

**APPLICATION OF MICROWAVE TECHNIQUES TO  
THE PROCESSING OF SULPHIDE ORES**

**M.Sc. Thesis by  
Tevfik Serhat ÖNOL**

**Department : Mining Engineering**

**Programme: Mineral and Coal Processing**

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Tevfik Serhat ÖNOL**

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**Supervisor (Chairman): Prof. Dr. Hayrünnisa DİNÇER**

**Members of the Examining Committee Prof.Dr. Gündüz ATEŞOK**

**Prof.Dr. Ercan AÇMA**

**JUNE 2007**

## **PREFACE**

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Tevfik Serhat ÖNOL

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## LIST OF ABBREVIATIONS

<b>NIR</b>	: Near Infrared
<b>°C</b>	: The degree Celsius
<b>Min</b>	: Minute
<b>KW</b>	: Kilowatt
<b>GHz</b>	: Gigahertz
<b>KWh</b>	: Kilowatt-hour
<b>T</b>	: Ton
<b>DMS</b>	: Dense Medium Separation
<b>g</b>	: Gram
<b>LIBS</b>	: Laser Induced Breakdown Spectroscopy
<b>LIF</b>	: Laser Induced Fluorescence
<b>UHF</b>	: Ultra High Frequency
<b>SHF</b>	: Super High Frequency
<b>EHF</b>	: Extreme High Frequency
<b>dB</b>	: Decibel
<b>μ</b>	: Millimetre

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## SÜLFÜRLÜ CEVHERLERİN ÖNZENGİNLEŞTİRİLMESİNDE MİKRODALGA TEKNİKLERİNİN UYGULANMASI

### ÖZET

Bu çalışma belirli bir mikrodalga etkisinde kalan farklı kimyasal ve minerolojik içeriğe sahip minerallerin, farklı derecede ısınması özelliğinden yararlanılarak sülfürlü minerallerin selektif bir şekilde ısıtılması ve ısıtılan malzemelerin bir otomatik ayırıcıda kızıl ötesi kamera ile belirlenerek ayrılmasını incelemek amacıyla yapılmıştır.

Çalışmanın ikinci amacı olarak, farklı minerallerin daha düşük mikrodalgaları yine farklı miktarda soğuracağı düşünülmüş ve bu amaçla deneyler yapılmıştır.

Her iki çalışmada da aynı numuneler kullanılmıştır. Numuneler belirli bir boyut altına öğütülmüş ve farklı boyut aralıklarında sınıflandırılmış kalkopirit ve pirit minerallerinin belirli yüzdelerde, yantışı temsil eden kuvars, feldspat ve çimento karışımı ile homojen olarak karıştırılması ile aynı boyut ve şekillerde hazırlanmıştır.

Her iki çalışmada da numunelerin soğurdukları mikrodalgaların miktarının numunenin metal içeriği ve içerdiği metallerin numune içerisindeki tane boyutları ile bağlantısı incelenmiştir.

Çalışmanın ilk safhasında deneyler Almanya'nın Aachen kentinde Aachen Teknik Üniversitesi (RWTH-Aachen) cevher hazırlama bölümünde yapılmıştır. Çalışmada hazırlanan temsili numuneler, 900 W gücünde ve 2.45 GHz frekansında mikrodalgalar üreten bir ısıtıcıda 20 sn süre ile bekletilmiş ve ısıtma işleminden sonra 30 dk boyunca her dakikada bir ölçüm yapılmak üzere kızılötesi bir termometre ile yüzey sıcaklıklarındaki değişimler incelenmiştir.

Sonuçlar kısmında numunelerin yüzey sıcaklığı-mineral içeriği, yüzey sıcaklığı-numune içerisindeki minerallerin tane boyları arasındaki ilişki irdelenmiştir.

Mikrodalgaların sülfürlü mineraller tarafından çok daha fazla absorbe edildiği ve diğer gang minerali olarak bilinen kuvars feldspat türü malzemelerin mikrodalgaları sülfürlü mineraller kadar absorbe etmediği görülmüştür. Absorbe edilen mikrodalgaların miktarı dolayısı ile malzemenin sıcaklık artışının, içerdiği mineral yüzdesi ile doğru orantılı olduğu saptanmıştır. Yine numune içerisinde daha küçük boyutta mineral dağılımına sahip malzemenin sıcaklık değişiminin diğerlerinden daha fazla olduğu tespit edilmiş ve bunun nedenleri tartışılmıştır.

Çalışmanın ikinci kısmı yine Aachen Teknik Üniversitesinin Yüksek Frekans Teknolojileri bölümü laboratuvarında sürdürülmüştür. Çalışmada numuneler biri mikrodalga yayınlayan anten diğeri ise alıcı görevi gören iki sarım arasında yerleştirilmiş ve 50 ile 220 MHz arası frekanslarda mikrodalgalar uygulanmıştır. Sarımların birinden yayınlanan bu mikrodalgalar numune içerisinden ve havadan alıcı görevi gören ikinci sarıma ulaşmış ve bu sarım üzerinde bir indüksiyon oluşturmuştur ve bu oluşan indüksiyonun frekansı ölçülerek farklı numunelerin uygulanan farklı frekanstaki mikrodalgalarda yarattığı eksilme ve sapmalar ölçülmüş ve bu doğrultuda mikrodalgadaki zayıflama-mineral içeriği, mikrodalgadaki zayıflama-numune içerisindeki minerallerin tane boyutları arasındaki ilişki sonuçlar kısmında irdelenmiştir.

Numunelerin düşük frekanstaki mikrodalgalar üzerinde değişime sebep olduğu çalışmada tespit edilmiştir. Bu sonuçlara ilişkin yorumlar sonuçlar bölümünde tartışılmıştır.

Bu çalışmanın gelecekte uygulanabilecek olan mikrodalga ısıtması ve sonrasında kızılötesi tarama işlemi ile çalışan bir otomatik ayırmada ve uygulanan mikrodalgadaki sapma ve zayıflamaların tespiti ile malzemelerin ayrılmasına dayanan bir otomatik ayırma işleminde beslenen malzemenin içerisindeki mineral yüzdesinin saptanmasını sağlamak amacıyla yapılmıştır.

Çalışma içerisinde bu konuda yapılmış diğer çalışmalardan, mikrodalga teknikleri ile ayırma gerçekleştiren yada gerçekleştirmiş olan tesislerden ve bunların raporlarından örnekler ve özetler verilmiştir.

## **APPLICATION OF MICROWAVE TECHNIQUES TO THE PROCESSING OF SULPHIDE ORES**

### **SUMMARY**

In this study different effect of microwave on the minerals, which have different chemical and mineral composition, selective heating of sulphide minerals and automated sorting of these minerals with scanning an infrared camera after microwave heating process has been investigated.

Because sulphide minerals absorb microwave more than other minerals, it has been thought that sulphide minerals also absorb low power microwaves which are more applicable in the industry and the second part of the study has been carried out to investigate this possibility.

Both first and second part experiments of the study same samples have been used. These samples were homogeneous mixture of chalcopyrite and pyrite with cement, quartz and feldspar. Samples contained different grade of ground and different size fractions classified chalcopyrite and pyrite as value mineral. Mixture of quartz, feldspar and cement represented gangue mineral in the ore.

In both experimental studies relations between absorbed microwave energy and mineral grade, particle size range were investigated.

The first experimental study has been carried out in the mineral processing department of Aachen Technical University (RWTH-Aachen) in Aachen/Germany. In this part artificial samples have been placed into a microwave heater with 900 W and 2.45 GHz and have been heated during 20 seconds. After heating process samples have been placed out of microwave heater and scanned the surface temperature with an infrared thermometer. This scanning process has been repeated every minute during 30 minutes and temperature differences in this period have been determined.

In results and discussions section relations of surface temperature-mineral grade, surface temperature-particle size range, have been explained.

It has been determined that sulphide minerals absorb microwave energy more and microwaves have had a little or no effect on microwave transparent minerals such as common gangue minerals, quartz and feldspar. It has been also determined that the effect of microwave directly proportional with the sulphide minerals grade in the ore

and also it has more effect on the minerals having smaller particle size range. The possible reasons of these proportions have been investigated.

The second experimental part of the study has been carried out in the department of High Frequency Techniques in Aachen Technical University. In this part samples placed between two spools. One of these spools (antenna) irradiates low power microwaves and the other receives microwaves after passed through the mineral and also air. Between 50 and 220 MHz microwaves have been applied from antenna and produce inductions on the receiver. The frequencies of produced inductions have been measured and the attenuation of microwaves has been determined and relations between attenuation-mineral grade, attenuation-mineral size range have been investigated and discussed in the discussion section of the study.

This study have been carried out to investigate the possibility of determining of mineral grade in the feeding ore in the sensor based sorting technology which has an infrared scan after preparation of ore in microwave heater or scanning the attenuation of applied microwaves.

In this study examples and short summaries of other related works and applications in the industry have been given.

## **1 INTRODUCTION**

Mineral processing engineering focuses on separating value minerals from unwanted or unvalued (gangue) minerals using differences of physical and chemical properties of the minerals.

After mining the ore from the earth crust by traditional mining methods, the material is fed into the processing plant to extract and concentrate the economic minerals contained. The first step in mineral processing is to decrease the particle size such that it is suitable to the following separation process. The separation process depends on chemical properties of minerals such as different solubility properties in a solvent, and/or different physical properties, such as specific gravity differences, magnetic properties, electrical conductivity, surface properties, optical properties and radioactive properties of the minerals.

Both, manual and automated separation, also called as sorting, rely upon different optical and radioactive properties of minerals. Manual sorting, also called “hand picking”, has already been applied in ancient times. Minerals having different optical properties, for example, colour, are sorted by hand through a flowing band conveyor. With changing free-market economy, scale of processing and decreasing metal content, hand sorting became uneconomically. Hence, in the late 1940s, automated sorters have been developed and replaced hand picking lines. These sorters consisted of a sensor unit scanning the feeding material, a computation unit steering the process of discharge.

Automatic sorting devices have been using in food, recycling industries and as sensor based control mechanism in many industry. The applications of automated sensors in food industry are mostly based on colour cameras, scanning the colour differences and laser sensors to scan width of foods and analyze size and shape. On the other hand, optical, near infrared (NIR) and inductive sensors have become an industry standard in paper, glass and metal recycling industry.

Automatic sorting also becomes more and more a standard technique in mineral processing applications for pre-concentration, intermediate and/or final product production with different sensor types, when the traditional processing techniques become inefficient or even infeasible.

### 1.1 Related Work and State-Of-The-Art

Another property for discriminating ores is their different behaviour in same microwave field. Walkiewicz reported different microwave heating characteristics of various mineral samples. The materials with a mass of 25 g, except for low density minerals where the volume was 18 ml constant, were irradiated in 1KW, 2,450 MHz microwave heater and the heating rates were determined (Table 1.1). A certain group of minerals has similar microwave behaviour such as sulphide ore types are easily heated, while oxide type ores are heated only a little. On the other hand microwaves do not have an effect on the common gangue minerals, quartz, calcite and feldspars [1].

**Table 1.1:** Microwave heating results (Walkiewicz 1988)

<u>Mineral</u>	<u>Chemical composition</u>	<u>Temperature [°C]</u>	<u>Time [min]</u>
Chalcopyrite	CuFeS <sub>2</sub>	920	1
Pyrite	FeS <sub>2</sub>	1019	6.75
Hematite	Fe <sub>2</sub> O <sub>3</sub>	182	7
Galena	PbS	956	7
Chromite	FeCr <sub>2</sub> O <sub>4</sub>	155	7
Magnetite	Fe <sub>3</sub> O <sub>4</sub>	1258	2.75
Molybdenite	MoS <sub>2</sub>	192	7
Quarz	SiO <sub>2</sub>	79	7
Sphalerite	ZnS	88	7
Orthoclass	KAlSi <sub>3</sub> O <sub>8</sub>	67	6

In the same study, Walkiewicz also reported that the rapid increase of mineral temperature in a microwave-transparent mineral matrix generates thermal stress sufficient to create microcracks at the mineral grain borders. He added that these microcracks at the grain boundaries should lead to a change liberation process, decreasing grinding costs and hence better mineral recovery.

Another investigation of microwave assisted grinding was reported by S.W.Kingman. Changing of bond indexes for selected mineral ores depending on microwave exposure was investigated and reported. Massive sulphide ore, massive ilmenite ore, highly refractory gold ore and carbonatite ore were selected for investigation by Kingman and each mineral ore was radiated by microwave for 10, 30, 60, 90, 100 and 120 seconds in a 2.6 KW, 2.45 GHz microwave heater. After microwave heating process bond work index in KWh/t has been determined by use of a laboratory rod mill and compared with reference ore of known bond index where bond index was determined for non-microwave treated ores. Kingman has reported that within microwave field material undergo different thermal expansion and it causes stresses at the grain boundaries. Kingman also added that after microwave treatment, bond work index of ilmenite, carbonatite and massive sulphide ores decrease with increasing microwave exposure times however microwave treatment have no effect on the work index of gold ore [2].

Different experiments were carried out to remove organic and inorganic sulphur from coal with peroxyacetic acid after microwave irradiation [3]. This report explains that C-S and Fe-S bonds of inorganic and organic sulphur in microwave irradiated coal are weaker than non-microwaved coal and it would be easier to break these bonds and desulfurize coal after irradiation pre-treatment with use of peroxyacetic acid. Jorjani carried out microwave irradiation experiments with different power and time values and reported that pyritic and some of organic sulphur has transformed to sulphate form and the removal of inorganic sulfur increase with enhancing power and time. However, with increasing power and time some of the organic sulfur converted to other forms which are not removed from the coal organic matrix. Removal of organic sulfur varied from 3.62% to 10.33%.

D. D. Bluhm reported that separating pyrite from coal with increasing magnetic susceptibility of pyrite use of dielectric heating would be possible. He added that the magnetic susceptibility of pyrite increases with increasing heating time but after a long period of heating coal pyrolysis problem would occur [4].

C. A. Pickles, described microwave heating behaviour of nickeliferous limonitic laterite ores in one part of his study [5]. Samples with a mass of 15 g. were microwated in a quartz crucible at different times. His results show that temperature

of limonitic laterite ore increased rapidly to 100 °C in about 2 min and in this period laterite ore temperature was slightly more than hematite ore. However, laterite temperature remained for about 3 min at about 100°C. Pickles explained the possible reason of this removal of large amount of free water from the ore surface. After the removal of the water, the samples' temperature increased rapidly. During this period, temperature differences between laterite and hematite increased about 40 °C. Pickles added that when the critical temperature is achieved with preheating the samples in a conventional heater, then the temperature of the samples increases rapidly.

Application of microwave techniques in the mineral industry was reported by J. D. Salter [6]. He reported the development of a new sorting process from laboratory up to a 100 t/h pilot plant. The new developed automatic sorting machine employs low-power microwaves as rock discrimination unit following by ejection of rocks by use of pulsed water ejectors in order to remove waste rocks prior to diamond liberation and the following recovery process. Kimberlite containing diamond absorbs applied microwave energy more than gabbro and the other premier waste rock types. It was reported that because of the lack of an existing selective excavation solution in the mining, feasible manual sorting option and a viable dense medium separation (DMS) process, a new sorting machine was developed. Material, which has been fed on the belt in a single layer into channels, are detected by detectors under each channel and separated by use of pulsed water. The application of this sorter was reported in a pilot plant with a capacity of 900 t/h and +60 mm particle size in order to separate kimberlite from gabbro.

## **1.2 Scientific Goals**

In this study, effect of microwave heating and microwave attenuation on the minerals for chalcopyrite and pyrite is investigated experimentally. The application of these effects in an automated sorting machine combined with a sensor in the chalcopyrite and pyrite pre-concentration and concentration process compared with the traditional concentration methods of these minerals.

The aim of this work is to investigate different microwave heating behaviours of different artificial samples, containing chalcopyrite as well as pyrite ores, having different mineral grade and different range of grain size. For this investigation a

domestic microwave heater with 900 W and a frequency of 2.455 GHz was used and after heating the cooling range of these samples was determined.

The second part of the study is about the effect of microwave attenuation of the same samples using a low power microwave field. Relations between attenuation, mineral grade and grain size distributions were determined.

