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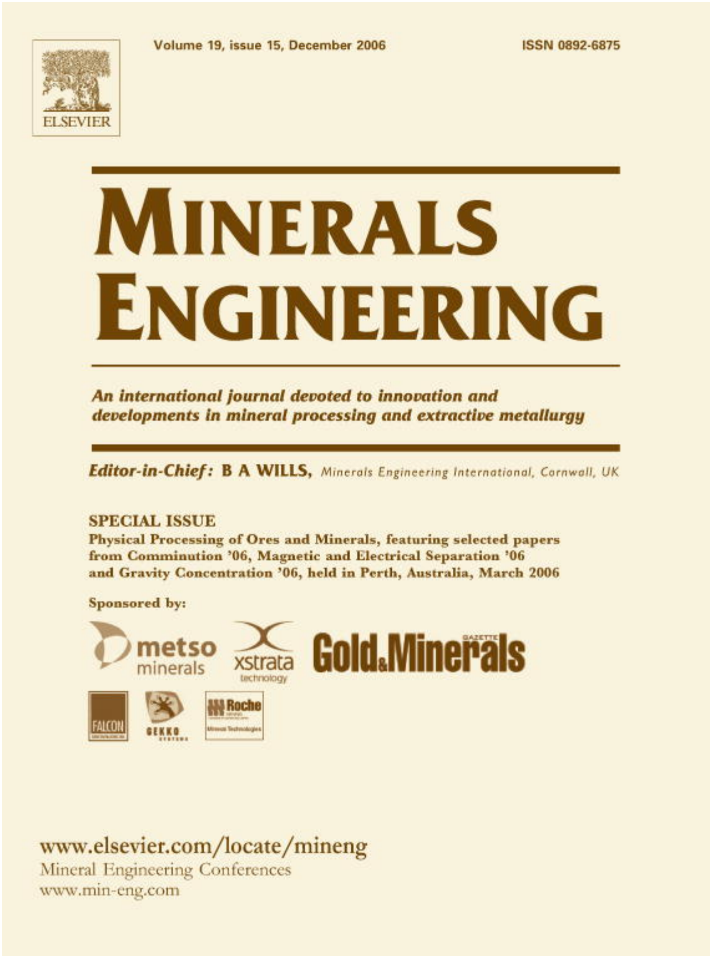

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Magnetic susceptibility measurement applied to the minerals industry

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Abstract

The efficiency of numerous mineral processing operations can be determined by measuring the magnetic properties of the process streams. This measurement, if done at all, is currently performed by laboratory testing of spot samples. This is an inherently slow process and, where feed grades are variable, optimum performance is generally not achieved.

This paper describes the rapid measurement of the magnetic properties of minerals. AC measurement techniques, including the analysis of the phase component of the magnetic vector; frequency dependent magnetic susceptibility and the effect of applied magnetic field strength will be discussed.

Industrial applications in mineral sands, copper smelting, ferrosilicon testing and drill core scanning will be reported.
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Keywords: Magnetic separation; Sorting methods; Pyrometallurgy; On-line analysis; Process instrumentation

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1. Introduction

The magnetic properties of minerals are used in separation, determination of a reaction completion, separator efficiencies, plant tuning, plant feed control and final product grade control. A variety of techniques are available to measure the magnetic properties of minerals including: fractionation with a magnetic separator (Stradling, 1991), Frantz isodynamic separator (Nesset and Finch, 1980; McAndrew, 1957), Magnetometer (Foner and McNiff, 1968; Lewis and Foner, 1976), SQUID (Sepulveda et al., 1994), Resonant Coil (Cooke and De Sa, 1981; Isokangas, 1996) and the inductance bridge (Drobace and Maronic, 1999; Stephenson and De Sa, 1970; Foner, 1991; Tarling and Hrouda, 1993). These techniques are generally considered laboratory methods due to the length of time required to process samples and/or their susceptibility to temperature drift and magnetic noise. The advantages of an industrial grade device to measure magnetic susceptibility was identified by Julius Kruttschnitt Mineral Research Centre (JKMRC) and it became an active area of research. This resulted in the development of industrial grade equipment to measure magnetic susceptibility (Cavanough and Holtham, 2001, 2004). This equipment is able to measure complex magnetic susceptibility (i.e. both phase and amplitude of the magnetic susceptibility vector) from 10 Hz to 100 kHz at infinitely adjustable field strengths and is suitable for on and off-line use. In both cases the sample is placed within an induction coil, with coil sizes ranging from 5 mm to 1 m in diameter and the sample can be moving or stationary. This paper reports on the application of magnetic measurement of minerals using various configurations of this equipment.

