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授　与　学　位	博士（工学）
学位授与年月日	平成11年10月13日
学位授与の根拠法規	学位規則第4条第2項
最　終　学　歴	昭和60年4月 フィリピン国マプア工業大学鉱山冶金学科　卒業
学位論文題目	Study on the Agglomeration Mechanism in the Sintering Process of Iron Ores (鉄鉱石焼結プロセスにおける塊成化メカニズムに関する研究)
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論文内容要旨

Chapter 1. Introduction

Iron ore sintering is the most widely used process to prepare burden of suitable metallurgical properties for the blast furnace (BF) iron making process. In this process pre-granulated mixture of iron ores, limestone and other fluxing reagents and coke as main fuel is charged into a sinter machine to form a packed bed of granules about 30-60 cm in height. The bed is ignited at the top and the hot gases formed by the combustion of coke and air is sucked through underneath the bed. The importance of the void structure of the iron ore sintering bed and of the sinter cake has resulted in cultivating much interest in the study of its formation mechanism and ways of control. A new simulation technique in the modeling of granular/particulate assembly known as discrete element method (DEM) has shown potential for application in modeling the iron ore sintering process. A DEM based model for iron ore sintering can directly consider the change in the void structure of the sintering bed. Both experimental and computer simulation studies were undertaken to try to delineate the factors that contribute to the coalescence of granules during sintering.

Chapter 2. Factors Governing Strength of Iron Ore Sinter

The essential factors contributing to the strength of agglomerates after sintering were studied by conducting three-point bending (TPB) and sintering experiments using simple sample models. To simulate particle agglomeration in actual sintering, "sandwich" samples consisting of a fine mixture of hematite and calcium carbonate reagent place in-

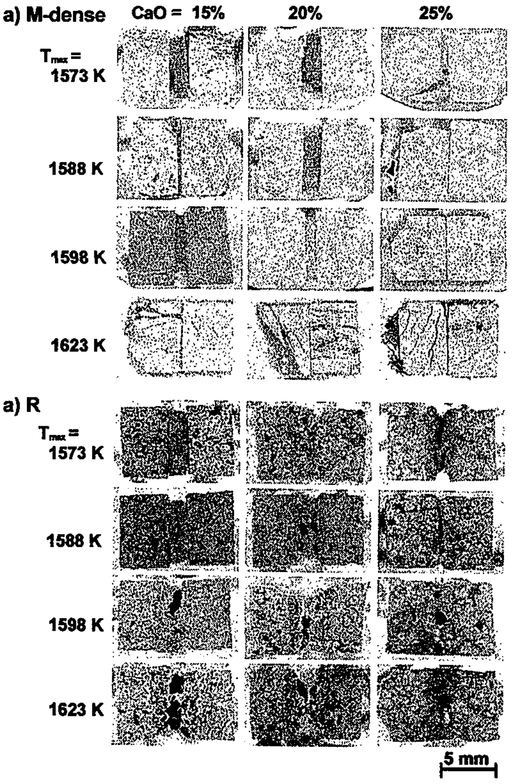


Fig.1. Photographs of the cross-sections of sintered "sandwich" samples.

between two coarse iron ore particles. The tests were done using different iron ore types, various compositions of the fine mixture and maximum temperature of sintering. Ores having higher combined water, *e.g.*, pisolitic geothite ores give both lower density and strength. Also, the relative strength of the ore, which is the ratio of the strength of the ore before heat treatment and after heat treatment is lower for ores having high combined water. An examination of the cross-section of the sintered "sandwiched" samples, as seen in Fig. 1, reveals that the inter-phase between the melt and the ore is clear for samples using hard hematite ore. However, the inter-phase is not clear for samples using ores with high combined water. The TPB strength of the sinters is much higher for samples using hard hematite ore as compared to samples using ores with high combined water content. The strength of the sintered samples using ores with high combined water content is in good agreement with the TPB strength of the ore after heat treatment. While the TPB strength of the sinters using hard hematite ores is much lower than the strength of the ore after heat treatment. This suggests that the strength can be attributed to the strength of the bonding due to the melt formed at high temperature.

