



1. INTRODUCTION

It is well known that the quality of sinter is mainly governed by the microstructure and phase composition of the sinter. The bonding phases make up the majority of phases within sinter (up to 80vol%). These phases are formed during the sinter process at temperatures above 1100°C. Therefore, the temperature-time-characteristics of the sinter process is an important parameter that contributes to the microstructure and phase composition of sinter. The sintering conditions are not the same through the sinter bed. This will result in a variation in the phase composition through the sinter bed. The aim of this investigation was to investigate the influence that the temperature-time-characteristics of the sinter process may have on phase formation and the sinter quality.

2. LITERATURE REVIEW

2.1 SINTER PROCESS DESCRIPTION

Sintering is a generic term that is used to describe a high temperature process in which a raw materials mixture is converted into a particular form of agglomerate known as sinter⁽¹⁾.

On a production plant the sintering process is divided into several sub-processes⁽¹⁾:

- Blending and granulation of the sinter mixture.
- Charging into sinter cars in the sinter machine to form a sinter bed.
- Ignition of the fuel in the surface of the bed.
- Sequential combustion of the fuel in horizontal layers.
- Reaction at high temperatures involving the liquid melt and solids.
- Cooling and solidification of the melt.
- Crushing of the agglomerate to obtain a manageable size distribution.

Iron ore fines, coke breeze, flux and other raw materials are mixed together. Water is added to the mixture. The mixture is then granulated into pseudo-particles in a rotary mixer. Granulation involves the layering of fine particles (<0.25mm) onto the surface



of coarser particles ($>1\text{mm}$). Therefore, the pseudo-particle consists of a coarse nucleus particle and fine particles attached to the nucleus particle. Particles in the range between, called intermediate fines, remain detached and find their way into the voids of the sinter bed. Good granulation coarsens the mix and narrows the size distribution.

The purpose of granulation is to improve the bed permeability that will enhance the flow characteristics of the combustion air through the sinter bed. This will contribute to improved sinter quality and productivity. During sintering the permeability of the sinter bed is adequately maintained because large nucleus particles remain unmelted. The voids between the pseudo-particles will collapse and the permeability of the sinter bed will consequently decrease if there are no such nucleus particles at all⁽²⁾. A binder such as quick lime may be added during the granulation process to help to keep the microstructure of the pseudo-particles stable when moisture is removed during sintering.

The granulated mixture is charged onto a grid layer of coarse sinter ($-40+20\text{mm}$) in sinter cars on the sinter machine. The height of the packed bed varies from process to process and can be up to 600mm in height. The bed immediately passes under an ignition hood where the fine coke in the surface layer is ignited by gas flames. As the sinter cars move forward, combustion is promoted by air drawn through the sinter bed into a series of wind boxes under the sinter bed. The pressure drop over the sinter bed can be up to 2000mm H₂O⁽³⁾.

In the sintering process the temperature of the granulated sinter mixture is raised to temperatures between 1250°C and 1400°C to achieve partial fusion. During the heating and cooling cycle different species react with each other to produce certain phases. Molten material is produced which crystallises or solidifies into various phases that bond the microstructure together⁽⁴⁾. Therefore, sinter consists of an assembly of various phases such as hematite, magnetite, SFCA and calcium silicate of varying chemical composition and morphology. Each of the different phases has a unique influence on the sinter quality.

The sinter cake is either cooled on the sinter strand (on-strand cooling) or outside the sintering machine (off-strand cooling). The sinter is crushed and screened to a size range desirable as a blast furnace feed for example -50+5mm.

2.2 SINTERING ZONES

The sinter mixture is subjected to different thermal and physical conditions during sintering. It is therefore possible to divide the sinter bed into different zones that coexist during the sintering process (**Figure 1**). Each of the zones has a profound influence on sintering performance and sinter quality⁽⁵⁾.

When the bed is sectioned vertically it is evident that combustion is confined to a thin layer between unsintered feed below and cooling sinter above⁽⁶⁾. This layer is known as the combustion layer (**Figure 1**). The combustion layer travels at 1cm/min to 3cm/min towards the grate⁽⁷⁾.