2. Magnetic characterisation of mineral sands feed stocks

2.1. Background

Magnetic characterisation of titanium minerals feed stocks is a routine procedure used for process control

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and assessment of mineral reserves (Panov et al., 2000). Currently, measurements are performed by separating small samples into their constituent magnetic fractions using a laboratory magnetic separator. Results are presented as the percentage of the feed material (by mass) at each level of magnetic separator field strength or speed (both of which are equivalent to magnetic susceptibility).

A significant amount of manual handling is required to perform this task, typically up to 40 min is required to process one sample.

The rapid magnetic characterisation method described in this paper results in considerable savings in labour, allows the processing of large samples and rapid repeat measurements.

2.2. Method

Cavanough and Holtham (2004) developed a method to calculate the individual magnetic properties of mineral sands grains by allowing the grains to pass through a small diameter coil in a configuration similar to an hour-glass. An industrial grade system has been built based using this method. Fig. 1 shows a picture of the measurement system. Mineral sample is fed into a hopper, the susceptibility measured as it passes through the coil, and the distribution of magnetics calculated, displayed and stored to file. Measurement of a 250 g sample takes approximately 1 min.

2.3. Results

Results from the measurement of four samples are shown in Figs. 2–5. Each graph compares the measurement results with physical separation results (samples were processed using a Permroll separator). Figs. 2–4 report the results as cumulative percent passing curves for levels of magnetic susceptibility.

Fig. 5 shows the results in terms of the mass recovered for Permroll RPM to illustrate that the device can completely mimic magnetic separator results.

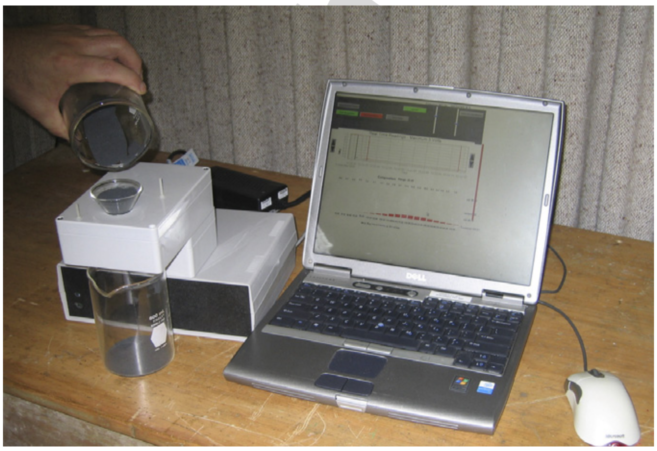

Fig. 1. Picture of the measurement system.

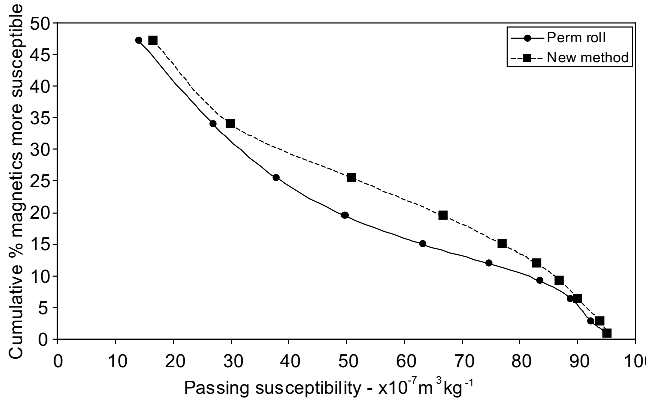

Fig. 2. Comparison of results for magnetics feed A.