## 2 PROCESSING OF CHALCOPYRITE AND PYRITE

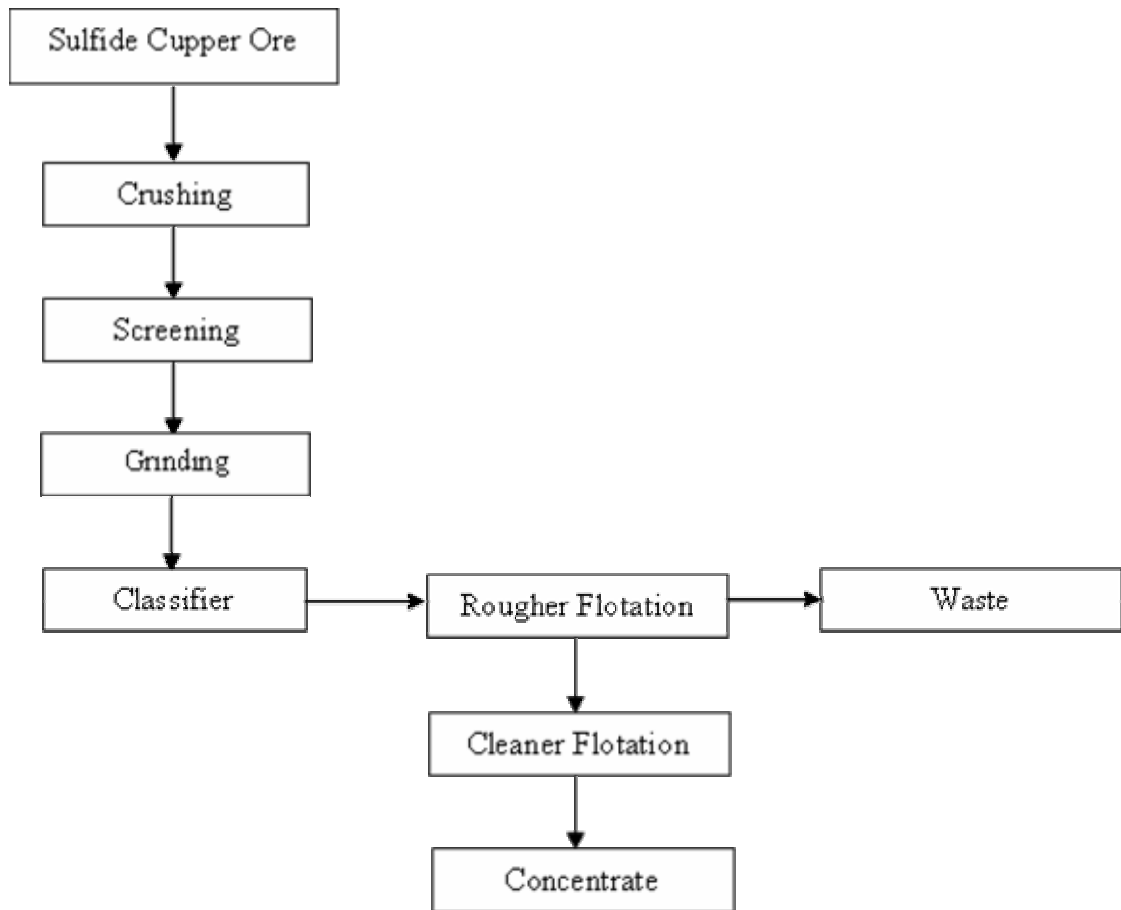
### 2.1 Chalcopyrite ( $\text{CuFeS}_2$ )

Chalcopyrite, because of its high Cu-content (34.6%), is one of the important copper minerals. It is a tetragonal sulfid-mineral with the chemical formula  $\text{CuFeS}_2$ . Hardness on the mohs scale between 3.5 and 4. It has a brassy to golden yellow colour, and its streak is dark green. The specific gravity of chalcopyrite is between 4.1-4.3  $\text{g/cm}^3$ , it is soluble in  $\text{HNO}_3$  and it becomes magnetic by heating. It is distinguished from pyrite by its inferior hardness.

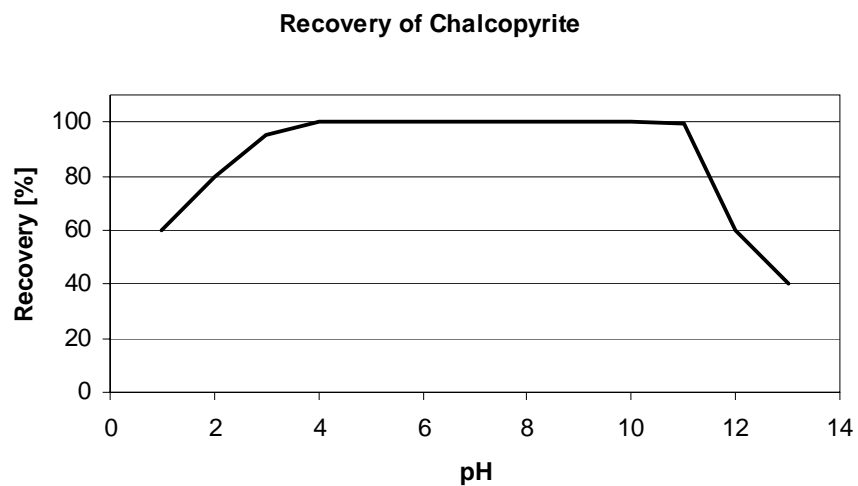
Chalcopyrite is a common mineral in the earth crust, found as gangue mineral in both magmatic and sedimentary rocks together with pyrite and bornit. Most common chalcopyrite deposits are porphyry type of deposits [7, 8].

Because of world demand and its price, the mining industry has always been and still is interested in copper ores. While oxide copper ores are processed by hydrometallurgical treatment, sulphide ores are concentrated by flotation or after roasting (oxidation) by leaching process. In Figure 2.1 the flow sheet shows a typical sulphide flotation process containing a rougher and a cleaner step [9].

After the liberation process, where generally a ball mill in close circuit with a classifier, the ore is fed into rougher flotation followed by a cleaner flotation step to concentrate the value mineral suitable for the following smelting process. As collector for chalcopyrite usually xanthate is used with pH value of about 3 to 11. Figure 2.2 shows the flotation recovery of chalcopyrite as a function of the pH value. Between pH 3 and 11 electrochemical oxidation of xanthate to dixanthogen as well as chemical absorption of xanthate are responsible for flotation. Depression of chalcopyrite occurs above pH 11.  $\text{Ca}(\text{OH})_2$  is used for adjustment of pH and cyanide is used as depressant of pyrite [10].



**Figure 2.1:** Concentration of Chalcopyrite with Sulphide Flotation [9]



**Figure 2.2:** Recovery of chalcopyrite as a function of pH with  $1.10^{-5}$  molar addition of Methyl xanthate [10]

Porphyry copper ores, chalcopyrite ores, mostly have low mineral grade and have to be concentrated. There is a problem occur during large scale mining operations.



The feeding ore of London Mill is a composite of four ores from four mines having different composition and flotation characteristics. These have to be mixed carefully to keep the feeding of the London Mill uniform.

At the mine -7 Inc crashed materials, are further crashed under -0.75 Inc and stored in the four fine ore bins which have 585 ton capacity each and controlled fed into the two primary grinding units to obtain an additional mixing of the material. Materials are ground under 48 mesh and fed to bulk rougher flotation and sulfides are floated as a bulk concentrate and ground again under 100 mesh to concentrate copper and zinc sulfides from iron sulfides by copper cleaner and zinc rougher flotation. Bulk flotation tailings are fed into the magnetic separator to concentrate magnetite from tailings including magnetite and 1/3 of sphalerite. Sphalerite is recovered in a zinc flotation. Talc, floated with copper, is depressed in the copper cleaner flotation by galactomannan. The zinc rougher concentrate including approximately 50% sphalerite and 50% pyrrhotite is upgraded by deactivating sulfur dioxides and concentrated by floating pyrrhotite.

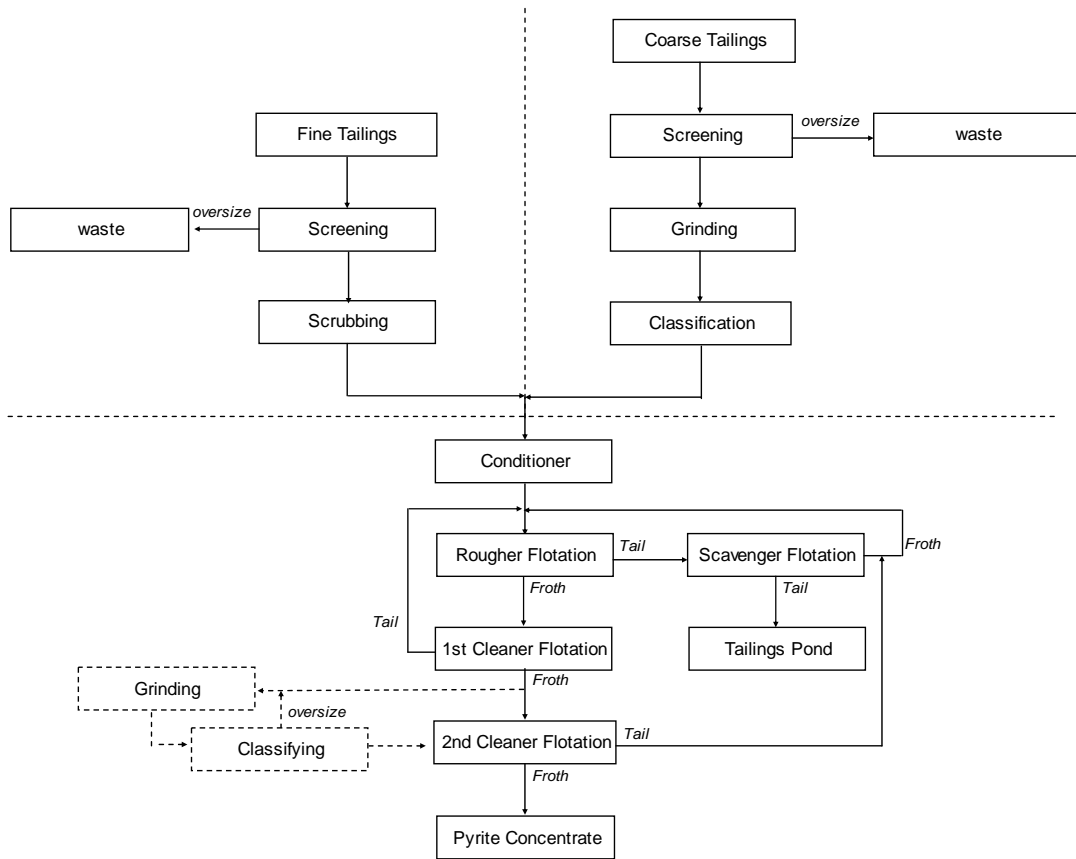
## **2.2 Pyrite (FeS<sub>2</sub>)**

Pyrite is one of the most common minerals in the earth crust. It contains of 46.55% Fe and 63.45% S with the chemical formula FeS<sub>2</sub>. It has more than 60 crystal forms and mostly occurs as cubic crystal system and also frequently occurs as octahedral crystals. It has yellow, golden yellow and brown colour, and its streak on white ceramic greenish-black to brownish-black. It is a brittle material, with hardness between 6 and 6.5 on mohs scale. The specific gravity of pyrite is between 4.95-5.10 g/cm<sup>3</sup>. Other properties of pyrite are smells sulphur, paramagnetic and insoluble in water. It is found in sedimentary, magmatic, metamorphic, and hydrothermal deposits [7].

Pyrite is a source of sulphur dioxide for the manufacturing of sulphuric acid. Regarding the treatment of pyrite, it is mostly recovered by flotation of certain metals as by-product by selective flotation. Coal washing is also a source of pyrite.

The Treatment of pyrite from tailing depends on the particle size of the tailings and the source. Regarding the flotation of tailings, no size reduction is required.

However, coarse material such as tailing from a gravity separator must be ground to a suitable size for the following selective flotation unit. In Figure 2.4 the flowsheet of pyrite recovery from both coarse tailing and fine tailings is shown. [9]



**Figure 2.4:** the Flowsheet of Pyrite Recovery from Tailings

Fine tailings could originate from a dry or a wet separation process such as flotation, but in either case, it should be screened and the oversize should be removed. The surface of pyrite is frequently oxidized which means a possible difficulty of flotation and less purity of the final pyrite product. Tailings material is fed into the scrubber, with a density of 70-80% solid to remove the oxidized surface than fed into flotation.

Since the particle size is not suitable for following flotation process and pyrite is not free from other materials, coarse tailings must be ground to flotation size by a ball mill and classified in a closed circuit.

After preparing into the prior unit, material from fine tailings or coarse tailings are fed into the conditioner where reagents are added into pulp. For pyrite flotation as a

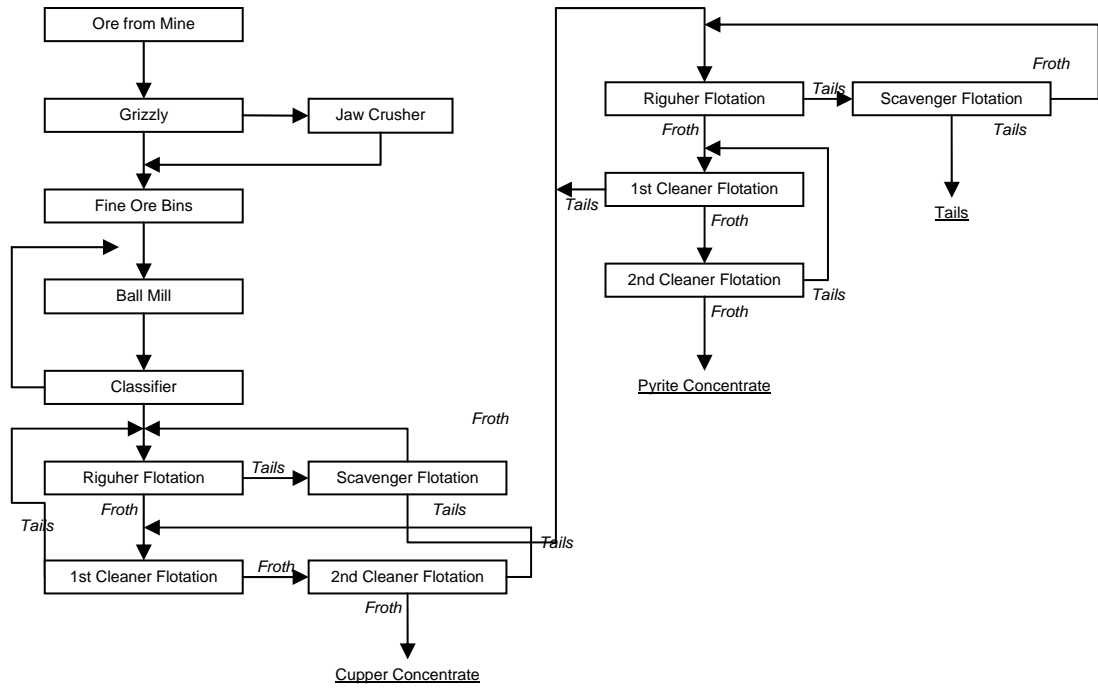
collector xanthate or dixanthogen is used in a pH of 6 or below. In order to produce the pH sulphuric acid is also added into the conditioner.

Reagents activated ore is fed into a rougher, scavenger and first step cleaner flotation cell to concentrate pyrite. The froth of rougher flotation flows into the first cleaner step, whereas the froth of scavenger flows either into rougher flotation in a close circuit or it is fed into the second rougher flotation in order to recover pyrite. If the froth material of first cleaner step includes middling particle, it will be reground in a close circuit with classifier and the overflow of the classifier is fed into the final cleaner flotation step to concentrate pyrite. Because the final cleaner flotation requires a pH from 6.5 to 7, lime can be added into the grinding circuit to neutralise the effect of the acid.

