intra-particle reaction area. Very little relict ore remains after sintering. For dense nuclear particles, assimilation occurs only on outer particle surfaces and the rate at which this occurs is highly dependent on the properties of the primary melt. Factors such as temperature and adhering fines chemical composition (in particular lime content) determine the fluidity of melt and, therefore, the assimilation and bonding phase properties.
As expected, temperature greatly influenced the kinetics of the assimilation reaction. For porous ore particles the effect of temperature is not as important because of the high reaction surface area. Increasing temperature is likely to produce a more fluid melt, which will increase penetration into nuclear particles, and also increase the rate of diffusion of iron oxide and gangue oxides through the melt. Also, increasing the length of time at maximum temperature was more important for dense ores since their assimilation was a slower process.

(5) The assimilation of dense nuclear ore particles is more dependent on particle size than porous ores because they rely only on their outside surface for reaction. For porous nuclear particles, the primary melt is spread thinly over a much larger area. The liquidus temperature of the melt increases sharply as its iron oxide level rises, which inhibits the ability of the melt to reshape and bubbles to coalesce. This could have a negative impact on sinter strength and yield. Increasing the amount of primary melt improves the bonding of nuclear particles, especially for porous ores. This could mean that a higher level of fine material could improve the strength of sinters produced from blends containing high levels of porous ores.

(6) Towards the end of sintering the assimilation reaction produces a melt containing unreacted nuclear particles, large voids and a melt containing entrained bubbles i.e. a solid–liquid–gas system is generated during sintering. In an earlier study sintered tablets were produced without nuclear particles in the mix. Compared to the earlier work, results indicate that sinter structure was less dependent on melt chemical composition. More work is required to understand the reasons for the differences.

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