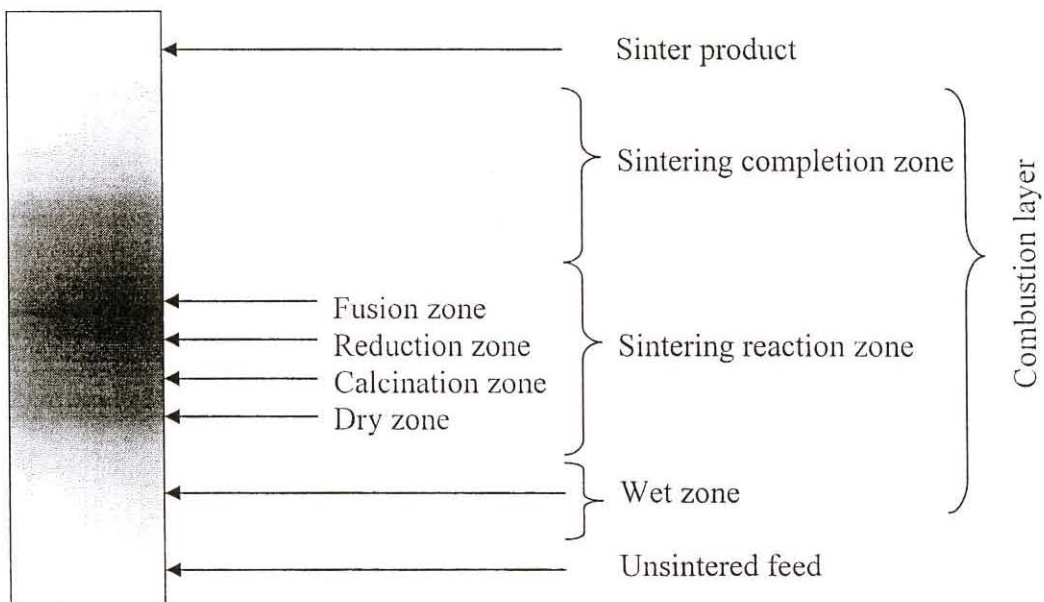


Figure 1: Sintering zones

As combustion proceeds through the sinter bed each part of the sinter bed is subjected to a characteristic temperature cycle. The temperature rapidly increases to a maximum temperature and remains there for a few minutes. As the combustion layer moves further down the sinter bed the material cools down with time.

Fundamentally sintering is an efficient heat transfer process in which heat is continually transferred downward through the bed⁽⁶⁾. Air entering the bed is heated by the warm sinter above the combustion layer and attains its peak temperature in the combustion layer. The gas leaving the combustion layer transfers heat to the feed below. The gas serves to ignite the coke breeze and to initiate endothermic changes and reactions⁽⁶⁾.

The combustion layer consists of the following zones⁽²⁾ (**Figure 1**):

- A wet zone.
- A sintering reaction zone.
- A sintering completion zone.

2.2.1 THE WET ZONE

The lower part of the sinter bed acts as de-humidifier and removes water from the flowing air. The accumulation of water in this part of the sinter bed results in the wet zone. The start of the wet zone is often well defined because of the presence of a thin layer of fines⁽⁵⁾. These fines have been detached from pseudo-particles in the sintering reaction zone and have been captured by the wet zone. Their presence will definitely increase the resistance of the wet zone to air flow⁽⁵⁾. As the combustion layer moves down so will this layer of fine captured particles. The wet zone basically acts as a very effective wet scrubber for fine particles. It is most likely that other material, e.g. volatilised alkali chlorides, could also be scrubbed out in the wet zone⁽⁵⁾. The wet zone disappears when the combustion layer has moved low enough down the sinter bed. The accumulated layer of fines and dissolved substances will leave the sinter bed in the off-gas⁽⁵⁾.

2.2.2 THE SINTERING REACTION ZONE

The height of the sintering reaction zone is approximately 70mm and the reaction time in this zone is 3min⁽²⁾. Various changes occur in this zone as the temperature rises and also during cooling. It is assumed that the process is complete when the temperature drops below 1100°C⁽⁴⁾. The following processes occur in the sintering reaction zone⁽⁴⁾:

- Solid state reactions.
- Melting of the products to form a primary liquid.
- Dissolution of solids in the melt to form a secondary liquid.
- Crystallization of the phases from the liquid on cooling.
- Solidification of the liquid to form glass.

The sintering reaction zone is further divided into the following zones⁽²⁾ (**Figure 1**):

- Dry zone.
- Calcination zone.
- Reduction zone.
- Fusion zone.

(a) THE DRY ZONE

Due to the downward movement of the combustion layer the mixture in front of the combustion layer is dried by the heat from the warm gas leaving the combustion layer.