Besides recovering from tailings, pyrite is also concentrated as a by-product by selective flotation where the demand of pyrite is suitable for marketable sulphuric acid production. In Figure 2.5 the flowsheet of copper-pyrite selective flotation based on a production capacity of 100 tons per day is shown. The ore includes chalcopyrite and pyrite and appreciable value of gold whereas silica is the gangue mineral. The plant is designed for the production of copper-iron sulphide ore containing gold and for the clean pyrite production. Gold particles are mostly associated with copper but pyrite also contains appreciable amount of gold [9].

Mine run ore is crushed and ground to flotation size with a jaw crusher, followed by a ball mill-classifier close circuit. The first step of flotation is concentrating copper ore. Ground ore is fed into the rougher flotation including four flotation cells. The froth of rougher flotation is cleaned by cleaner flotation in 2 steps and copper concentrate is thickened and filtrated. The tailing of the rougher flotation is fed into the scavenger flotation to concentrate copper middling and the middling is fed in the second cell of rougher flotation. The tailing of copper scavenger flotation is conditioned by sulphuric acid to a neutral pH value and subsequently fed in the second stage of the flotation to produce pyrite concentrate. The cell arrangement is same as in the case of copper flotation. The pyrite concentrate is filtrated and roasted for the acid production from the expelled sulphur and to produce a calcine for cyanidation.

The pyrite concentrate containing low grade gold and silver is marketed for its sulphur content. Low value pyrite marketing depends on the transport costs and sulphur demand from acid industry. The pyrite containing high grade precious metals can easily be marketed to a smelter.



**Figure 2.5:** Flowsheet of Copper-Pyrite Selective Flotation [9]

### 3 SENSOR BASED SORTING

Since automated separation does not depend on the actual physical properties of materials, sorters are different from other concentration techniques, in which the separation process relies upon the chemical and physical properties of the material. The principle of sorting is to detect the particle properties, comparing the detected properties with predetermined criteria and separate the particles to the different directions by using an applied force unit.

The sorting process consists of following four interactive sub-processes [12]:

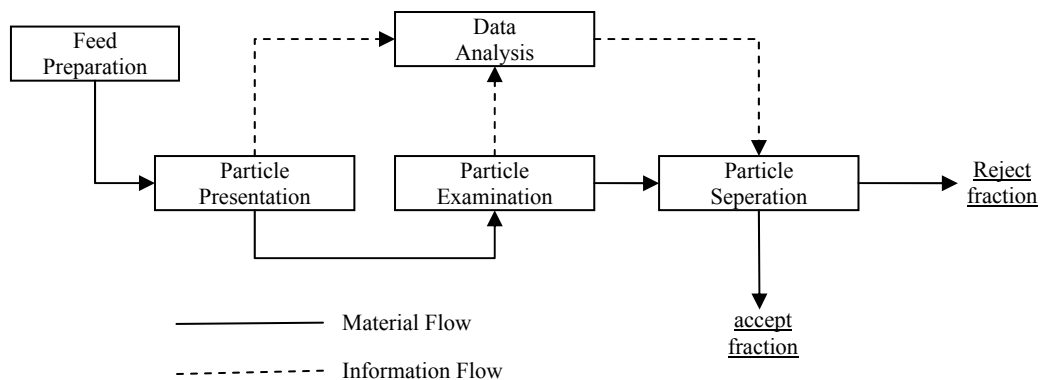
Particle Presentation

Particle Examination

Data Analysis

Particle Separation

Different sorters, developed by different manufacturers, are operating basically using the same or at least similar techniques. These interactive sub-processes are shown in Figure 3.1 and an example of sorting principle of an automated sorting machine is shown in Figure 3.2.



**Figure 3.1:** Sub-Process interaction of sorter machine [12]

*Particle Presentation:* Prepared and sized particles are fed on the belt usually by means of a vibrating feeder and either canalised into streams on the belt or randomly distributed. Stability of particles on the belt is important for the separation process. The preparation of the material consists of screening of the particles into a suitable size distribution, and if necessary washing and scrubbing of the particles in order to have a clean particle surface.

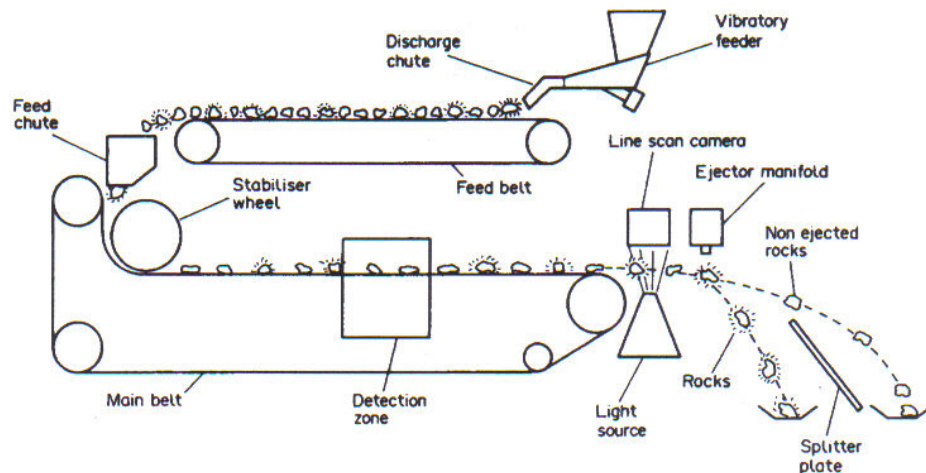
*Particle Examination:* Particles are carried by high speed belt running at 2-5 m/s or running on a chute through the detection zone in which the particles are detected and describing data for each particle are generated by detector.

*Data Analysis:* The data generated by detector are analysed by an electronic data processor, compared with predetermined criteria and the particles are identified either as accept or as reject fraction for the following separation.

*Particle Separation:* Particles, while they are in free flight at the end of the high speed belt, are separated by data processor activated fluid or air ejection valves. The processor activate the valves to blast at the same time when the selected particles on the point of intersection and this fluid or air force moves the particles from their natural trajectory into another.

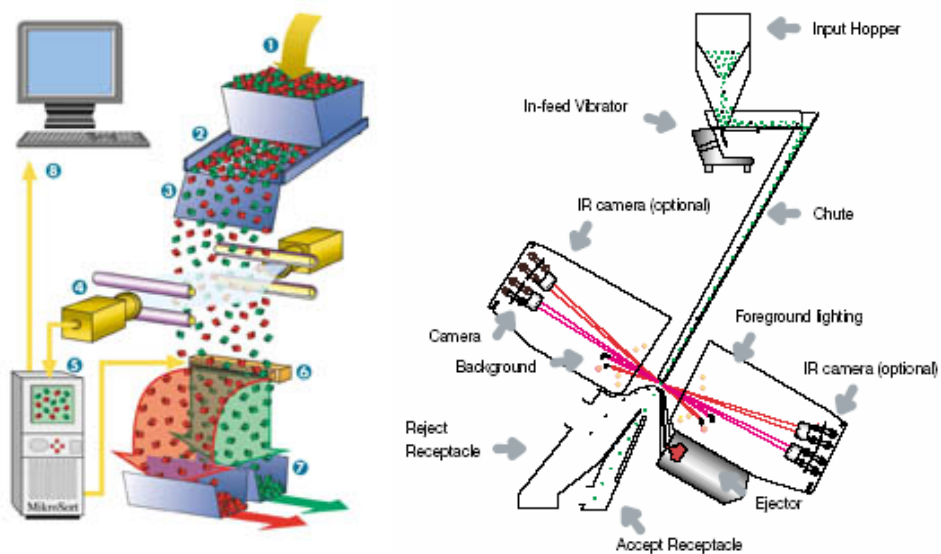
The applicability of sorting machines depends on the continuous identification of the particles within the time available for the examination and liberation of the accept fraction from the reject fraction at the size to be treated by the sorting machine. Also the throughput plays an important rule for the economical reasonable implementation of automated sorting.

Because basic of sorting is detecting and identifying every single particle of the feed, the feed material has to be a single layer and each particle has to have a certain distance from others in order to be presented separately to the detection unit. Distances between the particles should be more than minimum required distance for the successfully detection.



**Figure 3.2:** Functional principle of automated sorting machine [12]

This minimum distance is, e.g. for an optical sensor depending on the sensor around 1 pixel. To provide suitable feeding, two different types of sorters have been developed and are currently used. The feeding particles are presented either on a high speed belt with a velocity around 2 to 5 m/s so-called *belt-type-sorters* (Figure 3.2), or presented while sliding down a chute so-called *chute-type-sorters* (Figure 3.3). The particles are detected by the sorter either moving on the belt or chute or immediately after the belt or chute in free fall or ballistic curve [13].



**Figure 3.3:** Chute-type-sorters [14, 15]

### **3.1 Sensor Development**

The success of the separation process and application of sorters in the mineral industry depend on the available sensor equipment. The detection of the differences between waste and ore to discriminate accept and reject fractions is only possible by using a suitable detection unit.

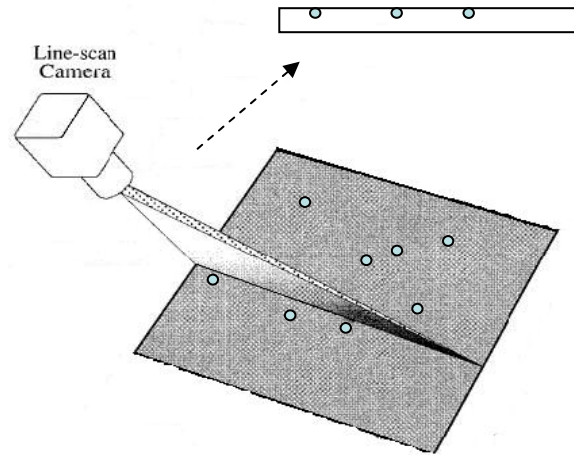
The sensor types that are currently being used and will be used for the sorting process are [13]:

- Optical Sensors,
- High-Sensitivity sensors which are used for detecting of weak visible light,
- X-ray Sensors,
- Infrared Sensors,
- Metal Detectors,
- Laser Induced Breakdown Spectroscopy and
- Laser Induced Fluorescence.

#### **3.1.1 Optical Sensors**

Optical sensors are used in sorting applications when ore and waste material have different optical properties such as colour, brightness, reflection or transparency. In Figure 3.4, the working principle of an optical sensor with a line scan camera is shown.

For most of the ores incident light from above is used in combination with a line scan camera but the sensor can only detect particle properties which are on the surface of the particle. Using a second camera as a so-called double side system, pictures from both sides can be taken in order to increase the detection accuracy. However, mineral distribution inside of the particles cannot be detected.



**Figure 3.4:** Schematic view of an optical sensor

The resolution of state-of-the-art cameras is relatively high which can detect around 0.1 mm on the object. But in case the mineral size are too small on the material matrix or the colour of both ore and waste material is too similar, the detection process For example, sulphides are hard to detect in the material matrix because of their too small mineral size distribution in the material.

On the other hand, transmitted light provide the detection of transparent or translucent minerals such as diamond and rock salt. Texture recognition systems can also be used in case the target and waste particles have similar colour and brightness but differ in their distribution pattern. In some cases, optical sensors can also be employed in combination with other sensors. For example metal detectors have to be combined with optical sensors to delimit the particles in a random feed.

Usually the surface of the particles has to be cleaned by water washing/scrubbing combined with screening in order to achieve reasonable results. Too much dust on the particles avoids the successful application of the optical sensors [13].

### 3.1.2 High Sensitivity Optical Sensors

Another optical property for discrimination between minerals is the fluorescence of minerals in a long or short wave UV light. Some minerals are fluorescent which is caused by activators that are mostly rare earth elements such as titanium, vanadium, chromium, and variety of other elements. The strength of the fluorescence also

depends on the power and spectrum of the UV light. The percentages of fluorescing minerals in some mineral groups are shown in Table 3.1.

**Table 3.1:** Percentage of Fluorescence minerals in each group [13]

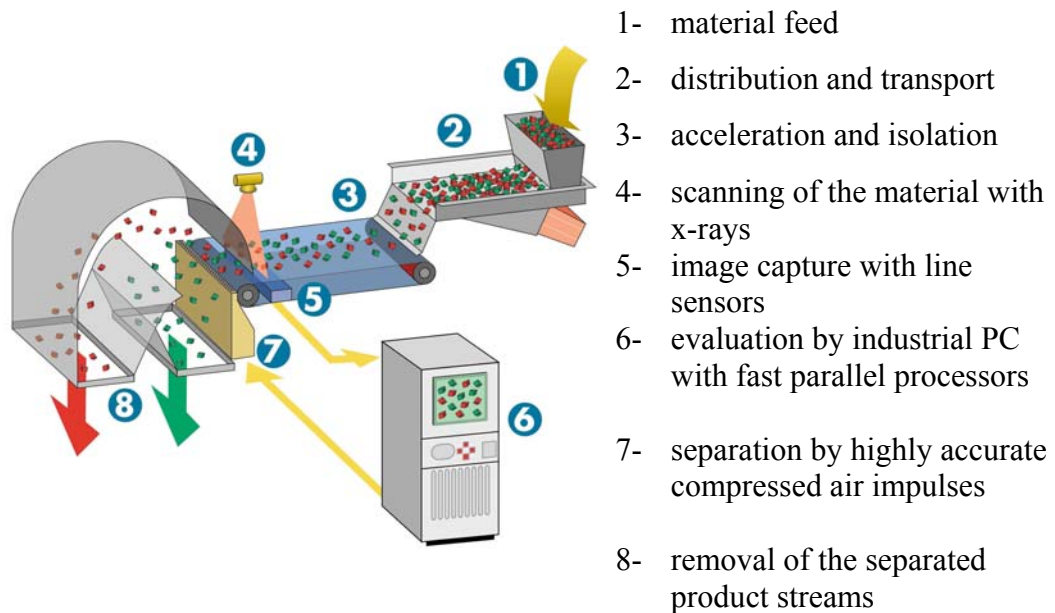
Mineral Group	Percentage With Fluorescence
Elements	<1%
Sulfides	5%
Sulfosalts	0%
Oxides/Hydroxides	5%
Halides	15%
Carbonates	30%
Borates	30%
Sulfates	10%
Phosphates/Arsenates	10%
Tungstates	15%
Silicates	20%

Fluorescent minerals on the material matrix can only be detected on the material surface as it comes along with the nature of optical sensors. Optical line scan cameras alone are not sufficient for these applications, high resolution cameras which produce a grey scale image are necessary to use with UV light for this application. The fluorescence can be strong when the source of the UV light is strong enough, so small piece of minerals can be detected by using high resolution line scan cameras. An example for the application of high sensitivity optical sensor is the sorting of scheelite ores.

### 3.1.3 X-Ray Sensors

Minerals, which contain elements of high atomic order, absorb x-rays more than elements with low atomic order. X-Ray radiation at certain energy levels penetrate the particles and pass them through. The intensity of remaining radiation is measured by sensitive and fast sensor arrays with the resolution of down 1mm

Particles are penetrated by radiation having a sufficient energy levels as a whole and ores containing by particles are projected onto the two dimensional area producing an image with greyscale differing locally and by intensity. The working principle of x-ray sorter is shown in Figure 3.5 [13].



**Figure 3.5:** Principle of Operation of X-Ray Sorting [16]

The influence of the different particle thickness can be eliminated by dual-energy x-ray method. With X-Ray scanning, minerals containing sulphide and also oxide metalliferrous can be detected. These sorters are working well with coal in the sense that different coal qualities can be determined. So far test with X-ray sorting oxide zinc metalliferrous ores have been carried out successfully and investigations with sulphide nickel and copper ores are ongoing [13].

The only disadvantage of x-ray sorters is that, x-ray sources are being used and saved by material thickness, this limit to a material thickness of about 60 mm limiting the possible throughput. They are also expensive because of the X-ray sources and regarding shielding because of safety at work.

### 3.1.4 Infrared Sensors

Infrared sensors can detect temperature differences of minerals below 1°K after previous energy input which can be heat convection or microwaves. Especially with microwave heating, different mineral containing ores are heated up differently with

the same energy input. These sensors and sorting techniques will be explained in more detail in the following chapters.

### **3.1.5 Metal Detectors**

Using metal detectors conductive materials and metals can be detected. The sensitivity depends on the distance between particle and sensor and frequency of detectors (2-200 KHz). With increasing distance, the detection sensitivity for the small particles decreases. Also penetration depth and sensitivity of small particles are in a relationship that with increasing frequency, the particle size, which can be detected, decreases; and the penetration depth into the particle decreases as well.

