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Mineralogy and texture of the Storforshei iron formation, and their effect on grindability

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ABSTRACT

Investigating how ore mineralogy and texture affect the recovery from the processing plant is important for any mining operation. The results will assist in production planning and optimising the utilisation of a deposit. Easily available validated tests are desirable and useful.

The Storforshei iron formation (IF) consists of several iron oxide deposits with mineralogical and textural differences. Although the Fe grades of the ores are similar, mineralogical and textural characteristics of the deposits affect the individual recoveries from the magnetic separation. For this paper three of the ore deposits were sampled, and important mineralogical and textural properties were investigated and tested. The investigations included geological mapping and optical microscopy, and the test work involved surface hardness measurements by Schmidt hammer and Equotip, and autogenous milling tests (i.e., grindability). The aim of the study was to investigate whether ore mineralogy and textures can be correlated to surface hardness measurements, and whether these three parameters can be used to evaluate grindability. The ores were classified into six ore types based on mineralogy and textures. The results show that the ore mineralogy and texture influence the surface hardness. Fine-grained ore types with irregular-to-no visible grain boundaries have higher surface hardness than coarser-grained ore types with straight grain boundaries. Furthermore, surface hardness measurements and grindability evaluations (using throughput (kg/h) and specific energy consumption (kWh/tonne)) of samples from three of the iron oxide deposits indicate that grindability decreases with increasing surface hardness. The relationship found between the parameters ore mineralogy, texture, surface hardness, and grindability suggests that geological mapping and surface hardness measurements can be used to evaluate grindability, and thus assess ore processing performance.

1. Introduction

Rana Gruber AS (RG AS) currently mines iron ore from underground and open pit operations in the Dunderlandsdalen valley, about 30 km north east of Mo i Rana, Nordland County, Norway. Four million tonnes of iron ore are mined from the Kvannevann deposit annually, and the main products are hematite and magnetite concentrates. There are 13 ore deposits in the Storforshei IF, with varying mineralogical and textural properties leading to variable recovery. The mineral processing at RG AS includes autogenous (AG) milling, wet low-intensity magnetic separation (LIMS) followed by wet high-intensity magnetic separation (WHIMS). The AG mills are in closed circuit, with 800 µm screens. The d_{80} of the mill circuit product is 210 µm.

The Kvannevann- and Stortjønna iron ores have a total Fe content of 34 wt% (NGU, 2017). The Stortjønna open pit was abandoned in 2013 after 2 years in production because recoveries did not reach expected levels, indicating that other properties than grade affect recovery. Samples were collected from the Kvannevann and Stortjønna deposits. Additionally, the Stensundtjern deposit, a possible upcoming mining target in the Storforshei IF, was included in this study.

The aim of the research presented in this paper was to investigate the effect of ore mineralogy, texture, and surface hardness on the ore grindability and on the particle size distribution of the mill circuit products. The throughput (kg/h) and specific energy consumption (kWh/tonne) in the AG mill were used to determine grindability.

The classification of ore types is based on mineralogical and textural characteristics of the iron ores. Contrary to previous work (e.g., Lopera, 2014; Mwanga et al., 2015), the classification is performed before surface hardness measurements and grindability testing. This approach is similar to the work of Voordouw et al. (2010) where platinum mineral assemblages were grouped based on ore mineralogy and trace elements. Lund (2013) defined preliminary geometallurgical ore types

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first according to mineralogy and geochemistry, and later included ore texture. Others like Lopera (2014) and Niiranen (2015) used surface hardness and mill tests to divide ores into different comminution domains.

The main objective of the present study was to provide increased predictability in the processing of highly metamorphosed iron ores. If surface hardness can be used to evaluate grindability, the iron ores can be tested by easy, fast and non-destructive methods prior to mineral processing.

The main research questions were:

– Is it possible to correlate ore mineralogy and texture with surface hardness?
– How is grindability affected by ore mineralogy and textures?
– Can surface hardness be used to evaluate grindability?

2. Background

2.1. Geological setting

The Storforshei IF is a metasedimentary iron formation and part of the Dunderland formation, located in the Uppermost Allochthon in the Norwegian Caledonides (Sovegjarto, 1972; Grenne et al., 1999). The IF belongs to a series of iron formations located between the city of Mosjøen (lat. 65°20′) in the south to the city of Tromsø in the north (lat. 69°40′), a distance of 550 km (Melezhik et al., 2015). The Storforshei IF is the only iron formation currently mined in Norway, and the main economic minerals according to NGU (2017) are hematite (40%) and magnetite (5%). The Neoproterozoic host rocks are mainly marbles and mica schists (Bugge, 1948; Sovegjarto, 1972). The sedimentary precursor of the IF was deposited on a carbonate-silica-rich shelf which was located either near a microcontinent or on the margin of Laurentia (e.g., Grenne et al., 1999; Melezhik et al., 2015). After deposition, the iron formation was subjected to several deformation phases, dominated by the Caledonian orogeny where Laurentia and Baltica collided (Sovegjarto, 1972; Roberts and Gee, 1985). The Storforshei IF was subjected to amphibolite facies metamorphism and is intensely banded reflecting mineralogy and textures (Sovegjarto, 1972; Ellefmo, 2005). The geology of the relevant area is shown in Fig. 1. The locations of the sampled deposits; Kvannevann, Stortjønna and Stensundtjern are highlighted on the map. Stensundtjern is a separate ore horizon located to the west in the Dunderlandsdalen valley. Kvannevann and Stortjønna belong to the same ore horizon. Kvannevann is larger than Stensundtjern, while Stortjønna is notably smaller than the other two deposits.

