International Journal of Mineral Processing 149 (2016) 56–68

Contents lists available at ScienceDirect

International Journal of Mineral Processing

journal homepage: www.elsevier.com/locate/ijminpro

Flow characteristics of the molten mix generated during iron ore sintering

Dongmei Liu *, Chin Eng Loo, Geoffrey Evans

School of Engineering, Faculty of Engineering & Built Environment, The University of Newcastle, NSW 2308, Australia

ARTICLE INFO

Article history:
Received 22 October 2014
Received in revised form 15 January 2016
Accepted 16 February 2016
Available online 18 February 2016

Keywords:
Iron ore sintering
Molten mix
Flow characteristics
Coalescence
Densification
Laplace number

ABSTRACT

In a sintering bed the generation of melt in the descending flame front causes the coalescence of material and the transformation of the particulate bed. Interspersed between the large voids are the densified lumps of sinter which are released on crushing and used as blast furnace feed. The bed transformation process is critical in sintering and is an outcome of the work done on the material by the surface and opposing viscous forces. Less densified, weaker sinter forms when the level of coalescence achieved is low. The process is extremely complex in that it involves a three-phase melt–solids–gas system.

In this study, the composition of the sinter bed was simulated using the pressed cylinders of laboratory grade chemicals and the coalescence process was studied by characterising the densification of the cylinders. The alumina, magnesia and basicity of the cylinders were altered (1–4%, 0–2% and 0–3, respectively) to change the properties of the melt and also its solid content. The estimation of solid–melt content, melt composition, viscosity and surface tension was obtained using a thermodynamic model (FactSage) and the reported equations in the literature. Using these results Laplace number of the system was determined as a function of temperature. At the completion of some tests the cooled solidified samples were studied under a microscope.

The experimental results showed that the higher sinter density and densification factor were obtained when temperature and sinter mix basicity increased and alumina levels decreased. The effect of magnesia level on densification was less because the porosity of the cylinders altered with magnesium carbonate levels. The trends obtained in sinter densification are consistent with the micro-structural information indicated by optical micrographs. The use of Laplace number to quantify the relative influence of the surface to viscous forces on coalescence was encouraging with a prediction error within ±10%. It was also concluded that the most influential factor determining densification factor was the apparent viscosity of the molten mix as the change in surface force was comparatively small.

1. Introduction

Nomenclature

A, B, C, D	constants	–
Bo	Bond number, $\frac{\rho g L^2}{\sigma_M}$	–
Ca	capillary number, $\frac{\mu_{App} v}{\sigma_M}$	–
F_{Den}	densification factor, ρ_T/ρ_C	m
H	tablet height	m
L	characteristic length	m
La	Laplace number, $\frac{We}{Ca^2}$	–
$m(T)$	tablet mass at a temperature of T	kg
m_0	tablet initial mass	kg
$\Delta m(T)$	total mass loss of the tablet at a temperature of T compared to initial mass	kg
$r(T, h)$	tablet radius at a height of h and temperature of T	m
v	characteristic velocity	m s^{-1}
We	Weber number, $\frac{\rho v^2 L}{\sigma_M}$	–
ρ	the density	kg
ρ_C	tablet density at $T = 1140$°C	m
ρ_T	tablet density at a temperature of T	kg m^{-3}
σ_M	melt surface tension	kg s^{-2}
μ_{App}	apparent viscosity	kg m^{-1} s^{-1}

Sintering is an important process used to produce a lumpy iron-bearing feed for the blast furnace (e.g. Ball, 1973; Venkataramana et al., 1999; Zandi et al., 2010). Fine iron ores, typically minus 6 mm, together with a range of fluxes (limestone and MgO-bearing minerals) and coke breeze are blended and placed on a strand which can be over 100 m in length (e.g. Kapur et al., 1993; Zandi et al., 2010). Suction is applied across the bed to create a downdraft of air. Close to the feeding end of the strand coke particles in the vicinity of the bed surface are

* Corresponding author.
E-mail address: Dongmei.Liu@newcastle.edu.au (D. Liu).

http://dx.doi.org/10.1016/j.minpro.2016.02.008
0301-7516/

set alight under an ignition hood. This forms a flame front which is 'pulled' downward through the bed by the flowing air (e.g. Yang et al., 2004; Lovel et al., 2009). The speed of the strand is adjusted so that the flame front reaches the bottom of the bed close to its discharge end. On discharging, the fully sintered bed disintegrates into lumpy product. The large particles are crushed and the 5–40 mm fraction is used in blast furnaces (e.g. Dawson, 1993).

The bed transformation process on the strand as part of the sintering process has been commonly termed "coalescence". This is an appropriate terminology because, with the formation of melt in the flame front, the three phase melt–solid–gas (or void) mixture preferentially flows, reshapes, deforms and collects into specific random locations (Liu et al., 2014). Aggregated regions can combine whilst undergoing shrinkage and densification (Ramos et al., 2000; Loo and Ellis, 2014). The coalescence process is very complex and is controlled by numerous variables. The volume of melt generated and its properties clearly have a significant influence on the ability of the solid–melt–gas mixture to undergo structural changes and transformation. In sintering, enhancing coalescence will lead to the formation of larger and denser (stronger) sinter particles, resulting in improved blast furnace performance (Srivastava et al., 2001; Topkaya et al., 2004).