(b) THE CALCINATION ZONE

The temperature has increased to a point where calcination of some of the raw materials for example dolomite may occur.

(c) THE REDUCTION ZONE

The combustion of coke begins between 700°C and 800°C⁽²⁾. With increasing temperature the CO₂-gas reacts with the coke to produce CO-gas. The CO-gas reduces hematite to produce magnetite. When further reduction occurs wustite is formed.



(d) THE FUSION ZONE

In the fusion zone reactions occur at high temperatures and are termed sintering reactions. These reactions determine the mineralogy and texture of the sinter and consequently the sinter properties⁽¹⁾. The reactions are extremely complex, involving physical and chemical factors of which many are inherent properties of the raw materials used.

2.2.3 THE SINTER COMPLETION ZONE

Crystallisation and solidification occur on cooling. Final reactions between the different phases and chemical species result in the final phase composition and microstructure of the sinter.

2.3 THE TEMPERATURE PROFILE AND HEAT INPUT

The temperature profile in the sinter bed is schematically shown in **Figure 2**. This profile is characterised by a steep rise to a maximum temperature (T_{\max}) during the heating cycle. It takes normally about two minutes⁽⁸⁾ to heat the raw materials to maximum temperature. The maximum temperature reached is often higher than 1300°C and may be as high as 1350°C⁽⁹⁾. The maximum temperature reached depends mainly on the quantity, location, amount of coke used and the combustibility of the coke⁽⁴⁾.

The depth of the bed and airflow rate also have a significant effect on the maximum temperature reached. A gentle slope after reaching maximum temperature indicates the relatively slow cooling of the finished sinter during the cooling cycle. The time to cool to room temperature is a function of the maximum temperature⁽⁶⁾. As the maximum temperature increases the time to cool down will also increase.

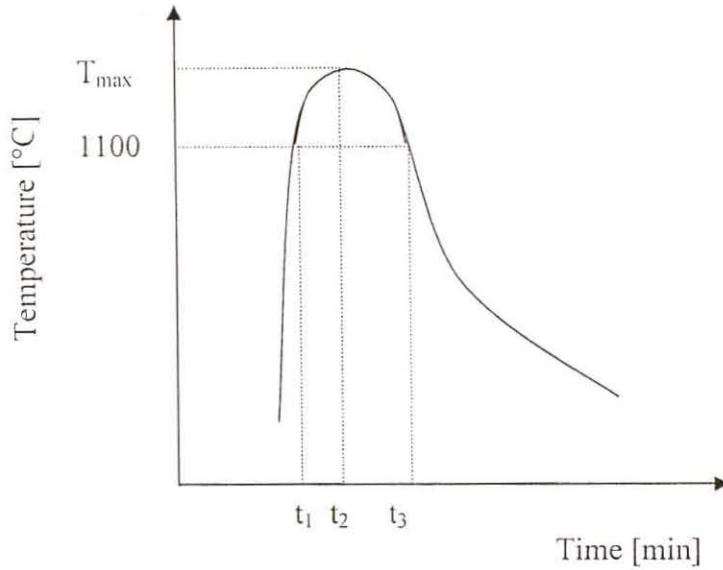


Figure 2: A schematic diagram of a typical temperature profile in a sinter bed

Energy is supplied during sintering when heat is continually transferred downward through the bed. The quantity that is continually transferred is equivalent to the sensible heat of the bed itself once the process is fully established⁽⁶⁾. The supplied energy will increase when the time at temperatures higher than 1100°C (t_3-t_1) increases (**Figure 2**).

Different temperature profiles are obtained from top to bottom in the sinter bed. Both the maximum temperature and the area below the temperature profile vary from top to bottom. The maximum temperature is lower and the retention time at the maximum temperature is shorter in the top layer than in the bottom layer⁽¹⁰⁾. To improve the microstructure of the sinter it is important to minimise the difference in temperature profile and to control it to a suitable heat pattern⁽¹⁰⁾. Because of these differences the discharged sinter may be classified as follows⁽⁶⁾:

1. Top sinter: generally weak and friable giving a poor yield of sinter with an acceptable size grading. This sinter is fused at a high temperature and chilled immediately thereafter. The sinter is discharged cold from the sinter strand.

