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Original Research Paper

# Comparison between the effect of microwave irradiation and conventional heat treatments on the magnetic properties of chalcopyrite and pyrite

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ABSTRACT

The effect of microwave radiation and conventional heat treatments of chalcopyrite and pyrite on their magnetic properties was investigated. Magnetic susceptibility of chalcopyrite increased significantly by increasing microwave power and treatment time. Pyrite magnetism was affected only at 500 W microwave power. On the other hand, magnetic susceptibility of both chalcopyrite and pyrite increased significantly by increasing heating temperature. X-ray diffraction and XPS characterization showed that the formation of more magnetic phases after chalcopyrite and pyrite treatment is the reason behind their increased magnetism. Dry magnetic separation of individual treated minerals at several magnetic field strengths from 0.5 Tesla to 2 Teslas was conducted. The results suggest that selective magnetic separation of chalcopyrite from pyrite is possible only in case of microwave treatment due to its selective effect in favor of chalcopyrite at lower power levels compared to pyrite.



## 1. Introduction

Sulfide minerals represent one of the main sources for several metals. They are usually found as complex ores consisting of several sulfide minerals. Froth flotation is the main separation technique applied for their separation from each other. In some cases, flotation faces difficulties achieving the desired grade and recovery, particularly, when sea water is used. Using sea water is growing due to fresh water scarcity in remote regions [1] and the need for flotation alternative methods is increasing.

Chalcopyrite is the most important copper bearing mineral and represents the major source of copper. Pyrite is the most common among sulfide minerals [2] and is needed to be removed from the other sulfide minerals to get the desired metal quality during extraction at smelters. It was found that conventional heat treatment of chalcopyrite and pyrite increases their magnetic properties and make it possible to be separated using magnetic separation process [2,3].

Microwave irradiation treatment gained more interest in mineral processing research due to its selective effect and low power consumption. Microwave heating depends on the ability of materials to convert electromagnetic energy into heat. The ability of material to absorb microwave energy depends on its dielectric constant [4] which is different from one mineral to another and is responsible for the microwave heating selective effect. Several researchers studied the effect of microwave radiation treatment on magnetic properties of iron bearing minerals. Omran et al. [5] concluded that phosphorus removal from iron ore using magnetic separation improved after microwave treatment (at 900 W for 60 s and 120 s) due to the increase in hematite magnetism. XPS characterization showed that the reason is due to the formation of ferromagnetic phases [6]. Uslu et al. [7] used kitchen type microwave for treating pyrite at 850 W for 495 s. They found that pyrite became more magnetic due to its decomposition to more magnetic mineral phases. They also reported that the pyrite magnetic properties increases by decreasing particle size and increasing power [7]. Waters et al. [8] found that magnetic recovery of pyrite treated using microwave irradiation at 1900 W for 120 s increased to more than 80% compared to 25% recovery without treatment. They explained that phenomenon by phase change of the pyrite surface.

Heat treatment of other iron bearing minerals (e.g. hematite and siderite) increased their magnetization [9]. Also, it was found

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to increase the magnetic properties of chalcopyrite and pyrite [2,3]. Sahyoun et al. [3] treated chalcopyrite in conventional furnace for 1 h at several temperatures. They found that chalcopyrite susceptibility and magnetic recovery fraction increased with increasing temperature up to 850 °C. They attributed this result to phase change detected by X-ray diffraction. Waters et al. [2] found similar results when heating pyrite for 1 h for temperatures ranging from 200 °C to 1100 °C. Pyrite heating increases its magnetic recovery from 25% without heat treatment to more than 90% after treatment. They referred that increase in magnetic properties to the formation of more magnetic mineral phases as pyrrhotite, magnetite and maghemite.

The aim of this work is to investigate the selective effect, if exists, of microwave irradiation and heat treatments on magnetic properties of chalcopyrite and pyrite and find out the reason. Another objective is to understand the involved mechanism in the increased magnetic properties after both treatment types using several characterization techniques.

## 2. Experimental

### 2.1. Materials

Pure chalcopyrite sample from Shakanai mine (Japan), while pure pyrite sample from Huanzala mine (Peru) were used for all experiments as single mineral samples.

### 2.2. Methods

#### 2.2.1. Microwave treatment

0.5 g of single pure mineral with particle size −125 +38 μm was put in a crucible made from silica. The crucible was then placed in 900 W Panasonic kitchen microwave with maximum power output of 500 W at the desired power for certain time. Three power levels were used, 100 W, 300 W and 500 W. Ultra compact digital radiation temperature sensor from KEYENCE company was used for measuring sample temperature which is connected to a computer where the temperature is saved automatically. Sample was taken out of microwave and the temperature was measured and the delay time between the end of microwave treatment and sample temperature measurement was recorded. Based on the sample cooling rate recorded in the computer, an estimation of the real temperature at the end of treatment can be calculated using curve fitting. Fig. 1(a and b) indicates the cooling rate of chalcopyrite and pyrite, respectively, treated at the three applied power levels.

