



A review on the characterisation and processing of oolitic iron ores

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ABSTRACT

Oolitic iron ores are a distinctive subset of iron ore deposits, and are characterised by their spherical grains composed of concentric layers containing hematite and goethite along with impurity elements such as silicon and phosphorus. Depending on their petrology, oolitic iron ores may require very simple or extremely complex flowsheets for their processing. This review focussed on beneficiation by conventional mineral processing techniques and also more energy intensive processes involving heating (roasting) or leaching. The aim of roasting is to transform minerals like hematite and goethite to magnetite or metallic iron, making them amenable to concentration by magnetic separation. The overall aim of this review was to highlight possible techniques for economically processing oolitic iron ores for the subsequent production of iron and steel. An attempt has been made in assembling this review to strike a balance between more historical documentation and a plethora of recent information readily obtainable by searching electronic data bases.

1. Introduction

The aim of this review is to collate and summarize selected information concerning the characterisation and processing of oolitic iron ores. There are many types of iron ore deposits that have been historically important as sources of iron minerals which hematite, magnetite, goethite and martite (hematite that has replaced primary magnetite) are dominant. The mineralogical, chemical and physical characteristics of iron ores have recently been reviewed by Clout and Manuel (2015), to which the reader is referred for general information. It is the purpose of this review to focus specifically on oolitic iron ores which have peculiar characteristics which have not been reviewed in detail. Oolitic iron ores can be classified as sedimentary oolitic ironstones and include deposits in Germany (Minette), Australia (Pilbara and Roper River), Canada (Peace River), Colombia (Paz de Rio) and the United States (Clinton). Oolitic iron ores often contain high levels of phosphorus that resist conventional mineral processing methods.

Oolites are sedimentary rocks formed from ooids which are spherical grains composed of concentric layers. The name derives from the ancient Greek word for “egg”. Oolites consist of ooids of diameters between 0.25 and 2 mm; rocks composed of ooids larger than 2 mm are called pisolites. Together these clasts are referred to as pelletoids. They contain a nucleus (usually hematite) and multiple cortices (usually goethite) (Beattie et al., 2017). Oolitic iron ore deposits occur in Newfoundland, Canada (Lyons, 1957), Lorraine, France (Durand et al. (1965), Colombia (van Houten (1967), Peace River district, Alberta, Canada, (Petruk, 1977), Agbaja, Nigeria (Adedeji and Sale, 1984) and

southern Egypt (Shulman, 1986). McGregor et al. (2009) have summarised nearly 400 occurrences of Phanerozoic oolitic ironstone deposits in terms of stratigraphy, grade, tonnage and iron bearing ore minerals on a global scale, which can be consulted for more detailed information.

A detailed description of the Robe River oolitic iron ores of the Hamersley Range region in Western Australia has been published by Boyum and Han (1964) which gives photographs of the various structures of magnetic and non-magnetic oolitic iron ores from that region. Harms and Morgan (1964) referred to this material as “pisolitic limonite” in their description of the history, stratigraphy, geomorphology, mineralogy and texture of this ore.

An important oolitic deposit in the Pilbara region of Western Australia is known as a “Channel Iron Deposit” (CID) (Clout and Manuel, 2015). The ooids consist of a simple or complex nucleus surrounded by cortex whereas the less abundant pisoids consist of goethite replacements of regolith particles. CID ore is typically composed of brown or yellow ochreous goethite pelletoids (ooids and pisoids) some of which can be partly dehydrated to hematite, ferruginized fossil wood/charcoal fragments and a minor goethitic matrix (Clout and Manuel, 2015). Another description is that they contain hematite nuclei with goethite cortices, fragments of fine-grained goethite and goethite-replaced wood fragments (Arvidson et al., 2013). A typical Australian CID ore assays 58.3% Fe, 4.7% SiO₂, 1.56% Al₂O₃ with a LOI (Loss on Ignition) value of 9.0% (Clout and Manuel, 2015) indicating a significant amount of goethite present. Detailed descriptions of the geology, petrology and mineralogy of these Channel Iron Deposits in

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the Hamersley Range have been reported by [Ramanaidou et al. \(2003\)](#) and their genesis by [Morris and Ramanaidou \(2007\)](#). The geochemical characterisation of typical Channel Iron Deposits in the Pilbara Region of Western Australia has recently been reviewed by [Beattie et al. \(2017\)](#). These deposits currently constitute a significant portion of Australia's iron ore exports. The CID ores typically contain 54–58% Fe and represent ~25% of the total 455 Mt of iron ore mined from the Hamersley Province in 2011–2012 and this tonnage is increasing annually ([Kneeshaw and Morris, 2014](#)).

2. Characterisation of oolitic iron ores

The key to understanding the efficient processing of oolitic iron ores, in fact all mineral processing operations, depends on a detailed knowledge of the chemical and mineralogical distribution of values and impurities. Methods such as X-ray Diffraction (XRD), Scanning Electron Microscopy (SEM) and chemical analysis are common tools used in the characterisation of iron ores. Ore hardness and liberation are also valuable information for determining the characteristics of a particular deposit. An excellent review of the mineralogical, chemical and physical characteristics of iron ore has been published by [Clout and Manuel \(2015\)](#). In that review, the mineralogy, chemical composition, and various physical properties including relative hardness, compressive strength and particle size have been discussed. Geometallurgical characterisation of Australian iron ores have also been reviewed recently by [Suthers et al. \(2016\)](#). Another recent reference that describes the use of chemical, XRD and SEM-EDS (Energy Dispersive X-ray Spectroscopy) for the characterisation of Indian iron ore fines has been published by [Jena et al. \(2015\)](#). Specific references on the use of XRD analysis of iron ores have been published by [de Villiers and Lu \(2015\)](#), automated optical image analysis of iron ore by [Donskoi et al. \(2015\)](#), SEM-based quantitative analysis by [Tonzetic \(2015\)](#) and for spectroscopic techniques by [Ramanaidou et al. \(2015\)](#).