Chapter 3. DEM Model of the Iron Ore Sintering Process

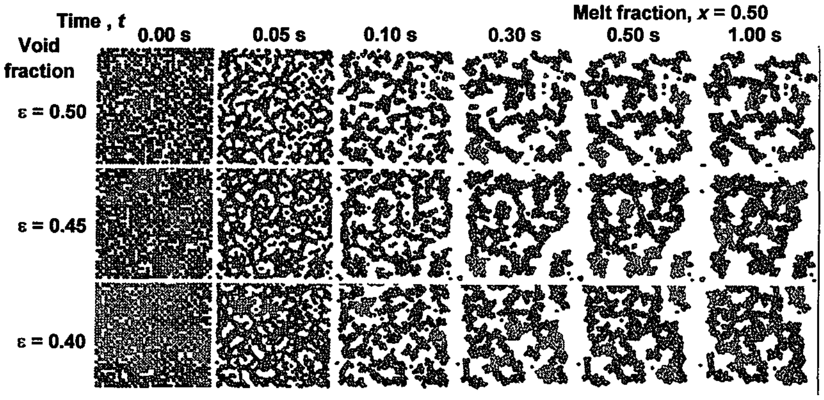


Fig. 2. "Snapshots" obtained from 2D simulation for different values of void fractions at melt fraction, x=0.50.

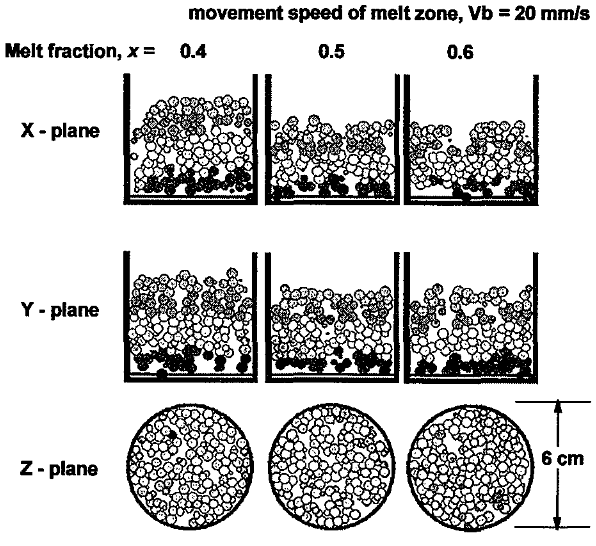
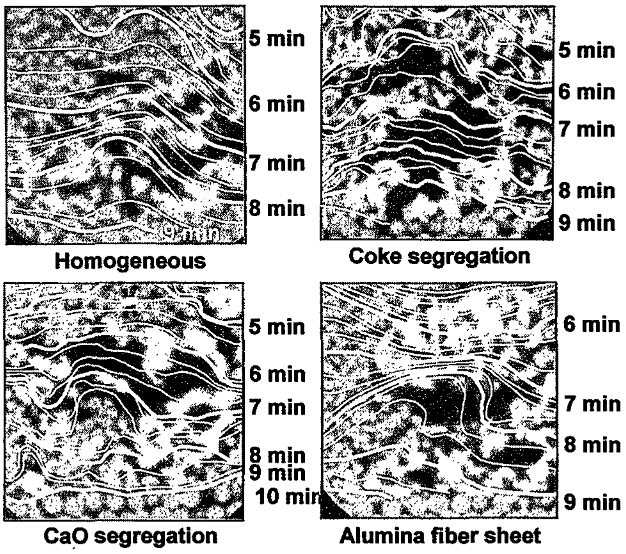


Fig. 3. Final structures obtained from 3D simulation at different melt fractions.