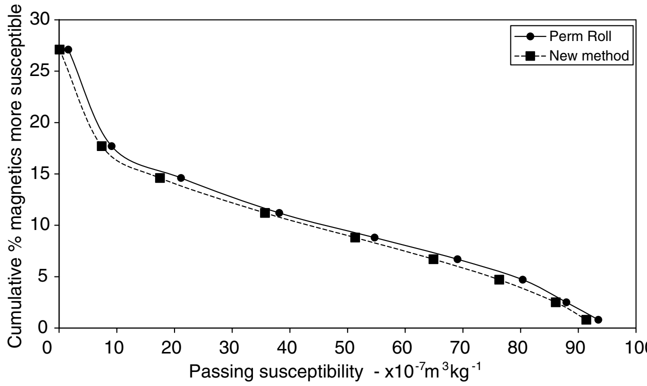

Fig. 3. Comparison of results for magnetics feed B.

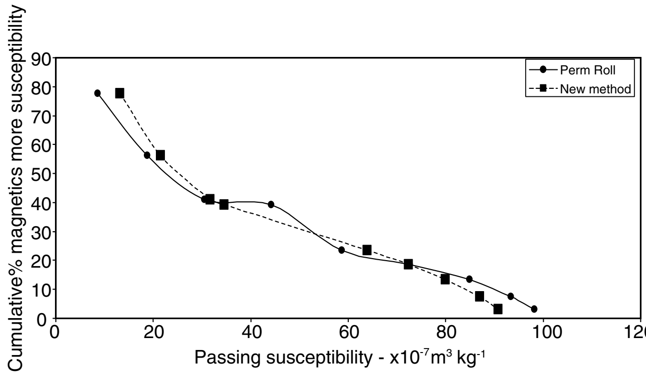

Fig. 4. Comparison of results for magnetics feed C**. (**Note: This sample had a large grab sample removed and therefore may contain an error due to non-random sub-sampling.)

3. Zircon magnetics

3.1. Background

Fig. 6 shows a schematic of a zircon magnetics circuit in an Australian titanium minerals dry plant. This is a scavenger magnetic circuit used to extract any remaining zircon from a tailings stream consisting of mainly monazite and stained zircon.

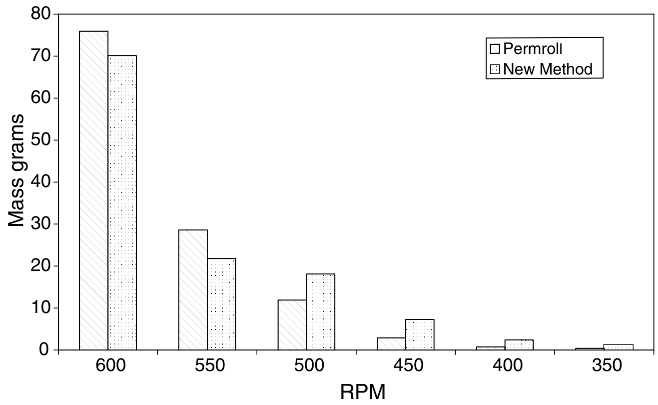

Fig. 5. Comparison of results for magnetics feed in terms of mass recovered at separator RPM.

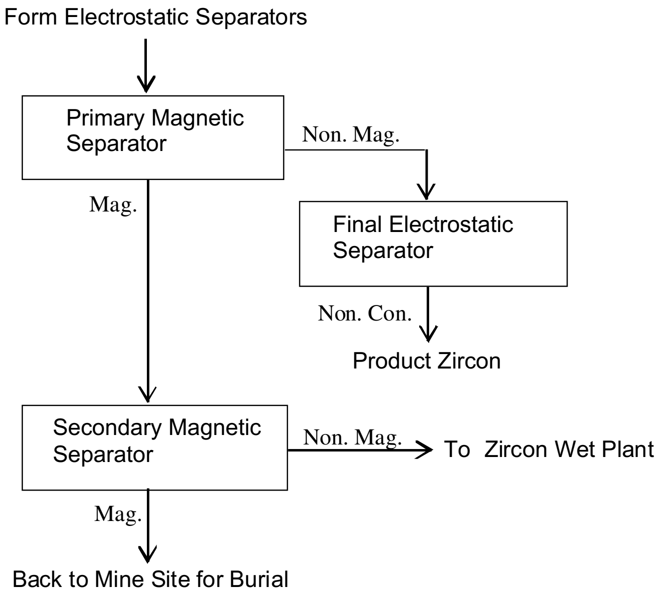

Fig. 6. Flow sheet of zircon magnetics circuit.