2. Middle sinter: This sinter is formed under optimum conditions for fusion and annealing and gives the maximum yield of sinter with acceptable size grading. The sinter is discharged cold from the sinter strand.
3. Bottom sinter: This sinter is discharged hot and is chilled severely as it passes through the breaker and over the discharge screen onto the cooler. This may result in poor physical properties giving a lower yield of sinter with acceptable size grading. If on-strand cooling applies, the sinter will have almost the same properties as the sinter in the middle layer.

2.4 MICROSTRUCTURE

Two types of sinter microstructure can be produced depending on the sintering conditions, in particular the sintering temperature⁽⁴⁾:

A homogeneous microstructure implies that the visual appearance of the sinter is homogeneous. Homogeneous sinter is produced at higher sintering temperatures ($T > 1300^{\circ}\text{C}$) and usually contains only precipitated phases.

A heterogeneous microstructure implies that the visual appearance of the sinter is heterogeneous in which a significant amount of large particles remains partially unreacted. This microstructure is produced at $T < 1300^{\circ}\text{C}$. An important characteristic of such sinters is the presence of unreacted ore particles⁽¹¹⁾.

2.5 PHASES

The main phases occurring in sinter are SFCA, unassimilated iron ore particles, precipitated oxides of iron (magnetite and hematite) and dicalcium silicate as matrix⁽²⁾⁽¹²⁾. In a study on South African sinters by PA Botha⁽¹³⁾ phases like hematite, magnetite, SFCA and calcium silicate were examined. This study revealed that hematite, magnetite and SFCA dominated in the sinter investigated with small quantities of calcium silicate, glass, periclase, wustite and manganosite⁽¹³⁾.

2.5.1 HEMATITE

Three types of hematite commonly occur in sinters namely massive hematite, crystalline hematite and secondary hematite⁽¹³⁾. Massive hematite is hematite originating from iron ore particles that did not fully participate in the sintering reactions. Massive hematite remains partly in its original state.

Crystalline hematite precipitates from the melt⁽¹²⁾. Crystalline hematite may exist at the periphery of the massive hematite particles. Crystallization occurs in the presence of oxygen usually near cracks and pores⁽¹³⁾.

Oxidation of magnetite to hematite may occur during cooling of the sinter in air⁽¹³⁾. The resulting phase is called secondary hematite. Secondary hematite is usually found around the edges of open pores in sinter⁽¹²⁾.

2.5.2 MAGNETITE

Magnetite is formed on crystallisation from the melt or solid state reduction of hematite or solid state oxidation of wustite. However, it is rare to find unassimilated magnetite in sinter. The magnetite precipitates from the melt as a spinel and contains small amounts of Mg, Si, Ca and Mn together with a variable but relatively small amount of Al⁽¹²⁾.

2.5.3 SFCA

The most common ferrite found in sinter is more accurately described as silico-ferrites of calcium and aluminium (SFCA)⁽¹²⁾. It contains significant amounts of silicon and aluminium as well as calcium and iron. This phase may vary considerably in composition and morphology⁽¹²⁾.

The term SFCA that is used in sintering refers to a wide range of compounds. **Table 1** gives examples of typical compounds in different systems⁽¹⁴⁾.

Table 1: SFCA

System	Compound
Binary system	CaO-Fe ₂ O ₃
Ternary system	CaO-Al ₂ O ₃ -Fe ₂ O ₃
Quaternary system	CaO-Al ₂ O ₃ -SiO ₂ -Fe ₂ O ₃
SFCA	7Fe ₂ O ₃ .2SiO ₂ .3Al ₂ O ₃ .5CaO 9Fe ₂ O ₃ .2SiO ₂ .0.5Al ₂ O ₃ .5CaO
SFCA general	xFe ₂ O ₃ .ySiO ₂ .zAl ₂ O ₃ .5CaO where x+y+z=12

Dendritic SFCA is the first type of SFCA that is formed during the sintering process⁽¹³⁾. Dendritic crystals are very small, usually smaller than 4µm. Crystal growth between 1200°C and 1300°C results in bigger crystals called acicular SFCA⁽¹³⁾. The crystals of acicular SFCA are larger than 4µm but smaller than 10µm. During the heating cycle acicular SFCA melts at 1300°C and will precipitate as columnar SFCA during the subsequent cooling cycle. These are rather large crystals with a typical size of 10µm and larger⁽¹³⁾.