A computer simulation using DEM was undertaken to describe the change in the structure of the iron ore sintering bed. Two-dimensional (2D) and three-dimensional (3D) simulations were conducted and considered the bonding force between granules due to the formation of melt at high temperature were considered in the formulation of the inter-granular force. In 3D simulation, gravity force was also considered in the computation of particle movement and a moving melt zone was introduced as a simple representation of the heat wave propagation in the sintering bed. A model granule based on a nucleus-type of granule was used as in the simulation, which consists of a hard spherical core, representing the coarse nucleus coated with a fine adhering layer. Result of the 2D simulation shows that cluster formation occurs in the early stage of sintering, which initiates at the contacts between granules. "Snapshots" of the structure obtained by the simulation shows similarity to cross-section of actual sinter cakes, see Fig. 2. Lower void fraction gives a complex structure with larger clusters of granules. Higher melt fraction promotes coalescence of granules and results in a simple structure with clusters of plain shape. Based on the average co-ordination number of the granules, higher melt fraction of the granules and lower void fraction result in a structure with denser packing. From 3D simulation, a reduction in the height of the sinter bed was observed from the "snapshots" in Fig. 3. Such reduction is due to combined effect of the compressive force due to gravity and the bonding force between granules. Greater reduction in the bed height is attained at higher melt fraction. The results of the simulation shows a validity of the DEM model for use in the analysis of the structural change in the iron ore sintering bed.

Chapter 4. "In Situ" Observation of the Structural Change in the Iron Ore Sintering Bed by an X-ray Computed Tomography Scanner (X-ray CTS)

Non-invasive experiments for the "in situ" observation of the iron ore sintering were conducted using X-ray computer tomography scan (X-ray CTS). Several sinter pot tests were undertaken to study the effect of raw material segregation on the structural change of the sintering bed. Different cases of segregation were considered using materials such as coke, high-CaO granules and alumina sheet. For all cases, large voids formed around the segregated parts independent of the coke-mixing ratio. The voids develop below the segregated part in the cases of coke segregation and the alumina fiber sheet, while it forms at the part of the segregation in the case of CaO segregation. A visualization scheme was developed to produce a structural change front map showing the progress of the change in the structure of the sinter bed with time, shown in Fig. 4. The structural change front lines show that sintering proceeds faster in the periphery of the bed, probably because of the large void fraction and lower bed temperature due to heat loss through the wall in these areas. For the cases of coke segregation and homogeneous mixture of granule and coke, the structural front lines shows similarity even though the resulting final structure of the sinter bed for both cases are entirely different. As for CaO segregation, the shape of the structural change front line shows similarity to the homogeneous case in the early stage of sintering. However, as the front line passes the place of segregation it flattens out. The formation of large voids at this area due to the greater extent of melting in the adhering layer of the granules result in the increase of bed permeability and uniform distribution of gas flow. The alumina fiber sheet, which does not allow high permeation of gas, disturbs the state of gas flow in the sintering bed significantly. However, no parts that are not sintered were observed at the place under the sheet.



Homogeneous

Coke segregation

CaO segregation

Alumina fiber sheet

Fig. 4. Structural change front maps for the different cases of materials segregation.

Chapter 5. Simulation Model of the Iron Ore Sintering Process by Combining Solution of the Gas-Granule Heat Transfer Equations with DEM Calculation

A comprehensive DEM simulation model was developed, which considered the major reactions and heat and mass transfer processes that occur in the iron ore sintering bed. The effect of various conditions in the sintering bed, such as amount of melt and coke content, in the structural change of the iron sintering bed were examined in the simulation. The simulation model for gas-granule heat transfer uses the Ranz equation for heat transfer in packed beds and included a two stage drying process and rate equation for coke combustion and limestone decomposition. The solution of the heat transfer equations gives the heat profile of the bed giving a history of the temperature change of each zone. Result of the simulation given in Fig. 5 shows that higher coke content in the mixture results in higher maximum bed temperature and longer holding above the T_{m2}. Less agglomeration of granules occurs at the upper bed compared to the lower bed. This means that the granules in the lower bed have a higher melt ratio due to the higher temperature at this zone resulting in a more intensive agglomeration. Increasing the amount of coke in the mixture increases the thickness of the sinter/melt zone. Also, higher levels of coke content give higher maximum temperature in the bed. The combination of both thicker sinter/melt zone and higher maximum temperature results in better agglomeration of granules as seen in the "snapshots". Also, more agglomeration of the granules at the upper bed is observed at lower T_{m2} of the adhering layer. More coke means more heat generated through combustion, which elevates the temperature of granule higher. Higher temperature results in greater amounts of melt being formed and better agglomeration of granules.