Metal detectors provide good sensitivity results with particles containing high metal grades, but with particles containing low metal grade or small sulphide particle size, measurements become inexact.

Metal detectors detect only the amount and size of the conductive material in a particle but give no information about the mineral grade. In order to sort particles with their conductive mineral grade, a second sensor should be installed to detect the two or three dimensional size of the particle such as optical sensors or a combination of a laser with an optical sensor.

Metal detectors are mostly used in the recycling industry to separate elemental metals and also used in the minerals industry especially for the detection and measurement of low grade sulphide ores.

### **3.1.6 Laser Induced Breakdown Spectroscopy (LIBS)**

Using LIBS systems the elemental composition of the plasma produced by to a single spot on the material surface focused pulsed laser can be determined. The photons of the plasma are measured by a spectrometer which can be calibrated for element specific spectral lines.

Regarding this technique, in order to measure surface of every single particle on the moving belt, it is necessary to have a diverging unit to scan the particles and determine the exact position of the particles on the belt and a focus position on the particle surface. Optical line scan cameras are used as a diverging unit.

Every laser pulse detects a small surface on the particle surface. ( $\ll 1 \text{ mm}^2$ ). In this case homogenous particle surfaces are scanned with high efficiency but the disseminated ores are difficult to detect if the laser beam meets with the particle surface where the associated mineral is placed, the result of detecting will be zero and the particle will be rejected. The other possibility is to hit the particle surface where the value mineral is placed. Splitting the laser beam into such sub-beams and detecting a particle on several places can improve this issue but can not overcome the zero detection. Therefore, LIBS is usually implemented in combination with other sensors such as LIF.

### **3.1.7 Laser Induced Fluorescence (LIF)**

LIF is used for analyzing a bulk material stream. An ultraviolet laser is used for exciting fluorescence on the mineral surface and spectrometers or photomultipliers are applied as detection unit with a resolution of down to 1 ns.

The disadvantage with the LIBS detector application is overcome with the larger detected surface. The laser beam can be widened up to a diameter of 80 mm, laser will still induce enough energy to excite fluorescence.

The advantage of this technology is the ability of producing fluorescence in the material which is not possible using standard UV lights. The measured signal is not a characteristic signal and has to be calibrated and matched for rock types separately for each deposit [13].

## **3.2 Application of Automatic Sensors**

Sensor based sorting devices have been installed and used in many industries such as food, mineral processing, and recycling industries.

In the minerals industry, sorters can be installed for pre-concentration, intermediate product production and final product production to help energy, environment, supply, quality problems [13].

*Intermediate and Final product production:* Automated sorting machines have been installed and used instead of hand picking process for suitable particle size

distributions. For example in diamonds processing, x-ray or optical sensors are being used for many years. Sorters used for industrial mineral processing.

*Pre-concentrations of minerals:* The purpose of pre-concentration of minerals is to only separate a certain amount of waste materials. This elimination process of broken conglomeration has the following advantages [13, 17]:

- For the same material production, the necessity of large concentrators can be avoided and capital costs will be reduced.
- Separation of waste materials before the concentration process reduces operation costs.
- Milling of waste materials will be avoided.
- Separation of waste materials in the underground reduces hoisting costs and storage in underground reduces the environmental effect and waste treatment costs.
- At open-cast mines, the elimination of the waste near production reduces transporting costs.
- Better process recovery.
- Installing a pre-concentrator increases the production capacity of the processing plant.
- The treatment of Uneconomic low grade mineral deposits becomes economically feasible.

On the other hand the disadvantages of an additional pre-concentration step are [13, 17]:

- Installing and maintenance costs of the pre-concentrator.
- Sizing of feeding material for the pre-concentrator.
- Sometimes washing and drying of the feeding materials before pre-concentration to have a clean particle surface for the sensor.

- Sometimes it is necessary to have a clean area to increase the sensor efficiency.
- Losing value minerals at the pre-concentration steps.
- Not applicable for the well disseminated minerals.

Energy consumption of an automated sorting machine as a pre-concentrator depends on the particle size and weight and is about 1-3 KWh/t mostly for compressed air during the separation process, while the grinding consumption of one ton waste material to flotation size is around 12-15 KWh/t [13].

### **3.3 Received (and Real) Limits to Sorter Application**

Two critical criteria are crucial for the success of automated sorting techniques [18]:

1. The accept fraction must be liberated from reject fraction at the size to be treated by sorting machine.
2. Both fractions must be consistently identifiable within the time available for examination by the machine.

Especially for pre-concentration process the former criterion is “economic liberation” where the liberation process is based on mineral grade rather than ore/waste liberation and where the economic criteria can be changed along with the economic conditions.

There are three main criteria limiting the application of a sorter. These reasons are put forward by the minerals processing industry not to consider the use of sorting machines. These are process, economic and operational limits [12, 18] and are explained in the following sections.

### **3.3.1 Process limits**

#### **Feed Preparation Requirements**

For an efficient sorting operation the feeding material is required to be washed and closely sized. Sorter applications require a prior screening process and a washing if require and/or a scrubbing process to clean particle surface for presentation to the sorter.

#### **Narrow Feed Size Range**

For an optimal sorting efficiency the top-bottom size range of each feed particle must not exceed a ratio of 3:1.

#### **Throughputs**

For applications of -120+60 mm feeding material, a sorter usually treats around 85-100 t/h, for -60+30 mm material feeding this capacity will be around 30-40 t/h. These throughputs are low if being compared with large crushing equipment or drewboy separators.

#### **Sorter Efficiencies**

Typically, sorters cannot achieve 100% efficiency in a single pass. However, using the correct discrimination criteria the efficiency of sorters is more than equivalent operations running without a sorting process.

#### **Ore Variability Limits**

Although these cases rarely occur, the variability of the headfeed may preclude the application of automated sorting.

Any material considered for sorting must have a range of variation suitable to the sensing devices of the sorter [18].

#### **Fine Headfeed Limits**

Due to sorting needs, washed and screened feed and more sorters requirement with decreasing feed size, friable or weathered deposits are not suitable for sorting

operations. If over-enthusiastic blasting during mining operations causes the fine headfeed, it may be the advantage to consider mining and processing relative costs. It is recognised that, because of rock mechanics factors the mill feed is finer with deep mining operations.

### **Autogenous Mill Options**

While autogenous milling simplifies the liberation process, it may or may not be efficient or economical than crushing / screening / sorting / milling depending on individual circumstances. If the option of autogenous milling is preferred it still leaves place for sorting. Many mines use pebble ports in their autogenous mills to remove critical or near-critical size material which is then crushed and returned to the mills. If this material is sorted before crushing then only the valuable material will need to be crushed while the barren material can be discarded. As a consequence, sorting may still be applied in the milling circuit with use of autogenous milling.

### **Lack of Discrimination Techniques**

The lack of reliable, applicable discrimination techniques is usually not caused by the non-existence of such methods, but mostly due to the fact that these techniques have not found their way into sorting machines yet [18].

## **3.3.2 Economic Limits**

### **Size of Deposit**

Large mining operations require a large number of sorters which requires a huge investment and also maintenance costs.. On the other hand, small mining operations are ideal for sorter applications, but small mine operations are put off by costs of the feed preparation and sorter plant. Instead of large sorter machines, small mobile type sorters are ideal for small mine operations.

### **Capital Costs**

Compared to other capital equipment, sorters are relatively expensive. The capital costs of sorters are not too expensive as other concentration machines with same amount of production capacity which is explained with cost/benefit ratio [12].

## **Operating Costs**

Operating costs of sorter is compressed air costs depending on the particle size and percentage of the material being ejected. For example for -120+60 mm material it is necessary to have a 170 KW compressor which will cause costs of around 1 USD/t treated material.

### **3.3.3 Operational Limits**

#### **Difficult to maintain**

Especially for small and isolated installations, it can be difficult to maintain sorters due to outmoded and inappropriate electronics and poor support from manufacturers. Using new electronics, appropriate design and a sufficient level of sorter field support from the manufacturer, new generation sorters overcome these difficulties [18].

#### **Simpler / Cheaper Process Options**

In case there is a cheaper process option available, this option must be preferred. Simplicity of operation is not a value factor dependent on the circumstances. With the development of new discrimination techniques, new feed presentation techniques, ejector technology, computerisation technology, new sorters will be developed and costs of having a sorter will be cheaper [18].

## 4 MICROWAVE

### 4.1 Function of Microwave

The term “microwave” is used to designate electromagnetic waves with a frequency between 300 MHz and 300 GHz corresponding to wave lengths ranging from 100 cm to 1 mm. The microwave spectrum is located between the infrared and radio spectrums. Microwaves frequencies include three bands “ultra high frequency (UHF)”, “super high frequency (SHF)” and “extreme high frequency (EHF)” according to recommendations of the international radio consultative committee (Table 4.1) [19]. However, certain frequencies for industrial, scientific, medical and instrumentations applications are licensed by the Federal Communication Commission [20].

**Table 4.1:** Microwave Band Frequency and Wave Length

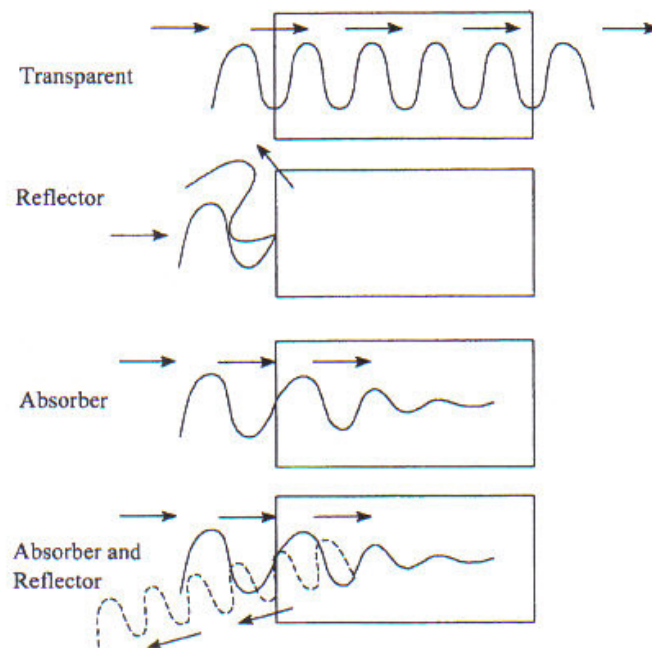
<b>Frequency Band</b>	<b>Wave Length Band</b>	<b>Designation</b>
0.3 to 3 GHz	1 to 0.1 m	Ultra High Frequency (UHF)/Ultra Short Waves
3 to 30 GHz	10 to 1 cm	Super High Frequency (SHF)/Super Short Waves
30 to 300 GHz	10 to 1 mm	Extreme High Frequency (EHF)/Extreme Short Waves

Microwaves are characterised by short wave lengths and large bandwidth and due to these properties, microwaves are used in many applications such as because of transmission in ionosphere and reflection from metal surface in radar technology, microwave heating and microwave resonance in atomic, molecular, nuclear systems and also in communications, in remote sensing, in basic and applied research, in astronomy, in biomedical applications.

## 4.2 Effect of Microwaves on Minerals

Basically, depending on the material properties, microwaves are reflected or absorbed by materials or simply pass through them without any changes (Figure 4.1).

Microwaves are reflected by some materials surfaces such as metal surfaces which have high conductivity. These types of materials are classified as conductive materials. Materials that reflect the applied microwaves are not heated under microwave radiation and therefore often used as conduits (waveguides) for microwaves.



**Figure 4.1:** Materials response under microwave radiation [3]

Some materials allow applied microwaves to pass through. This type of materials is classed as insulators also called “microwave transparent materials”. Some glasses, pottery, paper and most of the plastics are microwave transparent materials and are not heated during microwave radiation. These materials are often used in microwaves to support to material to be heated.

Other types of materials absorb the applied microwave energy and are easily heated; these are classified as dielectrics. Because of its polar molecular system, water is the best example for the dielectric materials [20].

### **4.3 Microwave Heating**

Microwave heating is an alternative to conventional heating because heat is generated directly in the material. Microwave ovens generally operate at a frequency of 2.45 GHz which correspond to a wave length of 12.2 cm. The energy of microwaves for domestic and industrial applications is usually about  $1.02 \cdot 10^{-5}$  eV which is lower than the energy of molecular bonds even Van der Waals forces that microwaves do not cause a breakage of chemical bonds [3].

Microwaves cause a molecular motion by migration species and/or rotation of dipolar species. The result of the molecular motion and rotation, the friction between molecules causes heating within the material. Microwave heating depends on the dissipation factor of the material. The Dissipation factor is a ratio of dielectric loss “loss factor” depends on the dielectric constant of the material and the dielectric factor is the ability of the material to retard the microwave energy as it passes through. The loss factor is the loss of the microwave energy in the material. Therefore, material having a high loss factor can be easily heated by microwave energy. The reasons for the microwave energy loss are ionic conduction and dipolar rotation within the material [20].

### **4.4 Microwave Attenuation**

When a beam of microwaves is applied to a piece of rock, the waves pass through the material and will be attenuated while passing through the rock. The degree of attenuation depends on the dielectric and electrical loss characteristics of the material and the absorbed microwave energy is transformed into heat inside the material.

With increasing frequency of applied microwaves, energy absorbed by the material increase so that attenuation of the signal after pass through the material increases. On the other hand the heat generated inside the material increase with increasing absorbed energy.

The attenuation is measured in decibel (dB) which is a logarithmic unit of the applied frequency divided by the attenuated frequency.

## 5 EXPERIMENTS

For the test procedure artificial samples were produced containing chalcopyrite, pyrite, which are representing value mineral in the ore, and a mixture of quartz, feldspar and plaster binder, representing gangue material in the ore. These samples were tested with the following two test procedures in order to discriminate the different microwave behaviour of the minerals.

Microwave Heating

Microwave Attenuation

### 5.1 Samples

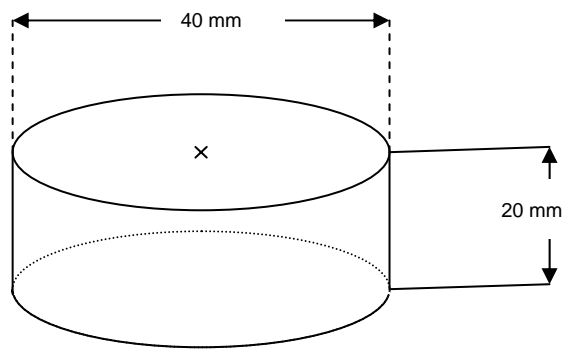
For the test program, two sets of artificial samples with different mixtures of ore and gangue material were prepared. As ore mineral chalcopyrite and pyrite were used for each sample sets and both sets have a mixture of quartz, feldspar and suitable plaster material (cement) as gangue material. Quartz and feldspar were crushed and screened to -2+1 mm and mixed with the binder material. Each set also has ore mineral with four different mineral grades combined with four different particle grain size ranges, shown in Table 5.1.

**Table 5.1:** Ore combination in the sample matrix

Mineral Grade [%]	0.40	0.80	1.60	3.20
Particle Size Range [ $\mu$ ]	-2000+1000	-1000+500	-500+250	-250+125

In total, 33 samples, from each set 16 samples and one sample without any metalliferous mineral were produced.

The samples are cylindrical shape with a diameter of 40 mm and thickness of 20 mm. (Figure 5.1).