Adjustment of the magnetic separators is made when either the saleable zircon product does not conform to specification or the zircon magnetics sample contains greater than 30% zircon. (The zircon magnetics sample is analysed weekly by performing a laboratory separation and grain count). It is estimated that 600 tonnes of zircon per year are lost because the measurement is only available once per week. Hence, significant financial gains will result from a real time measurement of the zircon component because it would allow immediate adjustment of splitter position.

3.2. Method

The new instrument was used to measure the magnetic susceptibility of the magnetic fraction. Figs. 7 and 8 show the results of these measurements. These results show correlation between both the magnitude and phase of the magnetic susceptibility vector and the zircon content.

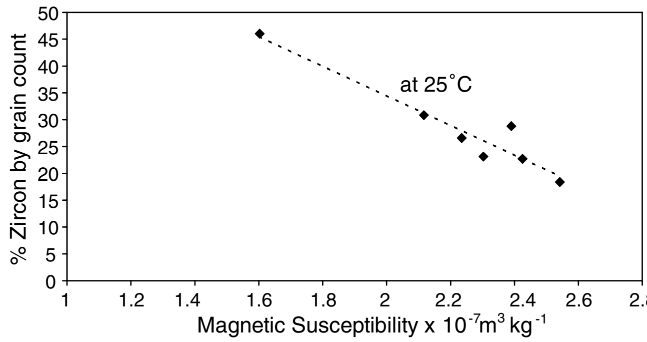

Fig. 7. % Zircon as a function of magnetic susceptibility.

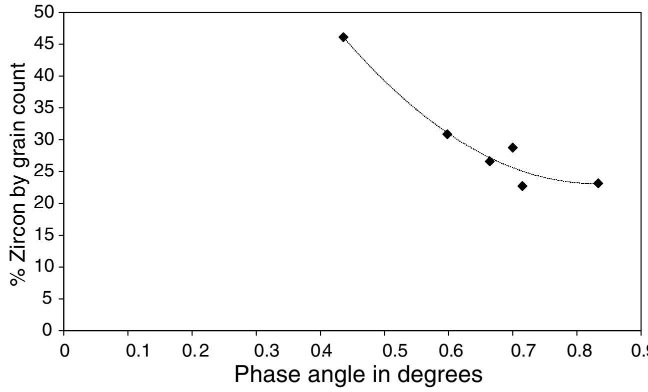

Fig. 8. % Zircon as a function of phase angle.

3.3. Results

Figs. 9 and 10 show typical measurements of % zircon and phase angle taken during plant operation. The noise spikes are due to "flash overs". "Flash overs" describe the high voltage arcing that occurs in the operation of electrostatic separators. An audible noise and burst of electromagnetic interference results from each "flash over".

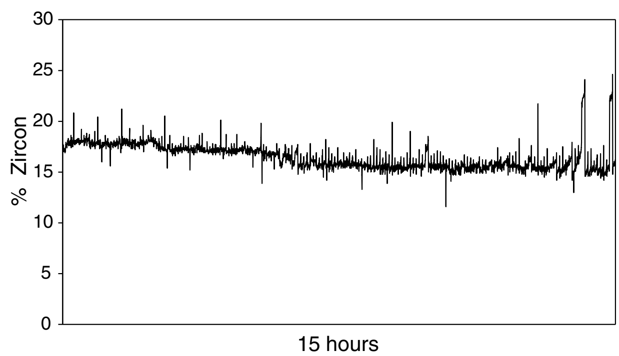

Fig. 9. % Zircon of zircon magnetics stream during plant operation.

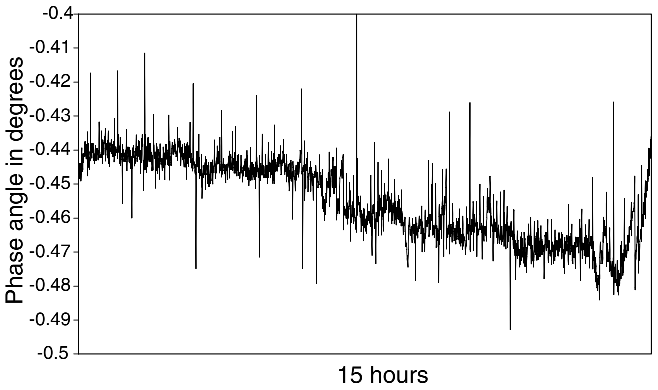

Fig. 10. Change in phase angle of the coil voltage for zircon magnetics stream during plant operation.