Clearly, understanding the coalescence (structure transformation) that occurs within iron ore sinter bed from a fundamental level is critical as it determines the properties of the product sinter and yield from the process. Whilst there has been extensive experimental and theoretical research into the coalescence in ceramic sintering area (e.g. Kingery, 1959; Waldron and Daniell, 1978; German, 1985; German, 1996), there have been relatively fewer studies into the coalescence in iron ore sintering process. Possibly, this has been because of the presence of a flame front in the real system and the associated difficulties of undertaken experimental measurements. Moreover, the coalescence phenomenon occurring during the iron ore sintering process is also difficult to investigate because it is a complex function of both physical and chemical properties of iron ore, melt composition, and sinter bed depth, velocity and air flowrate. Ramos et al. (2000) developed a numerical simulation model to describe the material agglomeration behaviour in a sinter pot with a few assumptions being made. Kasama et al. (1994), Kasai and Ramos (1999), Kasai et al. (2005), Nakano and Okazaki (2011) have used X-ray or CT-scanning methods to observe the physical changes that take place in a sinter pot bed. Loo and Heikkinen (2012), Loo et al. (2012) and Loo and Ellis (2014) similarly used a pot bed to relate mineralogy and both micro- and macro-structure to sinter tumble strength, yield, and reduction degradation index (RDI). The main challenge associated with the use of sinter pots is the difficulty in maintaining good temperature control and uniformity of both temperature and composition throughout the heterogeneous material. Consequently, a number of bench-scale studies have been undertaken using well-mixed analogue sinter mixes under closely controlled furnace temperature and heating rate conditions. For example, Loo and Leung (2003) used an infrared furnace (IRF) to focus on the effect of melt chemical composition and sintering temperature on the bonding phase micro-structure. Later, Liu et al. (2014) used a coal ash fusion furnace (CAF), and together with thermodynamic software and database information developed a density analysis methodology to provide information on material deformation and densification to understand coalescence and its controlling parameters. It was stated that coalescence was mainly driven by the interfacial forces and opposed by the viscous forces (Liu et al., 2014), and this could be characterised as capillarity driven viscous flow. In sintering, more flowable system could lead to the enhanced coalescence and densification, which may possibly be beneficial to reduce energy consumption as the required temperature might be lower when maintaining the comparable flowability. As such, the flowability of the molten mix is of significance and can be used to characterise the coalescence behaviour that occurs in the flame front. However, this has not been quantitatively studied in the open literature.

This study builds upon the earlier work of Liu et al. (2014) to give further insight into how the coalescence process is influenced by the properties of the molten mix. Pressed cylinders of analogue sinter mix with varying chemical composition and porosity are heated in a closely-controlled heating cycle. The sample projected area is measured and then related to chemical composition and physical properties. The solid–melt–gas system encountered is complex and information on melt properties is not always available. The chemical composition of the melt also changes with temperature as more solids are assimilated. In some cases thermodynamics will dictate that only certain solids can enter into the melt. For this work, the information on melt properties has been obtained from the open literature and also from the thermodynamic software and database package, FactSage. In particular, melt volume, viscosity and surface tension are obtained and utilised to quantitatively describe the coalescence behaviour and to carry out a theoretical assessment of the important factors driving and hindering coalescence.

2. Experimental

A bench-scale furnace was applied to heat the samples to their sintering temperatures. The sinter mix did not contain any fuel particles and no flame front was formed. Fine laboratory grade chemicals were used and blended to obtain a desired chemical composition. Aliquots of the mix were then pressed into cylinders. The cylinder dimensions were typically in 13 mm diameter and height varying between 5 and 15 15 mm depending on the porosity of the sample mixture. A camera was used to record the changes in the dimensions of each cylindrical sample as a function of temperature.

2.1. Apparatus

A Digital Carbolite Coal Ash Fusion (CAF) Furnace with a 79 mm inner diameter work tube made of mullite was used to heat the samples. The furnace has a maximum temperature of 1600 °C and a heating rate varying from 0.1 to 8 °C per min. In this study, the maximum temperature was set at 1350 °C to simulate conditions in iron ore sintering. The camera recording rate is up to 1 image per °C. The actual sample temperature was measured by the thermocouple inside the work tube.

2.2. Sample preparation

All analytical grade reagents (supplied by Sigma-Aldrich, Australia) had particle size of less than 10 μm. Limestone ($CaCO_3$), magnesium carbonate ($MgCO_3$) and kaolinite ($Al_2Si_2O_5(OH)_4$) were used to provide the CaO, MgO, Al_2O_3 and SiO_2. For some of the mixes, quartzite was added to meet the desired SiO_2 levels. The chemical compositions of sinter mixes are shown in Table 1. Sample E had a chemical composition fairly typical of commercial sinters produced in the Asia Pacific region and can be considered to be the standard mix. The composition of the sinter mix was then changed to study the effects of Al_2O_3 levels (1.00 wt.%, 1.72 wt.% and 4.00 wt.%), MgO levels (0.00 wt.%, 1.41 wt.% and 2.00 wt.%) and basicity (i.e., lime to silica ratio of 0.0, 1.9 and 3.0).

Table 1
Chemical composition of the samples

Sample ID	Mass percentage, %				
	Fe_2O_3	Al_2O_3	SiO_2	MgO	CaO
A	84.04	1.00	4.71	1.41	8.84
B	81.04	4.00	4.71	1.41	8.84
C	84.52	1.74	4.78	0.00	8.96
D	82.84	1.71	4.68	1.99	8.79
E[a]	83.33	1.72	4.71	1.41	8.84
F	91.40	1.88	5.17	1.55	0.00
G	79.13	1.63	4.47	1.34	13.42

[a] Standard composition.