**Figure 5.1:** Shape of samples

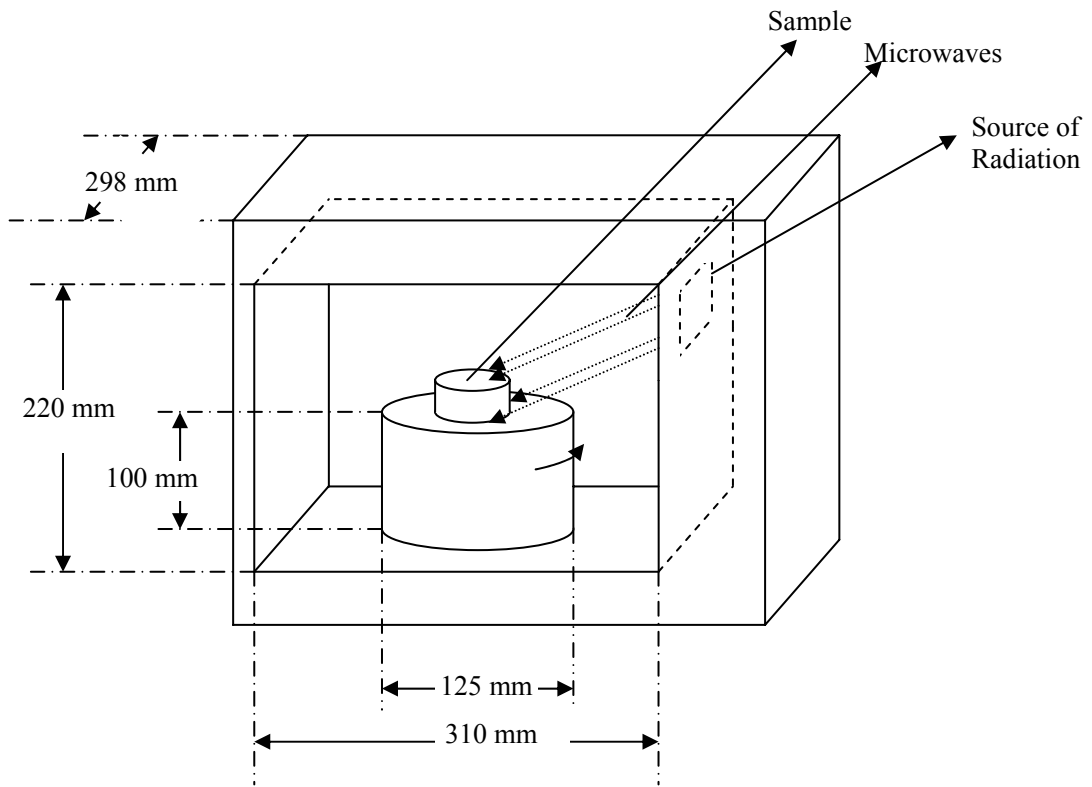
## 5.2 Microwave Heating Experiments

This part of the experiments were carried out in order to discriminate the microwave heating behaviours of sulphides and to investigate application possibility of an infrared sensor in sorting technique combined with previous microwave heating for this type of mineral.

In these experiments, the samples were placed into the heater chamber and heated for 20 seconds by microwave energy and after the heating process scanned by an infrared thermometer immediately and the absorbed energy was determined as measured temperature. The scanning process was repeated after every minute to determinate the decay of the absorbed energy.

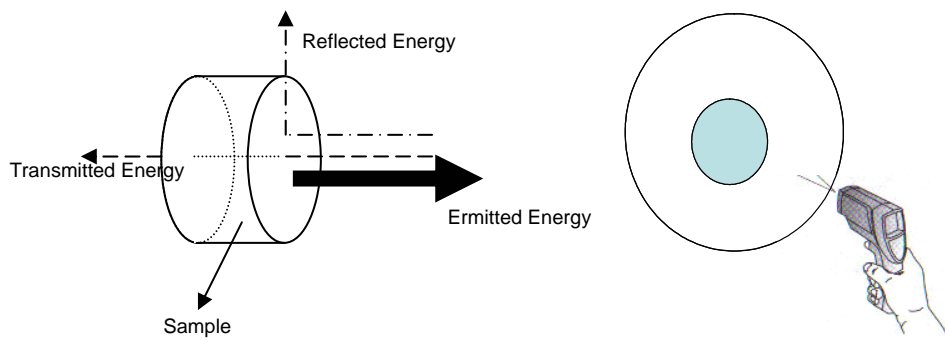
In order to investigate temperature decay of each sample, the samples were placed outside the heater, and the temperature decay was measured at room temperature.

The microwave heater used in the experiments is shown in Figure 5.2. The samples were placed in the middle of the heater chamber and microwaves were produced at 900 Watt with a frequency of 2.455 GHz. During the heating process, the samples were rotated in the middle of the chamber. The reason for this is to provide better absorption of the microwaves by samples. The rotating frequency of the samples is 6 repeats per minute.



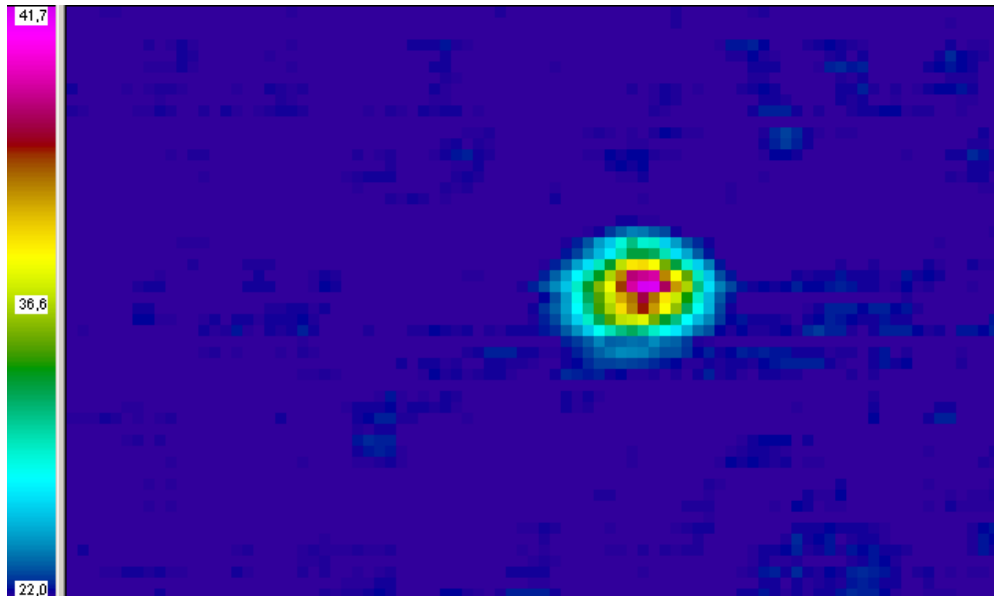
**Figure 5.2:** Microwave Heater

The working principle of the infrared thermometer is the same as an infrared camera. The thermometer's optics senses, collects and focuses the emitted, transmitted and reflected energy on the scanning surface into the detector. The electronic unit of the thermometer translates the scanned information into a temperature value. The working principle of both, infrared camera and infrared thermometer is shown in Figure 5.3. In the previous study surface temperatures of the samples were measured with the thermometer at a distance of around 50 mm which provides scanning an area with a diameter of around 10 mm.



**Figure 5.3:** Principle of infrared detection

The working principle of infrared camera is the same as the infrared thermometer. Infrared camera visualises the temperature results into dimensional colour system, from blue to red. One example of infrared camera scan is shown in Figure 5.4.



**Figure 5.4:** Visualised result of infrared scanning by infrared camera

The microwave heating behaviour of the samples was investigated regarding different mineral grades and particle size ranges for chalcopyrite and pyrite . The results are shown as temperature decay curves as a function of cooling time after microwave heating. These curves are shown for each sample regarding both the mineral grade and the grain size range.

### **5.3 Microwave Attenuation Experiments**

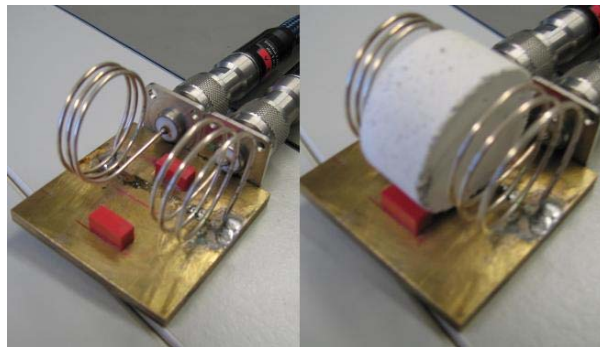
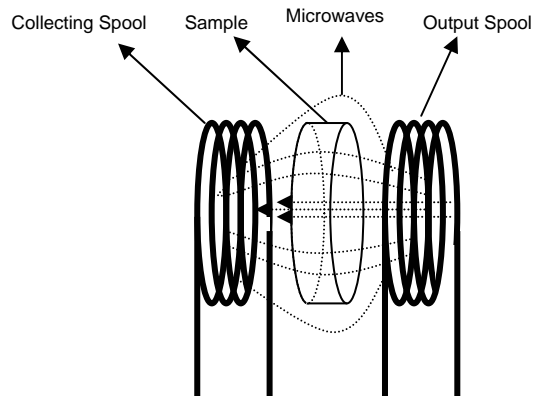
In this part of the study, low power microwave energy was used to discriminate the rate of absorbed microwave energy by the artificial samples.

When microwave beam applied to a rock, the signal will be attenuated depending on the dielectric and electrical loss characteristics of the rock. In this study these characteristics of artificial samples depending on the mineral grade and particle size distribution was investigated by measuring of the attenuation of applied microwaves.

Artificial samples were placed between an antenna and a sensor. The antenna emits microwave radiation of different wavelength at deferring energy levels and the receiving sensor can measure the deviation of the frequency and the attenuation of

the signal in order to discriminate the correlation between attenuation and the mineral grade/grain size range. The measurements were made in a broad frequency range from 50 MHz to 220 MHz.

The principle of the attenuation test set-up and the device used in these experiments are shown in Figure 5.5.



**Figure 5.5:** Microwave attenuation test set-up

The decay of the signal was measured in decibel (dB) as a function of frequency. The evaluation was performed with respect to the relation between attenuation and mineral grade/grain size range to the applied frequencies.

## **6 RESULTS**

In the following sections the results of both, the microwave heating and microwave attenuation tests will be shown followed by a discussion of the relation of absorbed energy and mineral grade/particle size range.

### **6.1 Microwave Heating**

The results for the microwave heating experiments are shown as temperature curves as a function of cooling time. The curves are presented for each mineral grade varying the particle size and vice versa to show whether there is a relation between these factors and the measured temperature.

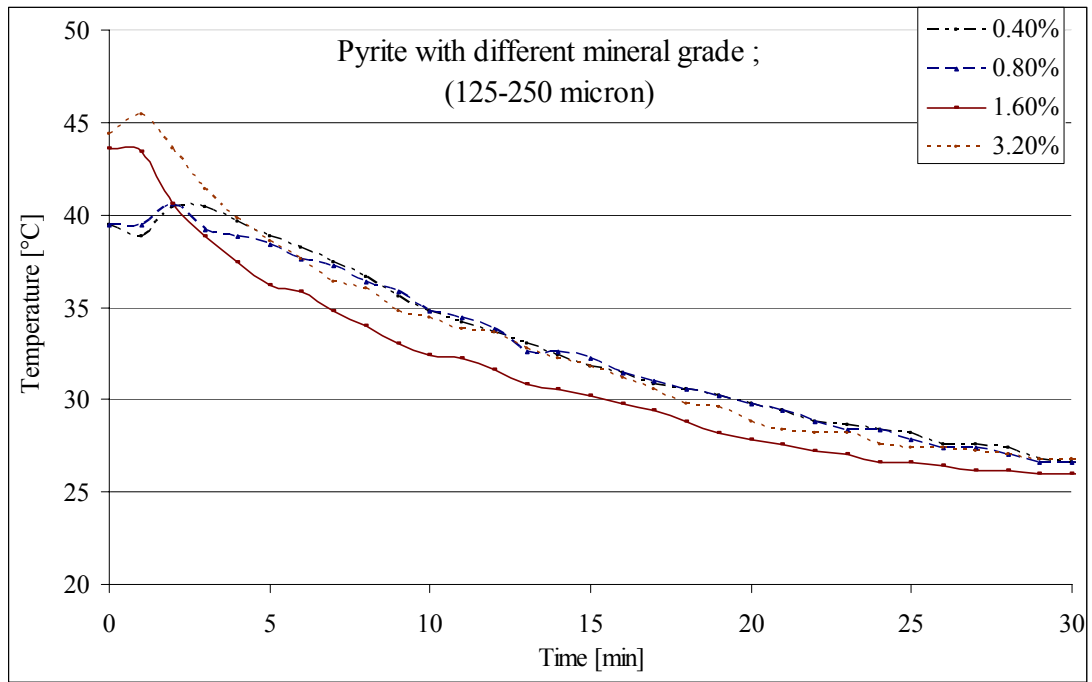
In addition to that, for each experiment, the temperature directly after heating, the maximum temperature and the temperature after 30 min is presented in tables for every group as described above.

The temperature of the samples right after microwave heating differs from the maximum temperature. This occurs, because the heat is produced inside the sample and reaches the border of the sample after a certain period of time. Surface temperatures of the all samples reach more or less the same degree after around 30 min of cooling.

#### **6.1.1 Constant Grain Size Variable Mineral Grade**

Cooling temperature results for pyrite after 20 seconds microwave heating process are shown in Figure 6.1, 6.2, 6.3 and Figure 6.4

In Figure 6.1, the cooling curve of -250+125  $\mu$  pyrite is shown with the different pyrite grades and Table 6.1 shows minimum, maximum temperature of the sample and the temperature, right after heating process. It is seen that with increasing mineral grade, the temperature increases.

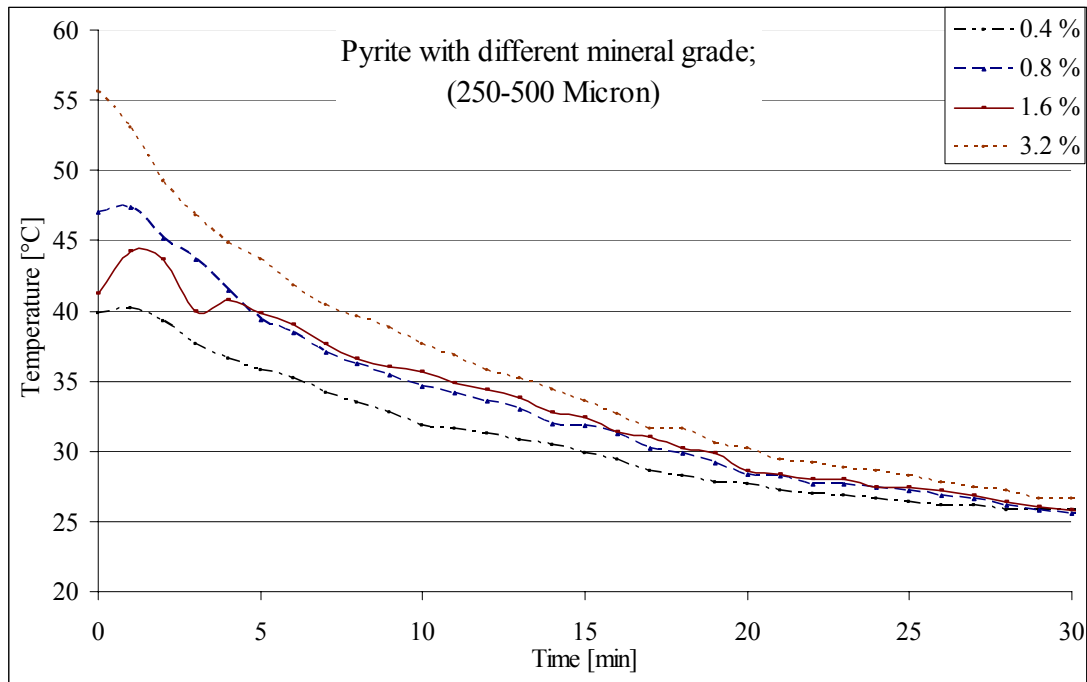


**Figure 6.1:** Cooling temperature of pyrite with  $-250+125\mu$ , having different mineral grade

**Table 6.1:** Microwave heating temperatures of  $-250+125\mu$  pyrite

	Mineral Grade			
	0.4	0.8	1.6	3.2
Temperature after Microwave	39.4	39.4	43.6	44.4
Max Temperature	40.4	40.6	40.8	44.4
Min Temperature(After 30 min)	26.6	26.6	26.0	26.8

Results for pyrite samples containing  $-500+250\mu$  particles are same as the others. Heating temperature is direct proportional with mineral grade. But in Table 6.2 and Figure 6.2 it is seen that, the temperature of pyrite with 0.8% mineral grade is higher than the temperature of pyrite sample with 1.6% mineral grade. The most likely reason for that the mixture of the artificial sample; that means the possibility of a heterogeneous mixture of pyrite particles in the artificial sample. Another reason for that, measuring point of the temperature, it is possible that surface temperature of the sample differing on measuring point depending on the particle distribution in the sample.