Table 1
Comparison of instrument measurements and laboratory results

	Week 1	Week 2	Week 3	Week 4	Week 5
% Zircon from measurement	18	22	19	22	20
% Zircon from laboratory analysis	19	23	18	22	20

The measurement device was installed in the same circuit as an automatic sampler. Sample cuts are taken by the sampler every six minutes and stored for weekly analysis.

To confirm the accuracy of the device, the readings for a week were averaged and compared to the automated sampler/laboratory analysis for the week. Table 1 compares % zircon measurements taken by the measurement device with the laboratory results obtained from the samples over a five week period. The results show that the device provides an online measure of the zircon loss with the same accuracy as the automated sampler and laboratory analysis.

4. Reduced ilmenite

4.1. Background

In the Australian titanium minerals processing operations the three valuable minerals recovered are zircon, rutile and ilmenite. Ilmenite consists of approximately 60% titanium dioxide and 25% iron and is the most abundant and least valuable of the three minerals. To achieve a higher market value ilmenite can be upgraded into a titanium dioxide pigment feedstock via the following processes:

- Reduction: A mixture of ilmenite, coal and sulphur are roasted in a rotary kiln to reduce FeO and Fe_2O_3 to metallic iron. The product of this process is reduced ilmenite.
- Aeration: Air is blown through a mixture of predominantly reduced ilmenite and water to "rust" the iron from the reduced ilmenite grains.
- Leaching: The "rusted" material is mixed with a weak acid solution to remove the iron. The ultimate product of these processes is a feed stock for pigment production containing greater than 90% titanium dioxide.

Processing in the kiln is continuous, while aeration and leaching are batch processes carried out in large mixing tanks. A measurement of magnetic susceptibility could be used to determine the completion of two of the processes by

- Determining the % metallic iron output from the kiln and establishing the level at which this value plateaus regardless of the increase in residence time and energy input.
- Determining the % iron content during the leaching process to determine the end point of the reaction.

In this section results of tests on ilmenite samples will be presented demonstrating how the magnetic susceptibility measurement device was able to determine the % metallic iron.

4.2. Method

The new instrument was used to measure the magnetic susceptibility of assayed samples.

All the samples had concentrations of less than 20% magnetics in a non-magnetic matrix; therefore the magnetic susceptibility is not affected by grain size and is directly proportional to the magnetics content of the mixture (Le Floc'h et al., 1992).

As the magnetic component is ferromagnetic it is expected that it will demonstrate the Hopkinson effect. That is the magnetic susceptibility will be relatively constant at temperatures around ambient temperature and then rise as the temperature approaches the Curie temperature of the material. Just below the Curie temperature very high levels of magnetic susceptibility will be evident and then drop to low levels as the temperature increases beyond the Curie temperature. To confirm this relationship an assayed sample of reduced ilmenite was heated in a furnace with a measurement of magnetic susceptibility taken as the temperature was increased. Fig. 11 shows a plot of the magnetic susceptibility as a function of temperature. The material clearly demonstrates the Hopkinson effect with the Curie temperature being between 500 and 600 °C.

4.3. Results

Tables 2 and 3 show the measurement results for each of the samples. These results show that calculations based on the magnetic vector amplitude are more accurate than

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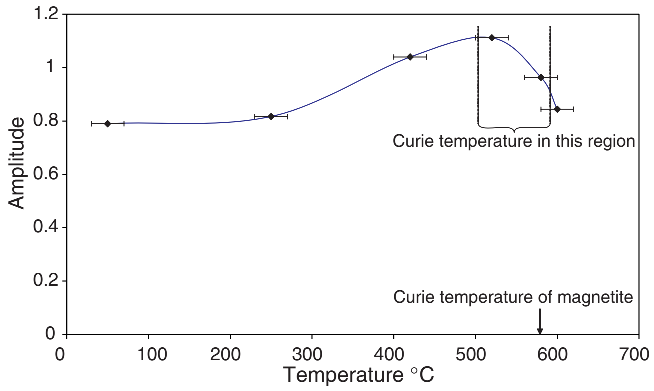

Fig. 11. Hopkinson effect for a reduced ilmenite sample.