Most of the articles on oolitic iron ores reviewed include particle size distributions and chemical analyses, often accompanied by mineral analysis by XRD. An example of the use of thermal analysis on the decomposition of iron ore has been reported by [Omran et al. \(2014\)](#). A description of the use of XRD and SEM-EDS as a function of particle size for a Chinese oolitic iron ore has been published by [Gao et al. \(2015\)](#) and the use of XRD and SEM-EDS to monitor the oolitic iron ore before and after acid leaching has been reported by [Yu et al. \(2013a\)](#).

3. Beneficiation by mineral processing

The articles reviewed in each topic are generally in chronological order to show the development of the various processes with time, rather than describing ore treatment for specific ores.

3.1. Use of different dry crushing mills ahead of magnetic separation

[Pasquet and Joco \(1965\)](#) compared the energy requirements and product size distributions resulting from dry grinding the Lorraine oolitic iron ores using either an Aerofall (autogenous mill with or without the addition of balls) or a Hardinge mill (Cascade mill) ahead of dry magnetic separation. The liberation size for the oolites was between 80 and 500 μm . Both these circuits included drying and recycle of oversize material. The authors concluded that although the products from the autogenous milling had a wider size distribution than those from conventional staged crushing, the liberation of the oolites was better when the autogenous mills were used. The pneumatic classification circuit associated with the autogenous mills removed the ultrafine particles which were impossible to upgrade magnetically, thus feeding the magnetic separators with dust-free material which led to a higher grade of concentrate at constant recovery. Dry milling also gave greater flexibility in the operation of the magnetic separation stage of the process, leading to a simpler flowsheet and lower capital costs.

3.2. Differential grinding

[Coghill and Delano \(1940\)](#) investigated differential grinding ahead of gravity concentration as part of the flow sheet for processing two ores: an oolitic red iron ore and a ferruginous sandstone, both from the Birmingham district of Alabama, United States of America. In both samples, rounded quartz grains were embedded in an oolitic “onion skin” matrix of hematite. The quartz grains had their customary hardness but the cementing hematite was relatively soft, hence there would be a difference in resistance to particle size reduction, which should be utilised if gravity concentration is to be applied. Differential grinding i.e. reduction in size of the softer particles of the ore while the harder particles were left in their natural discrete state was investigated. This was seen as essential for success in subsequent beneficiation by gravity concentration. Differential grinding should reduce the particle sizes of the hematite leading to almost complete liberation, while the quartz should remain unaffected. Successful differential grinding therefore should allow the hematite to be removed by conventional methods of desliming. Unfortunately part of the hematite in these ores was hard, high grade and resistant to milling, meaning that its recovery by gravity concentration was necessary. Previous liberation studies using sink-float analysis on five Alabama low-grade red ores by [Coghill \(1926\)](#) showed that a large proportion of the iron was distributed through intermediate densities, making recovery by gravity concentration difficult.

The red ore was reduced to all passing 9.5 mm and screened at 2 mm resulting in approximately equal amounts of oversize and undersize. The oversize was reduced to < 2 mm using either rolls crushing or rod milling. Careful rolls crushing in closed circuit gave poor results compared with rod milling using a rod volume of only 13% compared with the normal value of 45%. The use of a low rod volume meant that some of the particles would be subject to attritioning, and reducing the rotational speed of the mill to prevent cataracting the rods against the mill liner minimised the crushing of the quartz grains.

Previous studies on grinding certain Alabama oolitic iron ores showed that using rubber-coated rods ahead of classification and tabling produced slimes of much higher grade than the original ore, and could be added to the final concentrate ([DeVaney et al., 1929](#)).

For the ferruginous sandstone a similar approach was adopted, but in this case the rod mill discharge was screened at 0.5 mm with a circulating load of 250%. The authors believed that screening at 0.5 mm was much better than the use of classifiers since the amount of near size material was very small. The use of a lightly loaded rod mill run at moderate speed to differentially grind a feed as coarse as 9.5 mm showed a marked improvement in subsequent gravity concentration compared with conventional flow sheets.

[Manieh \(1984\)](#) investigated the use of either cylindrical pellets or rods of different diameters and grinding time to maximise the liberation of oolites from the Wadi Fatima iron ore in Saudi Arabia. Tests were conducted using a laboratory scale rod mill and the feed size range was 12.5–25 mm. The moisture of the ore created problems initially due to the caking of the fines and their sticking to the inner wall of the mill, so the ore was dried prior to milling. The most suitable rod size was 25.5 mm diameter and the best mass ratio of rod/ore mass was 4/1. The volume of the charge was about 33% of the mill volume. The Bond Work Index for oolitic iron ore reported by Bond was 11.33 kWh/short ton ([Bond, 1953](#)).

A subsequent article by [Manieh \(1986\)](#) took the product from milling the Wadi Fatima oolitic iron ore as described above and noted that the ground oolites were nearly covered by adhering gangue fines. These fines were washed away using water in a fluidisation tube using 5% detergent powder. The initial sample contained a considerable amount of goethite along with the hematite, and calcining the dried oolites at 400 °C for 8 h converted the goethite to hematite giving a product assaying 87.11% Fe_2O_3 .

More recently, [Hanna and Anazia \(1990\)](#) investigated the grinding

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