2.2. Previous relevant geometallurgical research

Lund (2013) quantified mineral processing properties of apatite-magnetite ores and developed a geometallurgical program for the Malmberget iron ore (Sweden), which enabled improved production and resource utilisation (Lund, 2013) based on a comprehensive characterisation and analyses of the iron ores. However, no surface hardness measurements or grindability tests were reported. Niiranen (2015) performed comminution tests on three apatite-magnetite ore types from the Kiirunavaara iron ore. The ore types were defined by their SiO_2 and P contents. After comminution, one ore type was divided into two subgroups, and a link between mineralogy and grindability was established. Available literature (i.e., Lund, 2013; Niiranen, 2015) focuses mainly on high-grade magnetite dominant ores; hence the present study contributes to increased knowledge on the processing behaviour of low-grade hematite ores.

The Schmidt hammer method is widely used in concrete and rock characterisation (e.g., Deere and Miller, 1966; Szilágyi and Borosnyói, 2009). Viles et al. (2011) used the Schmidt hammer and Equotip methods on dimension stone and demonstrated difficulties in comparing the two methods. Mining related research has focused on developing simple procedures to categorise ore types to predict comminution behaviour (e.g., Hunt et al., 2013; Lopera, 2014). Rock mechanical tests such as the JK Tech drop weight test (Napier-Munn et al., 1996), the JK Rotary Breakage Test (Shi et al., 2009), the SMC test (Morrell, 2004), and standard Bond grindability test (Bond, 1952) require at least 10 kg of material. The amount of material required for the procedures may, according to Mwanga et al. (2015), be an issue for greenfield exploration activities. Hence, Mwanga et al. (2015) developed the geometallurgical comminution test (GCT) as an approach to achieve representative results for test batches of 220 g material. The GCT is a small-scale comminution test which makes use of a lab-scale jaw crusher, a screen, and a small laboratory tumbling mill. Mwanga et al. (2015) argued that the GCT is a cost and time-efficient test that provides substantial data from limited sample sizes.

Ores are additive if the grindability of an ore blend is the same as the weighted average grindability of the ore types in the blend (e.g., Van Tonder et al. 2010 and the references therein). To evaluate grindability of an ore with notable internal variability in mineralogy and texture, larger homogenised test batches are needed to get representative and reliable results. Van Tonder et al. (2010) investigated mineral processing of platinum ores and the effect of ore blending in Rustenburg, South Africa. The ore blend consisted of four rather homogenous different ore types with a high inter-ore-type variability. They found through lab-scale tests that blends of ore types with varying metallurgical properties displayed non-additive characteristics. Larger test batches will therefore improve the prediction capabilities of the production-scale non-additive grindability.

Understanding the effect of mineralogy, geochemistry, lithology, and alteration on the comminution processes are valuable for processing any ore. Hunt et al. (2013) successfully modelled comminution parameters using information obtained from drill core logs, together with measured comminution data collected on site. The drill core log information included lithology and alteration type, as well as mineralogy and chemistry data. Hunt et al. (2013) included Semi-Autogenous Grinding Power Index (SPI), Bond Work Index (BWI), and Julius Kruttschnitt Mineral Research Centre (JKMRC) drop weight test (A*b) as parameters to characterise the comminution behaviour. These indices and tests were selected because they can be conducted at low cost and on drill core samples. Hunt et al. (2013) stressed the need to classify sample sets based on alteration type and lithology to identify correlations between mineralogy or chemistry and grindability. Lopera (2014) used surface hardness data together with mineralogy, chemistry, and a range of comminution tests to define comminution domains. Surface hardness measurements were collected from drill cores and hand specimens representing different lithologies. Surface hardness values varied between lithologies and were low in tectonically-induced weakness zones. Within each lithology variability was low (Lopera, 2014). Kekec et al. (2006) investigated the effect of rock textures on comminution. The investigations were based on experiments on different types of rock (granite, marble, travertine, and andesite). They observed that rocks of similar origin show differences in the crushing and grindability behaviour caused by the differences in rock texture. Xu et al. (2013) found that the specific energy required for breakage of a copper ore increases with decreasing particle size, and that grain boundary fractures require relatively low specific energy. By characterising the geochemistry, mineralogy, and grindability of the cemented layer, Philander and Rozendaal (2011) improved the mill design to accommodate a complex calcium-magnesium-rich cemented layer, part of the clastic Cainozoic ore-bearing sequence in the Namakwa Sands heavy mineral deposit (Brand-se-Baai, South Africa), previously not viable for production.