SFCA is the product of several successive reactions⁽¹⁴⁾:

1. The formation of monocalcium ferrite at temperatures from 1050°C to 1150°C.
2. The reaction between Al₂O₃ and CaO to produce calcium aluminate (1100°C-1150°C).
3. Dissolution of the calcium aluminate in monocalcium ferrite at 1100°C-1150°C to produce aluminous monocalcium ferrite.
4. Fusion of the aluminous monocalcium ferrite and reaction with Fe₂O₃ at 1200°C-1250°C to produce aluminous hemicalcium ferrite.
5. Reaction with SiO₂ at 1200°C-1250°C to produce SFCA.

Aluminium stabilises SFCA. The SFCA requires a critical level of ±3% aluminium to stabilise the phase⁽¹²⁾. At lower levels magnetite and dicalcium silicate are formed. There is a relatively constant ratio of calcium to silicon atoms close to two in this phase. The iron is in the ferric state⁽¹²⁾.



2.5.4 CALCIUM SILICATE

Glassy silicate, often referred to as slag phases, is formed when the melt from which primary phases have precipitated is rapidly cooled⁽²⁾. The most common silicate is based on dicalcium silicate but with varying amounts of calcium being replaced by iron^(1,2).

2.6 PHASE FORMATION

2.6.1 SINTERING MECHANISM

An iron ore granule consists of a large iron ore core particle or nucleus with a layer or coating of adhering fines when charged to the sinter bed. The layer of fines consists of highly reactive ore particles, fluxes and other raw materials that are in intimate contact. Therefore, it is assumed that the sintering reactions will begin within the layer of adhering fines⁽¹⁾.

Combustion of fine coke particles starts at temperatures between 700°C and 800°C and results in the formation of CO gas. The nucleus surface and the adhering fines of the pseudo-particle are reduced by the CO gas into magnetite.

As the temperature rises to 1100°C low melting point phases such as Fe₂O₃-CaO, FeO-CaO and FeO-SiO₂ are formed by solid-solid phase reaction between CaO and Fe₂O₃⁽²⁾⁽⁴⁾. SFCA and calcium silicate are formed in association with magnetite. Dicalcium silicate forms at 1150°C⁽⁴⁾. Complex SFCA is formed with silicate in solid solution.

During the heating cycle the formation of SFCA from the reaction between hematite and lime is the first reaction taking place. Al₂O₃ increases the dissociation temperature of SFCA and stabilises the phase as a result. Acicular SFCA starts to form below 1185°C⁽⁴⁾. With an increase in temperature to 1220°C much more acicular SFCA is generated⁽⁴⁾. The sinter mainly contains acicular SFCA and unreacted hematite at this stage.

When the temperature has risen to 1245°C the unreacted hematite disappears and the SFCA increases in crystal size⁽⁴⁾. Some granular magnetite grains grow in the SFCA microstructure. The magnetite grains are formed from the dissociation of SFCA. Some aggregated magnetite grains is also formed from the reduction of the unreacted hematite.

The SFCA begins to decompose when the temperature exceeds 1300°C⁽²⁾⁽⁴⁾. At decomposition it will change to hematite when the partial pressure of oxygen is high and the temperature is lower than 1350°C. It will change to magnetite when the partial pressure of oxygen is low and the temperature is higher than 1350°C⁽²⁾. The proportion of SFCA that is decomposed may increase when the time of exposure above the decomposition temperature increases or when the maximum temperature that is reached during sintering increases. Therefore, the sinter will contain less SFCA and more magnetite and calcium silicate. At a high oxygen potential the sinter will contain less SFCA and more hematite and calcium silicate⁽⁸⁾. The slag components are distributed into the melt. On cooling, the magnetite transforms to coarse skeletal rhombohedral hematite. The SFCA grows to large columnar shaped crystals. The acicular SFCA may also decompose to hematite at a high oxygen partial pressure⁽²⁾. If the maximum temperature does not exceed 1300°C or the residence time at high temperature is low the sinter will be composed of acicular SFCA with silicate in solid solution and unreacted hematite ore particles⁽²⁾⁽⁴⁾.

A low melting point slag forms at ±1200°C and Al₂O₃-bearing phases dissolve into the slag melt⁽¹⁾⁽⁴⁾. The hematite grain boundaries are broken by the penetration of the slag melt. The process is termed nucleus assimilation⁽¹⁾. Assimilation of the unreacted hematite particles will produce magnetite and acicular SFCA with silicate in solid solution⁽²⁾⁽⁴⁾. The following mechanism is proposed⁽¹⁰⁾:

1. The surface of the hematite particle is reduced to magnetite.
2. The magnetite reacts with the silicate melt and oxygen to produce SFCA.
3. The above reactions continue and penetrate through the hematite particle.