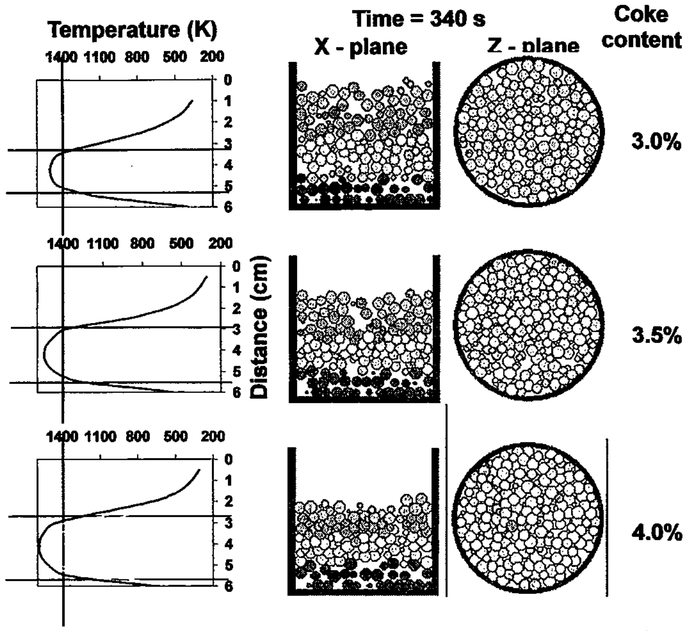


Fig. 5. Comparison of the structure of the sinter bed for different coke content in the mixture.

Chapter 6. Conclusions

The study has shown the validity of DEM as a tool for modeling the iron ore sintering process. For the first time, the DEM model proposed has directly considered the structural change in the iron ore sinter bed. However, limitation in the model, especially the large computation time required has open further possibilities for improvement. These are in areas of developing a faster contact algorithm and the consideration of 3-D gas flow inside the bed, which will make the model more complete.

審査結果の要旨

大量のエネルギーと資源を取り扱う製鉄産業では、大幅な二酸化炭素排出量の削減が要求されており、さらに優良鉄鉱石資源枯渇問題を抱えている。一連の製鉄過程において高炉製銑プロセスはとりわけエネルギー消費量が大きく、その安定化および高効率化が重要であると認識されている。本研究は、高炉操業に極めて大きな影響を及ぼす鉄鉱石焼結鉱の性状、特に強度の発現要因に関して検討したものであり、基礎的実験および数値シミュレーションを主体としている。本論文はこれらの成果を取りまとめたもので、全編6章より構成される。

第1章は緒論であり、本研究の背景、従来の研究結果の総括、焼結過程の粒子塊成化過程のシミュレーションに対する粒子要素法の適用に関する考え方等について記述している。

第2章では、粒子の焼結メカニズムと強度発現に関する基礎的な実験結果について述べている。基本的に焼結により形成された塊成体の強度は、溶融により生成した結合マトリックスと未溶融粒子のそれぞれの強度に依存すること、未溶融粒子の強度が極度に小さい場合はこれが全体の強度を規定することなどを示している。

第3章では、焼結過程における粒子の移動と粒子間の結合現象を粒子要素法を用いて計算する新しい数値シミュレーションモデルの構築について述べており、本モデルの概要と、2次元から3次元への拡張とそれらの計算結果を記述している。

第4章では、X線CTスキャン装置を利用して、実際の焼結過程における粒子の挙動を非破壊でその場観察可能な実験装置を作製し、種々の異なる条件下における焼結過程の観察を行った結果を記述している。大きな空隙の形成に対し、原料の偏析など不均一要因が大きく関与していることを初めて実証したものであり、焼結塊成体の構造、強度の制御および設計に対して重要な知見を与えるものである。

第5章では、上記の各成果に基づき、各種反応、熱と物質の移動現象、粒子の移動と塊成化を考慮した鉄鉱石焼結プロセスの総合的なシミュレーションモデルの構築とその計算結果について述べている。種々のプロセスパラメータと塊成化現象の関係に関する明確な知見を提供しており、今後の発展性も十分に認められる。

第6章は、結論であり、上記各章を総括している。

以上、要するに本論文は、鉄鉱石焼結プロセスにおける成品強度の制御と設計に関する新しい知見と手法を提示したもので、高炉製銑技術の高度化と地球工学・素材工学の発展に寄与するところが少なくない。

よって、本論文は博士（工学）の学位論文として合格と認める。