**Figure 6.2:** Cooling temperature of pyrite with 250-500 $\mu$ , having different mineral grade

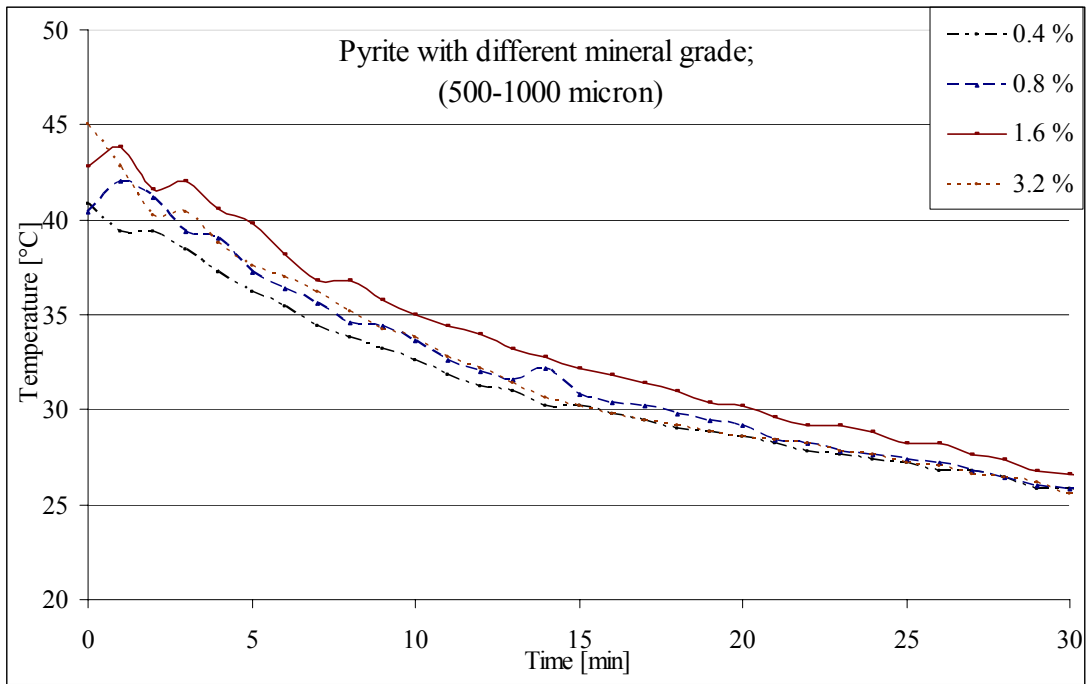
**Table 6.2:** Microwave heating temperatures of -500+250 $\mu$  pyrite

	Mineral Grade			
	0.4	0.8	1.6	3.2
Temperature after microwave	39.8	47.0	41.2	55.6
Maximum temperature	40.2	47.4	44.2	55.6
Minimum Temperature (after 30 min.)	25.8	25.6	25.8	26.6

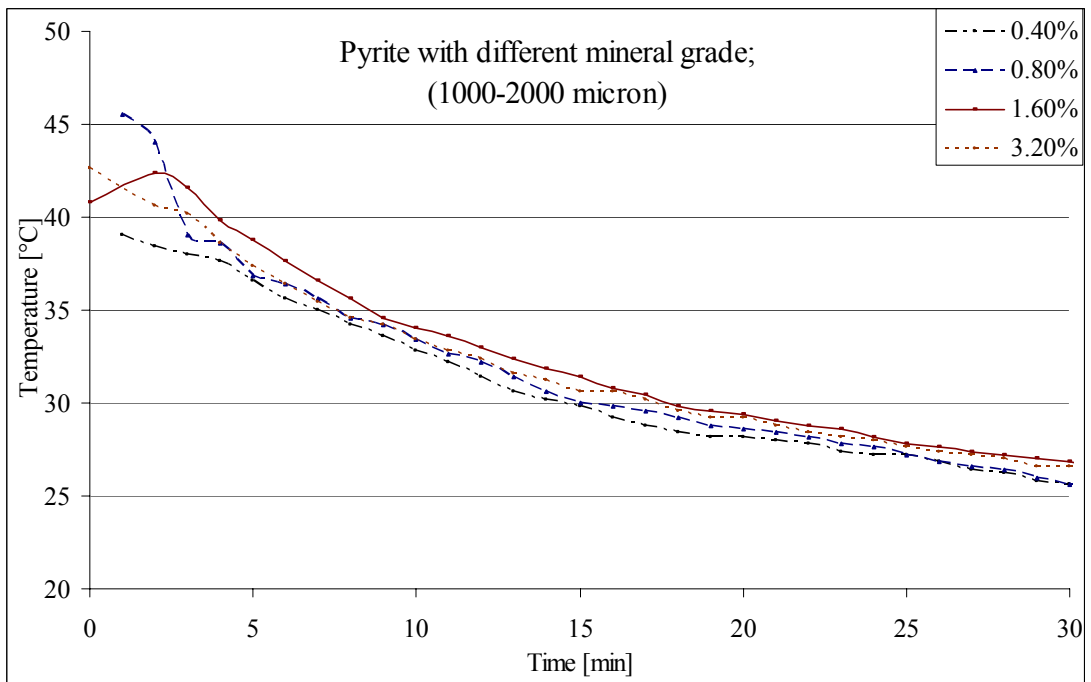
The result of microwave heating is not different for pyrite samples having -1000+500 $\mu$  particle size range. These results are shown in Figure 6.3 and Table 6.3.

**Table 6.3:** Microwave heating temperatures of -1000+500 $\mu$  pyrite

	Mineral Grade			
	0.4	0.8	1.6	3.2
Temperature after microwave	40.8	40.4	42.8	45.0
Maximum temperature	40.8	42.0	43.8	45.0
Minimum Temperature (after 30 min.)	25.8	25.8	26.6	25.6



**Figure 6.3:** Cooling temperature of pyrite with 500-1000 $\mu$ , having different mineral grade



**Figure 6.4:** Cooling temperature of pyrite with 1000-2000 $\mu$ , having different mineral grade

The graphic of -2000+1000 $\mu$  particle size distribution samples has the same results as -500+250 $\mu$  curves. Sample which have 0.8% mineral grade has, absorbed energy

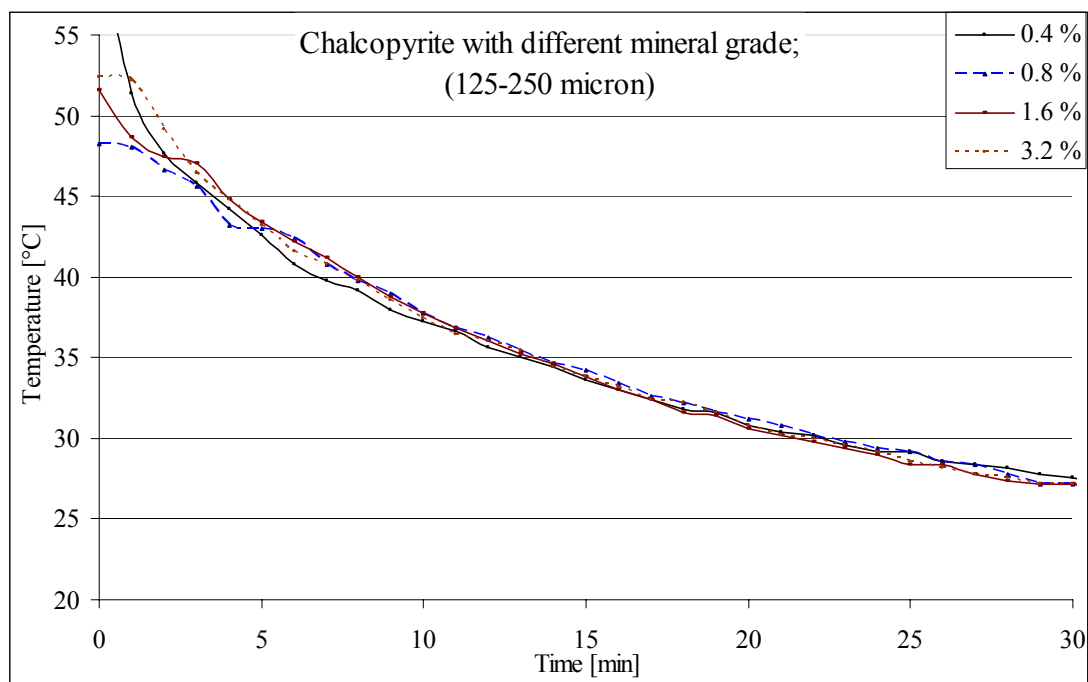
more than sample with 1.6% mineral grade. The possible reason is the same that the mineral particles are not distributed in the artificial sample. The effect of distribution of mineral and particle size will be investigated below.

**Table 6.4:** Microwave heating temperatures of -2000+1000 $\mu$  pyrite

	Mineral Grade			
	0.4	0.8	1.6	3.2
Temperature after microwave	39.0	45.5	40.8	42.6
Maximum temperature	39.0	45.5	40.4	42.6
Minimum Temperature (after 30 min.)	25.6	25.6	26.4	26.2

Following graphics and tables shows the effect of mineral grade in the microwave heating for chalcopyrite.

From graphics and tables it can be clearly seen that chalcopyrite absorbs microwave energy more than pyrite.



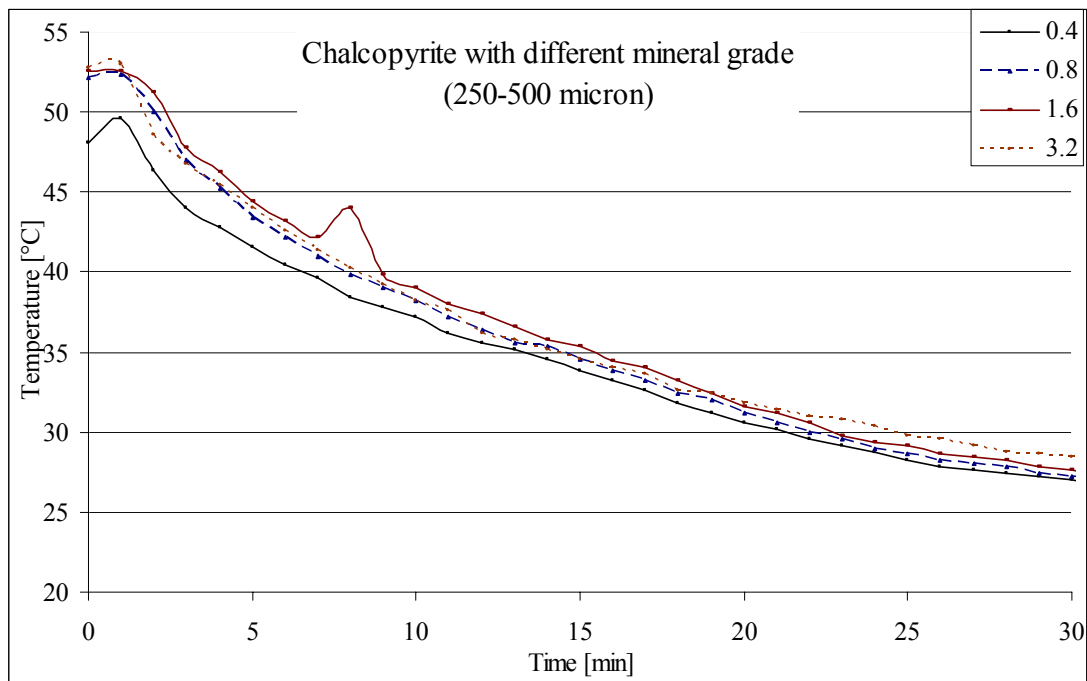
**Figure 6.5:** Cooling temperature of chalcopyrite with 125-250 $\mu$ , having different mineral grade

The results of chalcopyrite which have a particle size range between 125 and 250 microns are shown in Figure 6.5 and Table 6.5 Sample having 0.4% mineral grade

were heated rapidly and more than others on the other hand cooled rapidly as well (Figure 6.5, Table 6.5 ).

**Table 6.5:** Microwave heating temperatures of -250+125 $\mu$  chalcopyrite

	Mineral Grade			
	0.4	0.8	1.6	3.2
Temperature after microwave	60.4	48.0	51.6	52.2
Maximum temperature	51.4	48.2	48.6	52.4
Minimum Temperature (after 30 min.)	27.6	27.2	27.2	27.2

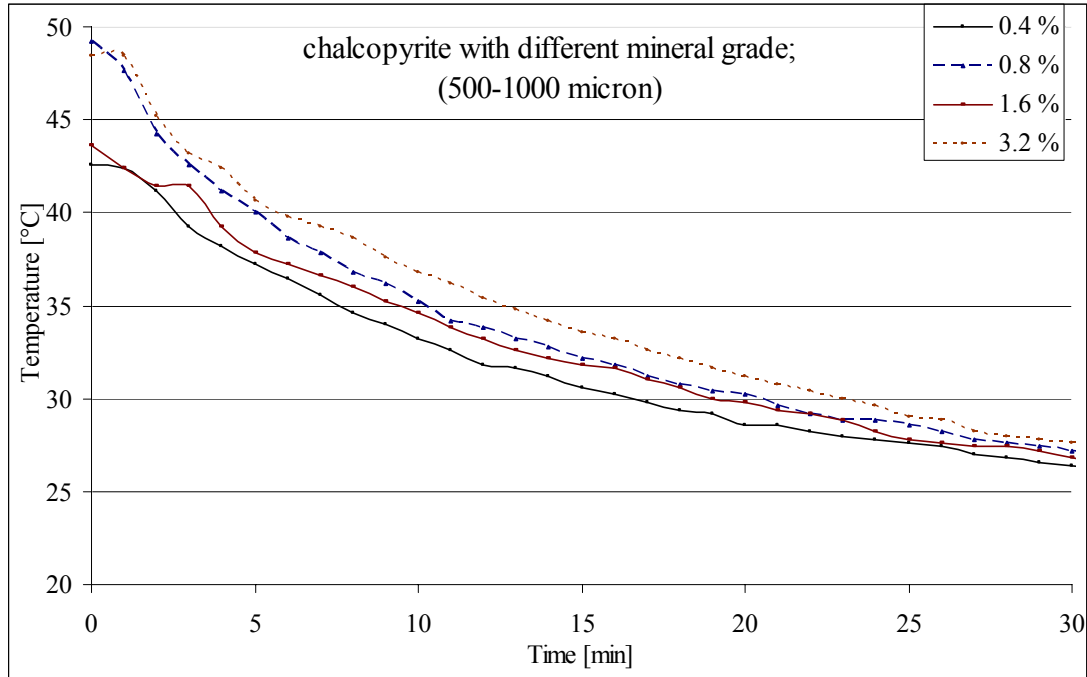


**Figure 6.6:** Cooling temperature of chalcopyrite with 250-500 $\mu$ , having different mineral grade

From the results of -500+250 $\mu$  chalcopyrite, it is seen that the surface temperature of sample with 3.2% mineral grade has the best heating range and it is also easily seen from the table and graphic that the heating temperature of chalcopyrite is proportional with the mineral grade but the differences at the surface temperature of samples is not much, deferring around 1 °C. At the cooling curve of 1.6%, there is a peak point at 8<sup>th</sup> minute; the reason of this could be the measuring point and heterogeneous mineral distribution of that point (Table 6.6, Figure 6.6).