Table 2
Percent magnetics in non-magnetics calculated from phase measurement

% Mag in non-mag	Calculated at 25 °C	Calculated at 35 °C	Calculated at 45 °C
1.2	1.5 ± 0.1	1.6 ± 0.3	1.3 ± 0.5
3.8	4.0 ± 0.3	3.3 ± 0.6	3.5 ± 1.2
4.6	4.4 ± 0.3	4.8 ± 0.8	4.7 ± 1.6
11	12.0 ± 0.9	12.4 ± 2.2	12.6 ± 4.2

Table 3
Percent magnetics in non-magnetics from amplitude measurement

% Mag in non-mag	Calculated at 25 °C	Calculated at 35 °C	Calculated at 45 °C
1.2	1.2 ± 0.2	1.2 ± 0.2	1.2 ± 0.2
3.8	3.0 ± 0.5	3.0 ± 0.5	3.0 ± 0.5
4.6	4.3 ± 0.6	4.2 ± 0.6	4.0 ± 0.6
11	11.6 ± 1.4	11.7 ± 1.4	11.3 ± 1.4

those based on phase. Phase readings are many orders of magnitude less than amplitude readings and therefore are of lower precision.

5. Copper smelting

5.1. Background

In copper smelting the Converter operation is a batch process in which air is blown through the copper matte for a certain time following which further matte is added together with additional silica to act as a fluxing agent to remove magnetite created during the blowing (oxidation) cycle. Correct silica addition is important because if too little silica is added (under fluxing) insufficient magnetite is removed resulting in a viscous slag; if too much silica is added (over fluxing) then the excess silica also results in a viscous slag. Both conditions can result in significant copper losses.

The current method of assessing the oxidation state of the matte is to use a magnet to determine the magnetite content. This method is subjective and hence inaccurate. A rapid method of determining the magnetite content was needed to improve converter operation. Laboratory analysis is too slow to be of use to the operators, a field tool was required adjacent to the converters. The industrial grade magnetic susceptibility measurement is being used for this purpose.

5.2. Method

The requirement was to keep the sample preparation and analysis as simple as possible. The following two sampling and analysis regimes have been proven to produce accurate results:

1. A sample of slag is obtained by dipping a cold bar into the slag stream as it is skimmed off. The sample is then cooled, and crushed using a flail mill to provide an acceptable final sample size distribution. A measuring cylinder is filled to overflowing with the crushed sample and the top leveled off. The fixed sample volume is transferred to a plastic sample bottle and presented to the system for analysis.
2. Alternatively, the sample of slag is cooled and crushed to approximately 5 mm particles using a hammer. The sample is weighed and then transferred to a sample bottle and the sample presented to the system for analysis.

5.3. Results

Fig. 12 shows magnetite concentration as a function of magnetic susceptibility for constant volume samples (magnetite component measured using XRF).

Fig. 13 shows a plot of $CuFe_2O_3$ as a function of magnetic susceptibility for mass corrected measurement of the slag of an electric furnace ($CuFe_2O_3$ component measured by XRF).

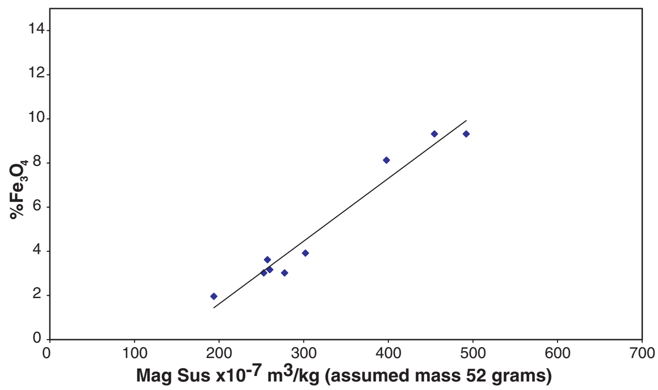

Fig. 12. Magnetite as a function of magnetic susceptibility for copper slag.