The degree of assimilation depends on the properties of the initial melt and nucleus. The greater the reactivity of the melt, the greater its ability to digest the solid nucleus. The greater the assimilation resistance of the solid nucleus, the less the amount that

would be assimilated. Assimilation starts with the local formation of a primary liquid phase that dissolves the bulk of the solid nucleus⁽¹⁵⁾. Liquid formation is promoted by the presence of fine-grained fusible and well-blended materials in the mixture.

During assimilation the slag elements diffuse selectively into the solid nucleus or iron ore crystals and influence their melting behavior⁽¹⁵⁾. The liquid slag penetrates between the oxide crystals and fills up holes and cavities. During this penetration the slag becomes more and more acid and rich in iron. The diffusion of calcium oxide into the magnetite lattice lowers the melting point of magnetite significantly. This phenomenon accelerates iron ore dissolution⁽¹⁵⁾. Calcium ions diffuse into the magnetite lattice during penetration of the liquid slag while iron ions diffuse into the liquid slag. Magnesium and aluminum ions also diffuse into the magnetite lattice⁽¹⁵⁾.

The assimilation process terminates when the temperature of the melt surrounding the nucleus drops below the liquidus temperature due to the saturation of the melt by FeO or when the sintering temperature drops sufficiently to cause solidification of the melt or when the nucleus is completely assimilated⁽¹⁾.

Magnetite precipitates on resolidification and cooling. This phase contains Mg, Ca, Al and Si ions. Mg ions preferably dissolve in magnetite rather than in other phases⁽¹⁵⁾. An increasing MgO input will increase the magnetite spinel phase and consequently decreases the amount of hematite. Although the saturation concentration of MgO is much higher than CaO in magnetite, the CaO concentration of the mix exceeds that of MgO by far⁽¹⁵⁾. Therefore, the CaO content of the magnetite is generally higher than the MgO content. This leads to a decrease in the CaO content of the residual liquid phase when magnetite forms. When magnetite is cooled at a low rate and brought into contact with oxygen, it could also transform to hematite⁽²⁾. Hematite generally precipitates after magnetite formation.

SFCA precipitates at lower temperatures after magnetite and hematite⁽¹⁴⁾. SFCA crystallises from the melt and grows from small and thin columnar to large and columnar shaped SFCA⁽²⁾. If the maximum temperature does not exceed 1300°C during sintering or the residence time at the high temperature is extremely short, the microstructure of the sinter on cooling will be acicular SFCA with silicate in solid

solution and unmelted hematite ore particles⁽²⁾. In the cooling cycle it is possible for both hematite and magnetite to be resorbed by reaction with the silicate melt to form SFCA. This phenomenon is favoured by slow cooling and results in the formation of large crystals of SFCA, often in association with magnetite and glass⁽⁴⁾. Under reducing conditions magnetite is preserved and no SFCA is formed. However, under more oxidizing conditions magnetite is resorbed to produce SFCA. Calcium silicate instead of SFCA can form during rapid cooling⁽⁴⁾.

The last phase that solidifies is the silicate melt as calcium silicate and glass⁽¹⁵⁾.

2.6.2 EFFECT OF COKE CONSUMPTION

A high coke consumption (50-60kg/t) during the sintering process results in a typical microstructure⁽²⁾ where columnar SFCA and magnetite co-exist surrounded by a relatively large amount of glassy silicate. A small number of fine pores exists in this microstructure. The magnetite is a multicomponent system and contains Al_2O_3 , TiO_2 and MgO . Skeletal rhombohedral hematite is often formed in the vicinity of the large open pores. This hematite is produced by the transformation of magnetite during the cooling process. This type of microstructure is usually to be found in the lower part of the sintering bed where the maximum temperature was high and the cooling rate was low⁽²⁾.

Another type of sinter microstructure is formed at a low coke consumption (40kg/t)⁽²⁾. Fine acicular SFCA is the main phase of this microstructure. The crystal growth is dense with small voids between the crystals that are relatively free of slag. This porous microstructure together with the type of SFCA result in a high reducibility of the sinter. No skeletal rhombohedral hematite is formed but unreacted ore particles exists in this microstructure surrounded by and/or penetrated by glassy silicate⁽²⁾.