**Table 6.6:** Microwave heating temperatures of -500+250 $\mu$  chalcopyrite

	Mineral Grade			
	0.4	0.8	1.6	3.2
Temperature after microwave	48.1	52.2	52.6	52.8
Maximum temperature	49.6	52.4	52.6	53.0
Minimum Temperature (after 30 min.)	27.0	27.2	27.6	28.4

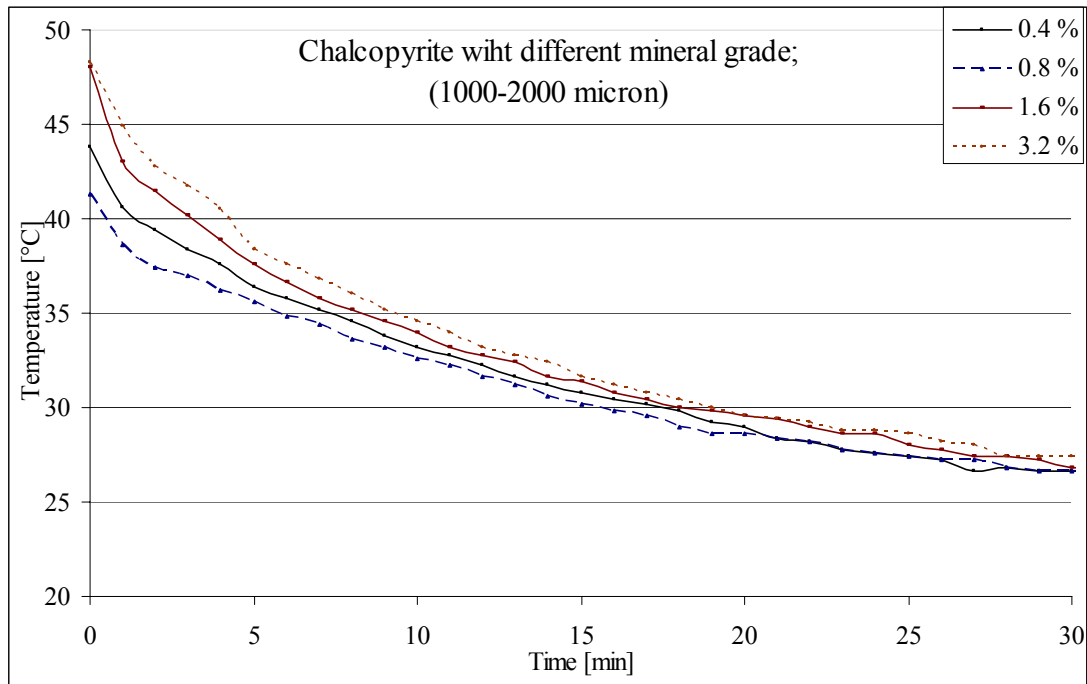


**Figure 6.7** Cooling temperature of chalcopyrite with 500-1000 $\mu$ , having different mineral grade

In Figure 6.7 and Table 6.7 sample with 8% mineral grade has the maximum heating grad but same sample has a rapid cooling grad and after 1-2 minutes temperature of 0.8% chalcopyrite sample is less than 3.2. There is another reason depending on the mineral distribution in the sample. When the minerals are closed to the sample surface heat reach to the surface faster and also be cooled faster

**Table 6.7:** Microwave heating temperatures of -1000+500 $\mu$  chalcopyrite

	Mineral Grade			
	0.4	0.8	1.6	3.2
Temperature after microwave	42.6	49.2	43.6	48.4
Maximum temperature	42.6	49.2	43.6	48.4
Minimum Temperature (after 30 min.)	27.2	26.8	27.6	26.6



**Figure 6.8:** Cooling temperature of chalcopyrite with 1000-2000 $\mu$ , having different mineral grade

**Table 6.8:** Microwave heating temperatures of -2000+1000 $\mu$  chalcopyrite

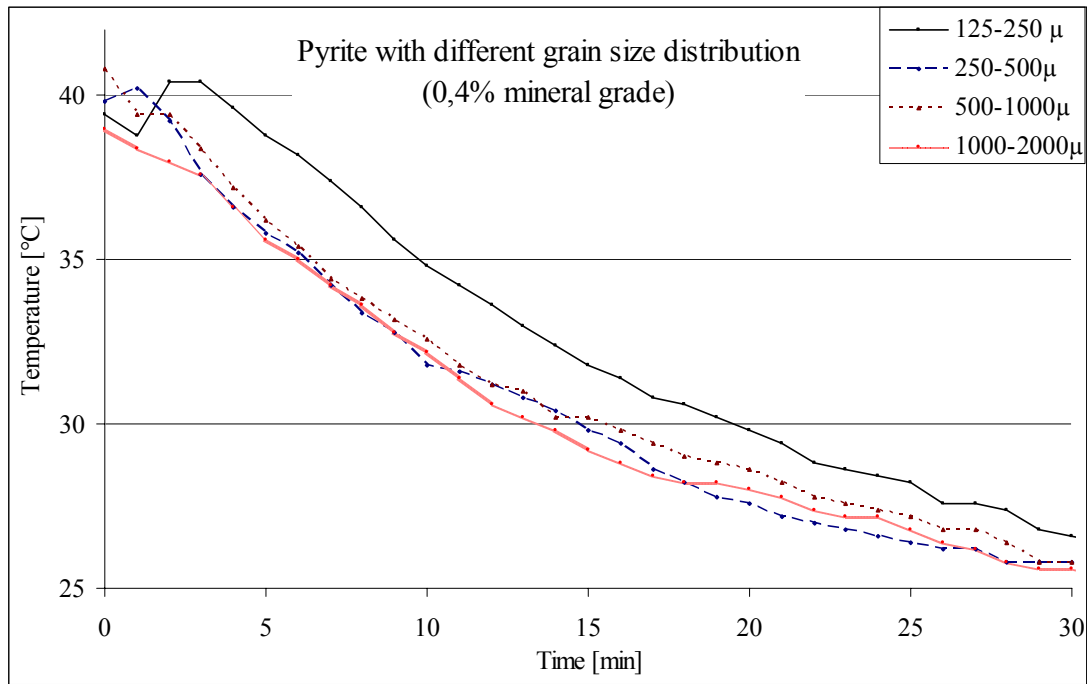
	Mineral Grade			
	0.4	0.8	1.6	3.2
Temperature after microwave	46.2	41.8	48.0	48.2
Maximum temperature	46.2	44.4	48.0	48.8
Minimum Temperature (after 30 min.)	26.6	27.2	27.4	28.0

Table 6.8 and Figure 6.8 show the cooling curves of chalcopyrite samples with the particle size distribution -2000+1000 $\mu$ .

### 6.1.2 Constant Mineral Grade Variable Grain Size

The effect of grain size is direct proportional with the heating. But it also depends on the particle distribution and position of the particles in the rock. Because of the particles near sample surface, some samples were heated more than others even though they have less mineral grade. On the other hand this type of particles was cooled faster because of, conductivity of heating energy from inside to outside.

With following tables and graphics the effect of particle size range to microwave heating for pyrite and chalcopyrite will be discussed.



**Figure 6.9:** Cooling temperature of pyrite with 0.4% mineral grade for different grain size range

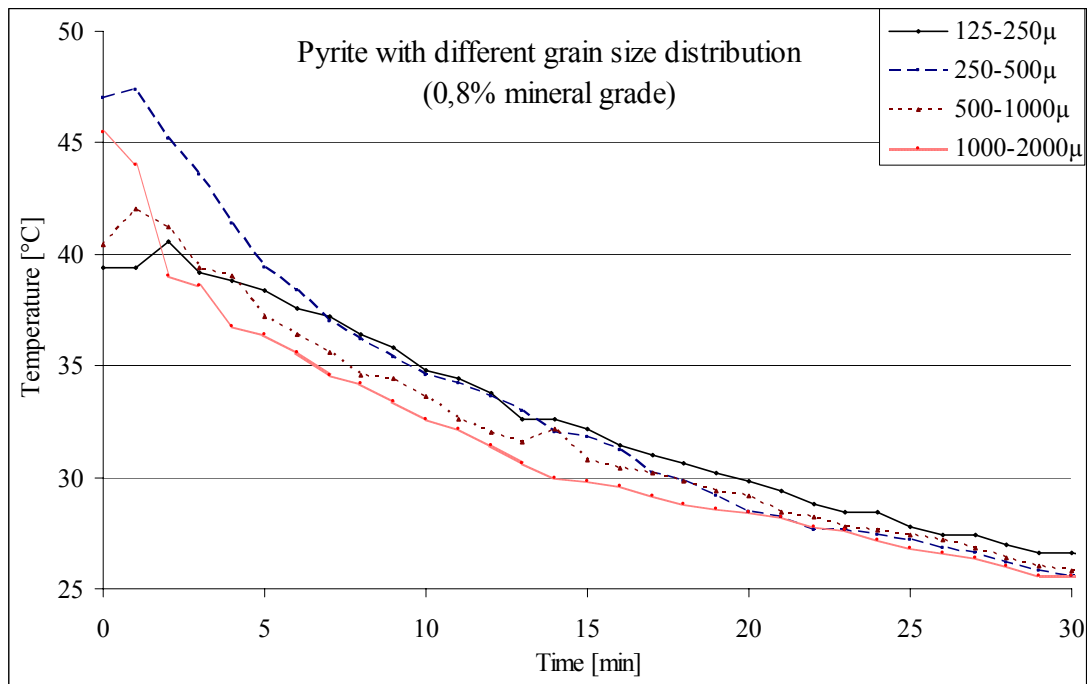
**Table 6.9:** Microwave heating temperature of 0.4% pyrite samples

	Size range			
	-250+125 (μ)	-500+250 (μ)	-1+0.5 (mm)	-2+1 (mm)
Temperature after microwave	39.4	47.0	40.4	45.5
Maximum temperature	40.6	47.4	42.0	45.5
Temperature after 30 min.	26.6	25.6	25.8	25.6

Result of pyrite Samples having 0.4% mineral grade but different size range, are shown in Figure 6.9 and some important temperature data, recorded during cooling, are shown in Table 6.9. It is fact that, samples which have smaller particle range have conducted heating energy better because of larger surface area. It is seen in the graphic of the sample having -250+125μ size range, have a peak point at the first cooling time. That means heat conducted from inside to the surface of the sample in this minute.

Table 6.10 and Figure 6.10 show the result of microwave heating and cooling of samples with 0.8% mineral grade. It is hard to say a relation between particle size range and absorbed energy from these results. The mixture problem discussed above cause the divergence between results but it could be said that the difference between

heating temperature after microwave and maximum temperature of samples are higher for smaller particle range samples.



**Figure 6.10:** Cooling temperature of pyrite with 0.8% mineral grade for different grain size range

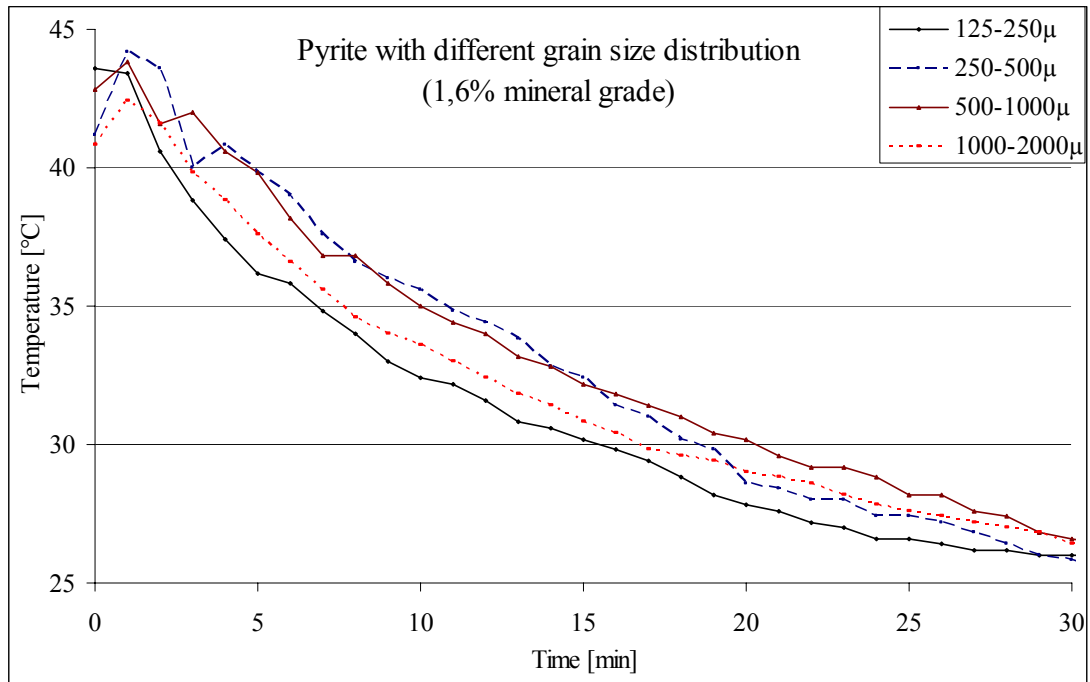
**Table 6.10:** Microwave heating temperature of 0.8% pyrite samples

	Size range			
	-250+125 (µ)	-500+250 (µ)	-1+0.5 (mm)	-2+1 (mm)
Temperature after microwave	39.4	39.8	40.8	39.0
Maximum temperature	40.4	40.2	40.8	39.0
Temperature after 30 min.	26.6	25.8	25.8	25.6

Result of heating for pyrite with 1.6% mineral grade are shown in Figure 6.11 and Table 6.11. Temperature differences for different samples having different particle size range are differing around 4°C. In the application of automated sorting with an infrared camera, it is possible to separate particles with a temperature differences above 1°C.

**Table 6.11:** Microwave heating temperature of 1.6% pyrite samples

	Size range			
	-250+125 ( $\mu$ )	-500+250 ( $\mu$ )	-1+0.5 (mm)	-2+1 (mm)
Temperature after microwave	43.6	41.2	42.8	40.8
Maximum temperature	43.6	44.2	43.8	42.4
Temperature after 30 min.	26.0	25.8	26.6	26.4

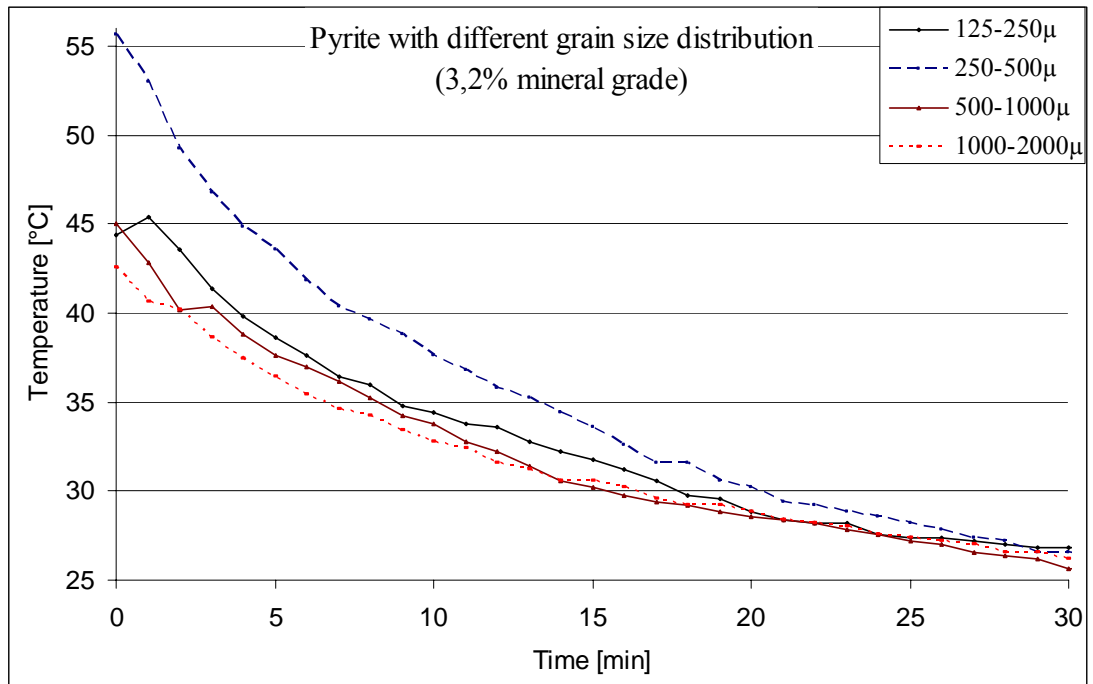


**Figure 6.11:** Cooling temperature of pyrite with 1.6% mineral grade for different grain size range

Results of the samples which have 3.2% mineral grade is same as other results stayed above except for -500+250 $\mu$  particle size range (Figure 6.12, Table 6.12). This sample has absorbed microwave energy and produced heating inside with the degree around 56°C.