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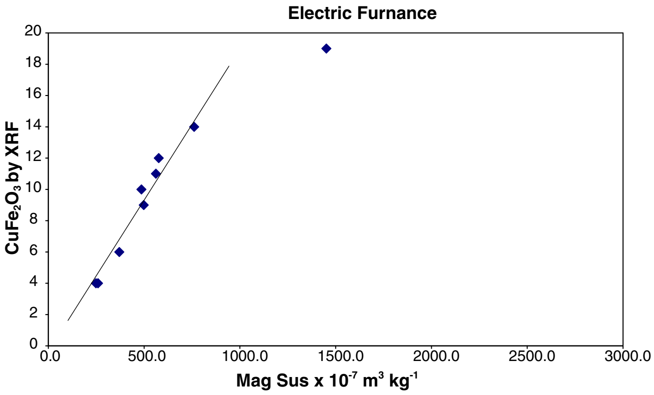

Fig. 13. Magnetite as a function of magnetic susceptibility for copper slag from an electric furnace.

Table 4
Change in magnetic susceptibility as ferrosilicon corrodes

State of ferrosilicon	Magnetic susceptibility $\times 10^{-4}$ m^3 kg^{-1}
As supplied	12.5
Partially corroded	11
Corroded	10

6. Ferrosilicon

6.1. Background

Ferrosilicon is an alloy powder that is used as a heavy medium in dense medium separation. The magnetic susceptibility of ferrosilicon can be use to determine the level of magnetic recovery and the level of corrosion.

The magnetic susceptibility of ferrosilicon is a function of the applied magnetising field. A true representation of magnetic susceptibility would require the measurement at a range of levels of applied DC magnetic field. However, in dense medium separations the major concern is the ability to recover ferrosilicon using a wet magnetic separator. Attraction to the magnetic separator is a function of the magnetic susceptibility with isolated particles having a magnetic susceptibility equivalent to that when there is no DC field applied. Low field AC measurement will provide a measure of the magnetic susceptibility when there is no applied DC magnetic field.

6.2. Method

Samples of 40 g mass were diluted by volume in a 5:1 ratio. Dilution mimics the dispersed state of ferrosilicon particles in a dense medium separation plant. Table salt (NaCl) was chosen for the dilution material because of it's availability and low level of magnetic susceptibility.

6.3. Results

Table 4 shows measurement of a ferrosilicon sample for levels of corrosion.

7. Core logging

7.1. Background

Core logging systems are used to measure the magnetic susceptibility of drill and mud cores. The conventional

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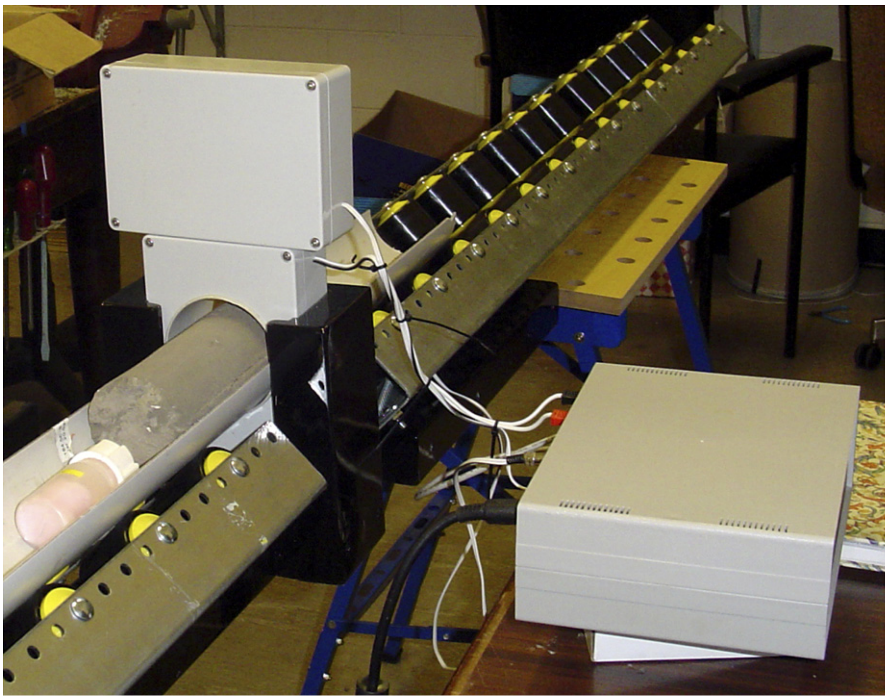