#### 2.2.2. Conventional heat treatment

0.5 g of single pure mineral with particle size −125 +38 μm was put in a crucible made from alumina and placed in conventional furnace preheated to the desired temperature 60 s. The tests were performed under normal atmospheric conditions.

#### 2.2.3. Magnetic susceptibility measurements

Magnetic susceptibility of samples before and after treatment was measured using susceptibility meter "Bartington, UK" MS3 sensor and MS2G meter assembly for powder samples connected to computer for data display and saving. Samples are placed in 1 cc plastic vials for the measurement after calibration using calibration sample provided by the manufacturer. The MS2G meter has a field amplitude 500 μT peak to peak at 1.3 kHz. The output results are dimensionless measured using the cgs system.

#### 2.2.4. Magnetic separation

"Nippon Magnetic Dressing Co. Ltd., G - type" dry magnetic separator has been used. 0.5 g samples before and after treatment were separated using three field strengths, namely, 0.5 Tesla, 1 Tesla, and 2 Tesla. The non-magnetic product of 0.5 Tesla is used as the feed for 1 Tesla and so forth until getting the final non-magnetic product at 2 Tesla. All products were collected and weighed and the cumulative recovery was calculated.

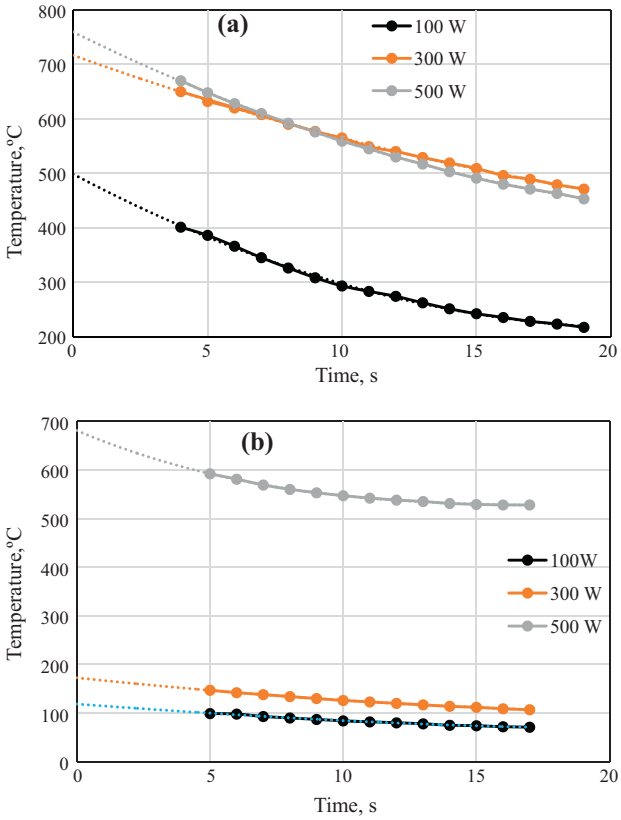


**Fig. 1.** Cooling rate after microwave treatment for 60 s at different power levels for: (a) chalcopyrite and (b) pyrite.

#### 2.2.5. X-ray diffraction

An "Ultima IV" XRD (RIGAKU, Akishima, Japan) using Cu Kα radiation (40 kV, 40 mA) at a scanning speed of 2° $min^{-1}$ and scanning step of 0.02° has been applied to characterize mineral samples before and after treatment.

#### 2.2.6. X-ray photoelectron spectroscopy (XPS)

Untreated and treated mineral samples were analyzed by X-ray photoelectron spectroscopy (XPS) using AXIS 165 (Shimazu-Kratos Co., Ltd.) with Al Kα X-ray source (1486.6 eV) operated at 105 W, providing an analysis area 1 mm × 1 mm, and a charge neutralizer was used for the measurements. The pressure in the analyzer chamber was $10^{-8}$ Pa during analysis. The samples were first examined in wide scan (80 W of the analyzer pass energy) to identify all the elements present, then the various elemental regions were scanned (40 W of the analyzer pass energy) in order to extract information on chemical bonding and oxidation state. The collected data were analyzed with Casa XPS software (Ver., 2.3.16). Background corrections were made using the Shirley method [10] for the C1s, O1s, Fe2p, Cu2p and S2p spectra. Peak shapes were defined using a Gaussian-Lorentzian function. Binding energy ($E_B$) calibration was based on C1s at $E_B$[C1s] = 284.6 eV.