2.6.3 EFFECT OF OXYGEN POTENTIAL

The oxygen potential during the heating and cooling cycle will affect phase formation during the sintering process⁽⁸⁾. Material near coke particles is subjected to conditions of low oxygen potential during the heating cycle due to the combustion of the coke

particles and CO-gas formation⁽⁸⁾. Material adjacent to open pores is subjected to conditions of high oxygen potential during the cooling cycle due to the flow of air through the pores. Material further away from the pores is cooling at conditions of low oxygen potential⁽⁸⁾.

During the heating stage SFCA transforms to hematite and silicate at a high oxygen potential. At a low oxygen potential it transforms to magnetite and silicate⁽⁸⁾⁽¹⁰⁾.

Magnetite near pores in the sinter microstructure is cooled under high oxygen potential conditions and tends to oxidise to hematite during the cooling stage. Magnetite cooling under conditions of lower oxygen potential will react with the silicate melt and oxygen to produce a large amount of columnar SFCA. If the region is near to coke it is cooled under low oxygen potential conditions. The magnetite will be preserved. This region will contain a large amount of magnetite⁽⁸⁾⁽¹⁰⁾.

It is concluded that with a decrease of the oxygen potential the magnetite content will increase but the SFCA content will decrease. The highest SFCA content is obtained at an intermediate level of oxygen potential⁽⁸⁾.

2.7 SINTER QUALITY

Sinter quality refers to the physical and metallurgical properties of the sinter. The quality of sinter is usually defined in terms of:

- The physical strength of sinter at room temperature as measured by the shatter or tumbler test.
- Breakdown of sinter following reduction at low temperatures (550°C) determined by the reduction degradation test (RDI).
- Reducibility of the sinter determined by the reducibility test (RI) at 900°C.
- High temperature softening and melting properties of the sinter.

Sinter is an aggregate of bonding phases, unmelted particles and pores. Therefore, sinter quality is mainly governed by the microstructure and the phase composition of

the sinter. The size, shape, distribution and mutual interaction of the different phases present in the sinter are of great importance⁽¹⁶⁾.

The sinter quality is also related to the temperature profile in the sinter bed during sintering⁽⁹⁾:

- The FeO content of the sinter is related to the maximum temperature.
- The reducibility increases if the area below the temperature curve decreases for temperatures above 1100°C. Therefore, the reducibility increases with decreasing heat input⁽⁴⁾.
- The reduction disintegration properties of sinter deteriorate with faster cooling rate during the sintering process⁽⁴⁾.
- Sinter strength increases with increasing area below the temperature curve for temperatures above 900°C.
- Sinter cold strength can be increased by increasing the coke rate up to some critical limit thereafter strength begins to fall⁽⁹⁾.
- Reducibility increases as the amount of magnetite decreases⁽⁹⁾.

2.7.1 PHYSICAL PROPERTIES

The individual phases of the sinter have a profound influence on the sinter strength⁽⁴⁾. The fracture toughness decreases from primary hematite to secondary hematite to magnetite to SFCA and finally to glass with the lowest strength⁽⁴⁾.

The bonding phases (usually SFCA and calcium silicate) originate during the sintering process. The bonding phases make up the majority of phases within sinter (up to 80vol%)⁽¹²⁾. The sinter properties are therefore strongly related to the bonding phases. The phases are formed during the sinter process at temperatures above 1100°C. During cooling, internal tensions are developed because of the difference in shrinkage of the phases⁽⁶⁾. Cracking may occur that may lead to the breakdown of sinter particles.

The strength of sinter is determined by the size and shape of hematite, magnetite and SFCA which are dispersed in the glassy silicate matrix of the sinter⁽²⁾. The presence of

cracks in unassimilated hematite particles is the result of phase changes caused by oxidation or reduction. The reduction of hematite to magnetite during the sintering process is always associated with an apparent volume increase that may result in the formation of pores and cracks⁽¹²⁾. Secondary hematite particles do not appear to crack easily and this is thought to be a function of the smaller particle size⁽¹²⁾. SFCA is known to improve the sinter quality. The needle morphology of SFCA is heavily faulted and will arrest cracks. The porous microstructure of the ferrite can absorb stresses and prevents crack development⁽¹⁷⁾.

Unmelted particles are mainly residual, large ore particles and sometimes unreacted residual flux particles. Since the sintering process is completed in a very short time the slag melt may not adequately surround the bigger unmelted particles. After cooling, the unmelted particles are not closely bonded by the surrounding bonding phases. Cracks will readily propagate through the weaker bond⁽²⁾.