Fig. 14. Core scanning for magnetic susceptibility measurement.

measurement procedure is to position the core adjacent to or inside an induction coil. Magnetic susceptibility and the coil position relative to the core is measured to allow a measurement of the magnetic susceptibility along the length of the core. As each reading of susceptibility requires the core to be stationary and a measurement of core position to be made the procedure is labour intensive and relatively time consuming. A system has been developed to significantly reduce both the time and the labour requirements for core scanning using high speed measurement.

7.2. Method

Fig. 14 shows the measurement system. The system used an induction coil and displacement transducer and high speed data logging. Samples slide on a roller conveyor through the induction coil. A displacement transducer continually measures sample position regardless of speed. Induction coils and displacement signals are recorded at 1000 samples per second with the computer calculating magnetic susceptibility as a function of position after the scan is completed.

Both frequency and magnetic field intensity can be adjusted to allow the study of magnetic viscosity.

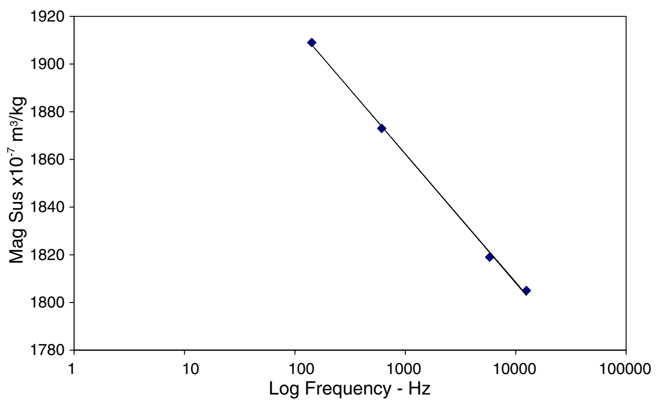

Fig. 15. Frequency dependent susceptibility of magnetite.

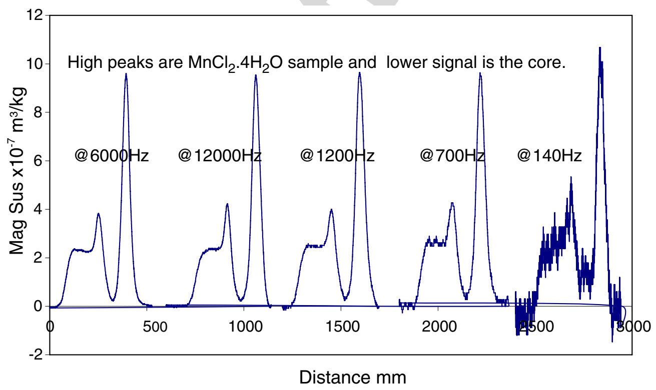

Fig. 16. Core and chemical salt sample scans at a range of frequencies.

7.3. Results

Fig. 15 shows the frequency dependent susceptibility of a magnetite section of a core. Fig. 16 shows scans of the core at a range of frequencies. Note the chemical salt calibrant has been placed in front of the core.

8. Conclusion

A range of applications for measurement of magnetic susceptibility has been presented. These measurements highlight the use of magnetic susceptibility measurements in optimising mineral processing operations with the major conclusions being:

- A system has been developed to determine the distribution of magnetic components in a titanium minerals feed stock sample. This system has been proven through mathematical derivation of the operating principal, simulation and testing of plant samples. This system provides the same results as obtained by using a perm roll separation with the following advantages over perm roll separation:
  - No sample mass measurements are required.
  - The measurement takes approximately 1 min per sample compared to 40 min per sample for a Perm Roll separation.
- Magnetic susceptibility can be used to determine the zircon content in the magnetic fraction of a zircon magnetics circuit.
- Magnetic susceptibility can be used to determine the metallic iron content in reduced ilmenite.
- Magnetic susceptibility can be use to determine the magnetite content of copper slag.
- A system has been developed to determine the distribution of magnetic components in drill and mud cores. This system has the following advantages over other systems:
  - No distance measurements are required.
  - The measurement takes approximately 20 s per core.

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