Sinter is a porous, brittle material. There is a wide variation in porosity, from open to closed and from macroscopic to microscopic. The porosity decreases with increasing sinter temperature⁽⁹⁾. The degree of breakage depends on the ease with which cracks propagate through the sinter particle. Sinter with many large open pores tends to break down more easily than sinter with a dense microstructure⁽²⁾. A high porosity may promote the transformation of hematite to magnetite during reduction⁽¹⁸⁾ because the reduction gas easily accesses the porous sinter microstructure.

Sinter strength is determined by the sintering and annealing history of the sintering process⁽⁶⁾. To improve the cold strength of sinter sufficient retention time above 1100°C must be allowed. A residence time of 3-5min above 1100°C is recommended. This can be achieved by controlling the airflow through the bed which is a function of permeability, bed depth, strand speed and the pressure drop over the sinter bed⁽⁹⁾.

Sinter strength also increases with increasing maximum temperature⁽⁹⁾. Experiments show that the sinter strength slightly increases with temperature up to 1275°C due to the increasing SFCA content⁽⁹⁾. It rapidly increases above this temperature due to densification and melt formation which were reflected by lower porosity and

increased glass content. Fine fibrous SFCA minimises the number of cracks and large pores and therefore improves the cold strength of the sinter⁽⁹⁾.

2.7.2 REDUCTION DISINTEGRATION

The reduction disintegration index (RDI) of the sinter is determined by the ISO 4696 reduction disintegration test. The RDI is a quantitative measure of the degree of disintegration of the sinter that could occur in the upper part of the blast furnace after some reduction.

Breakdown as a result of reduction normally increases with the amount of reoxidised hematite in the sinter because of the transformation of hematite to magnetite during reduction at $\pm 550^{\circ}\text{C}$ ⁽¹⁸⁾. Coarse secondary hematite (skeletal rhombohedral hematite) are the main cause of reduction degradation⁽⁴⁾. The formation of secondary hematite is minimised by lowering the maximum sinter temperature⁽⁹⁾.

2.7.3 RI

The ISO 4695 reducibility test (RI) is one of several procedures used to evaluate the behaviour of sinter under specific conditions i.e. isothermal reduction, reduction in a fixed bed and reduction by means of carbon monoxide. The results of this test should be considered in conjunction with the RDI results.

Each phase in the sinter microstructure will respond according to its reduction behaviour when the sinter is reduced in the blast furnace⁽¹⁷⁾. The quantity of fine open pores and SFCA may increase the reducibility of the sinter. The reducibility may also vary with the morphology of the SFCA in the sinter. Experiments show that acicular SFCA is more reducible than columnar SFCA⁽²⁾. Acicular SFCA has a highly porous microstructure allowing good gas flow to the reaction surface. It is also chemically more reducible than the other morphologies of SFCA. The reducibility decreases as the density of SFCA increases when it becomes increasingly more columnar SFCA⁽⁴⁾⁽⁹⁾⁽¹⁶⁾.

2.7.4 HIGH TEMPERATURE PROPERTIES

High temperature properties can be referred to as high temperature softening and melting properties of the sinter at reduction temperatures above 1100°C. An increasing sinter reducibility usually leads to better high temperature properties⁽⁴⁾.

3. AIM OF THIS INVESTIGATION

The aim of this investigation was to investigate the influence that the temperature-time-characteristics of the sinter process may have on phase formation and the sinter quality.

By changing the airflow rate through the sinter bed it should be possible to change the temperature-time-characteristics of the sinter process. The temperature-time-characteristics should have an influence on the phase composition and morphology of the phases produced. The resulting effect on phase formation will be investigated. Sinter quality is strongly related to the phases present in the sinter. The correlation between the phases present and the sinter quality will be investigated.

According to literature it is important to minimise the difference in temperature profile and to control it to a suitable heat pattern to improve the microstructure of the sinter⁽¹⁰⁾. Because of the different temperature profiles in the different layers the discharged sinter has different physical properties. Sinter in the top layer is generally weak and friable giving a poor yield of sinter with an acceptable size grading and has therefore poor physical properties⁽⁶⁾. The sinter in the middle layer is formed under optimum conditions for fusion and annealing and gives the maximum yield of sinter with acceptable size grading and has therefore optimum physical properties⁽⁶⁾. If on-strand cooling applies, the sinter in the bottom layer will have almost the same properties as the sinter in the middle layer⁽⁶⁾.

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