**Table 6.12:** Microwave heating temperature of 3.2% pyrite samples

	Size range			
	-250+125 ( $\mu$ )	-500+250 ( $\mu$ )	-1+0.5 (mm)	-2+1 (mm)
Temperature after microwave	44.4	55.6	45	42.6
Maximum temperature	45.4	55.6	45.0	42.6
Temperature after 30 min.	26.8	26.6	25.6	26.2

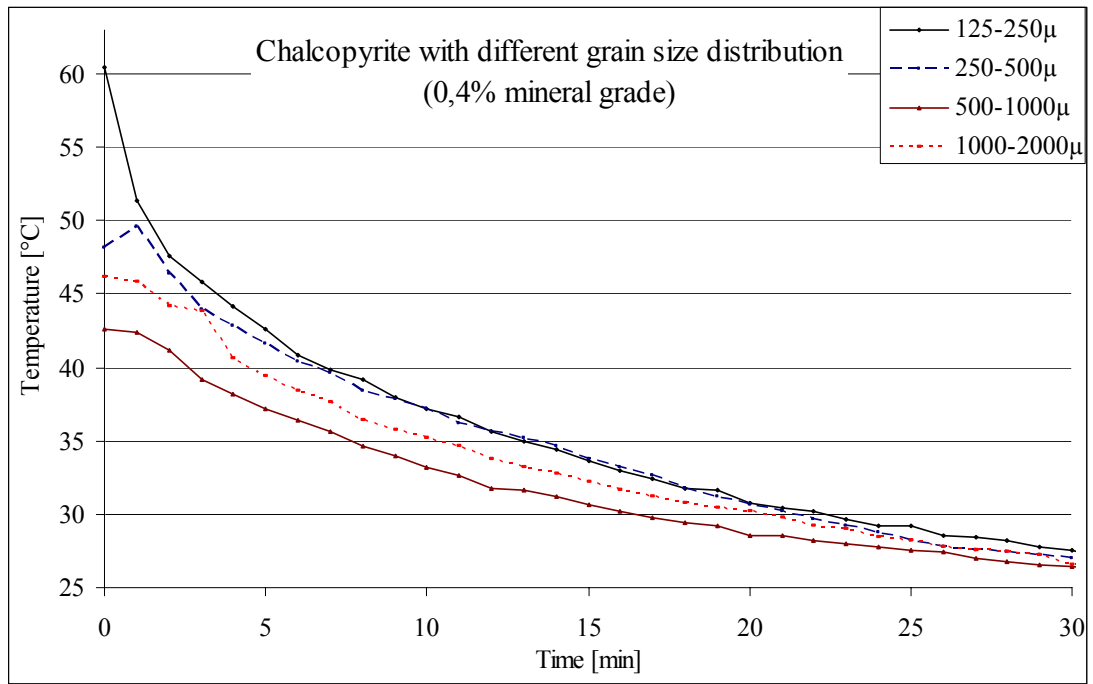


**Figure 6.12:** Cooling temperature of pyrite with 3.2% mineral grade for different grain size range

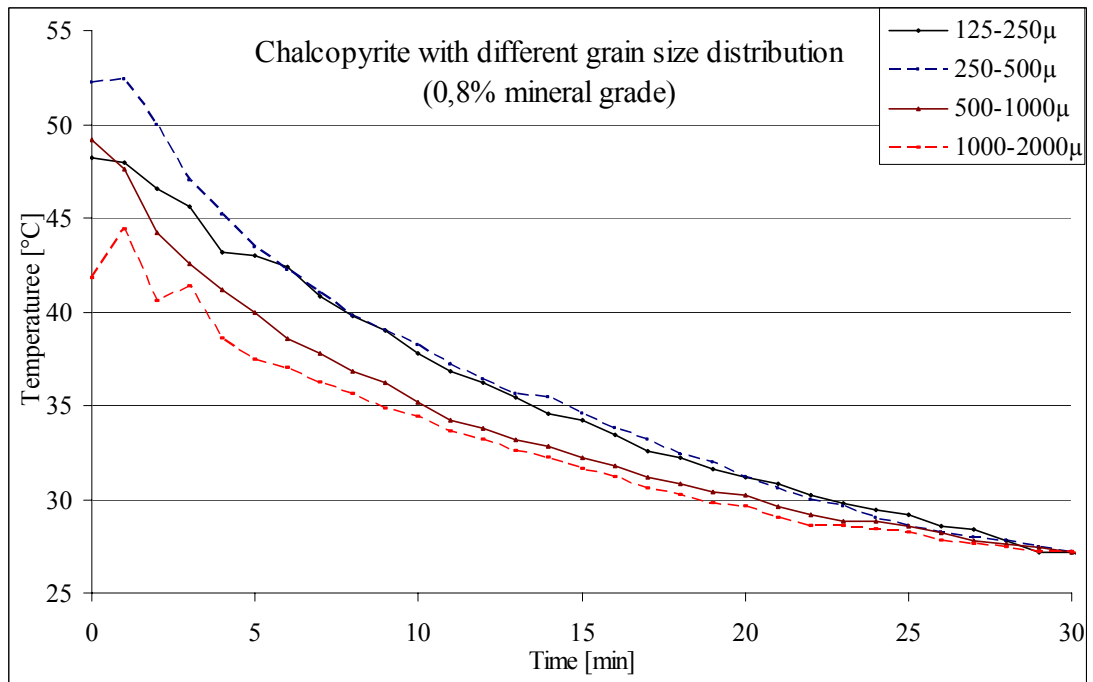
Following graphics (Figure 6.13, 6.14, 6.15 and 6.16) and tables (Table 6.13, 6.14, 6.15, and 6.16) show how differently change the temperature of chalcopyrite samples during cooling time depending on the particle size range in the sample

**Table 6.13:** Microwave heating temperature of 0.4% chalcopyrite samples

	Size range			
	-250+125 (µ)	-500+250 (µ)	-1+0.5 (mm)	-2+1 (mm)
Temperature after microwave	60.4	48.1	42.6	46.2
Maximum temperature	60.4	49.6	42.6	46.2
Temperature after 30 min.	27.6	27.0	26.4	26.6



**Figure 6.13:** Cooling temperature of chalcopyrite with 0.4% mineral grade for different grain size range



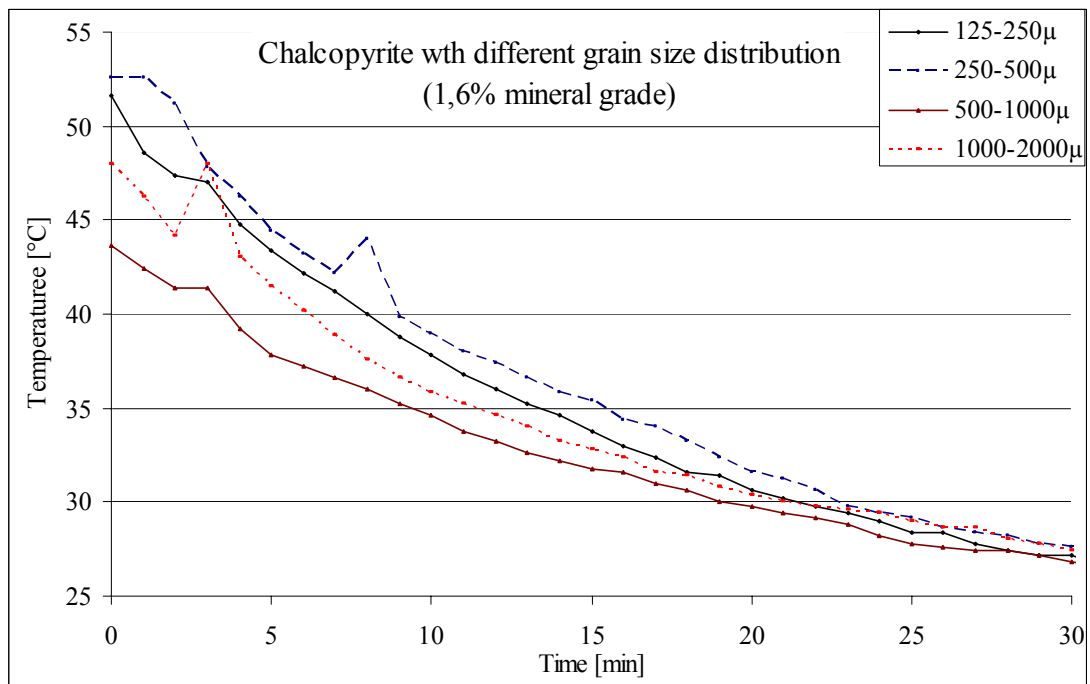
**Figure 6.14:** Cooling temperature of chalcopyrite with 0.8% mineral grade for different grain size range

Table 6.13 and Figure 6.13 show heating and cooling results of chalcopyrite samples with a mineral grade of 0.4%. As it is seen, absorbed energy in chalcopyrite is also direct proportional with particle size ranges

Temperature differences between samples are less than 1°C after a cooling time of around 10 min. it is seen in Table 6.14 and Figure 6.14 that after a cooling time of 30 minutes all the samples have the same temperature degree. That means the sample which has absorbed microwave energy more than other samples, is cooled faster than other samples.

**Table 6.14:** Microwave heating temperature of 0.8% chalcopyrite samples

	Size range			
	-250+125 ( $\mu$ )	-500+250 ( $\mu$ )	-1+0.5 (mm)	-2+1 (mm)
Temperature after microwave	48.2	52.2	49.2	41.8
Maximum temperature	48.2	52.4	49.2	44.4
Temperature after 30 min.	27.2	27.2	27.2	27.2



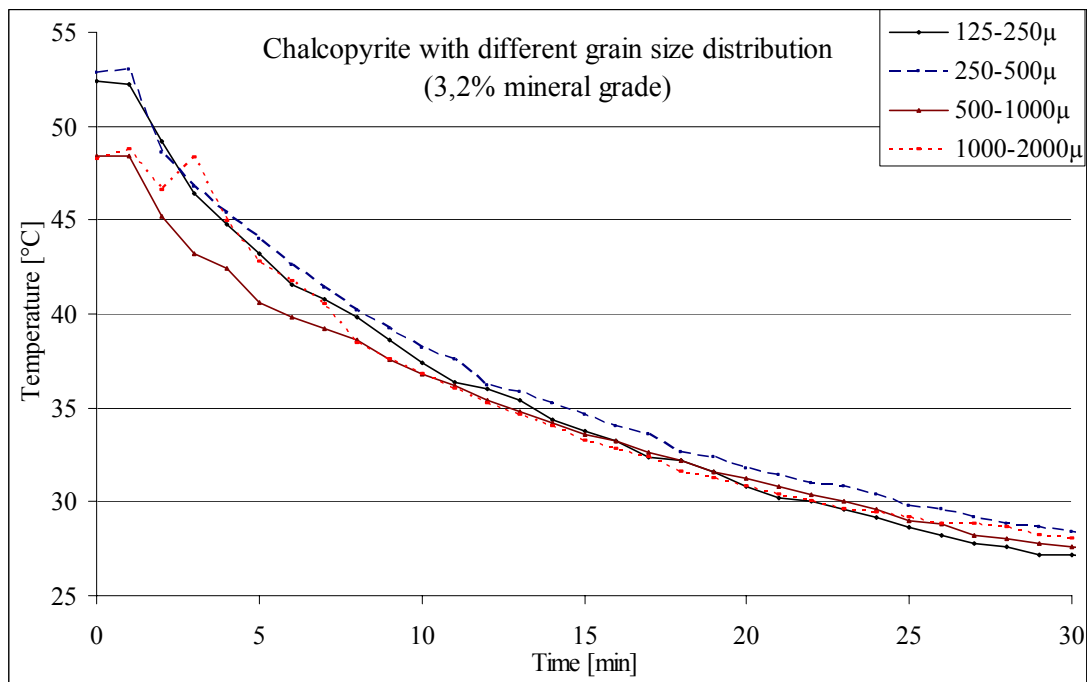
**Figure 6.15:** Cooling temperature of chalcopyrite with 1.6% mineral grade for different grain size range

Results of chalcopyrite samples having 1.6% mineral grade are given in Figure 6.15 and Table 6.15. The reason of the peaks on the 250-500 and 1000-2000 $\mu$  curves is the measuring location. Temperature of the samples is differing at the sample surface depending on the particle distribution in the sample.

**Table 6.15:** Microwave heating temperature of 1.6% chalcopyrite samples

	Size range			
	-250+125 ( $\mu$ )	-500+250 ( $\mu$ )	-1+0.5 (mm)	-2+1 (mm)
Temperature after microwave	51.6	52.6	43.6	48
Maximum temperature	51.6	52.6	43.6	48
Temperature after 30 min.	27.2	27.0	26.8	27.4

Results of samples having 3.2% chalcopyrite grade are given in Table 6.16 and Figure 6.16. These samples have highest temperature degree after 20 sec. microwave heating process. Both 125-250 and 250-500 $\mu$  curves have about same temperature degree differences is less than 1 $^{\circ}$ C which makes the automated sorting impossible in today's infrared camera technologies. On the other hand a sorting between pyrite and chalcopyrite is possible.



**Figure 6.16:** Cooling temperature of chalcopyrite with 3.2% mineral grade for different grain size range

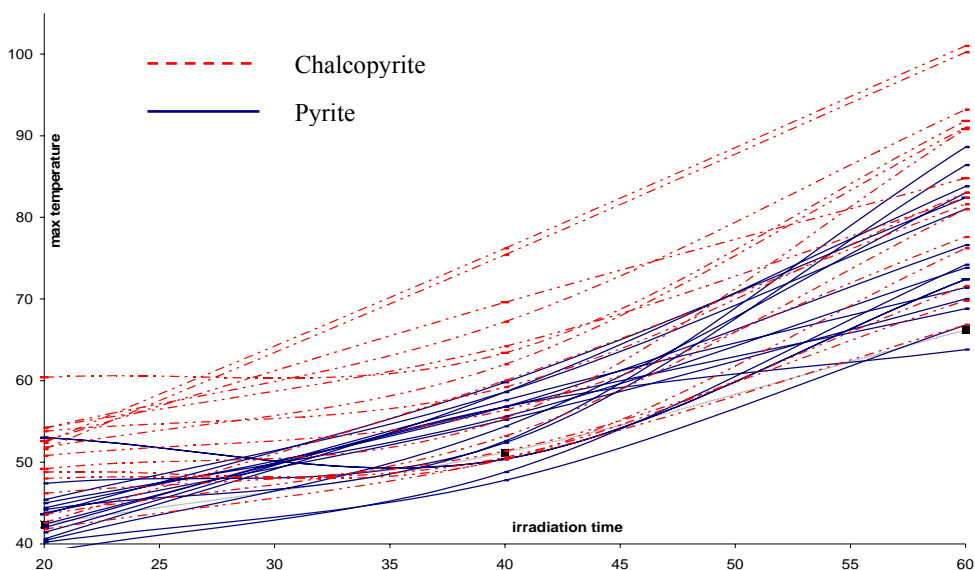
**Table 6.16:** Microwave heating temperature of 3.2% chalcopyrite samples

	Size range			
	-250+125 ( $\mu$ )	-500+250 ( $\mu$ )	-1+0.5 (mm)	-2+1 (mm)
Temperature after microwave	52.4	52.8	48.4	48.2
Maximum temperature	52.4	53.0	48.4	48.8
Temperature after 30 min.	27.2	28.4	27.6	28.0

### 6.1.3 Heating with Variable Radiation Time

In this experiment, same artificial samples were radiated by 2.45 GHz microwaves with different radiation times. Particles temperature curves are shown as a function of heating time. The temperature change of each sample is shown in 6.17. It is seen from graphic that the chalcopyrite particles absorbed microwave energy and produced heat more than pyrite particles. From these results the pre-concentration possibilities of chalcopyrite is calculate for different heating time and different temperature set-up for separation.

Chalcopyrite separation results after certain time of microwave heating are shown in Table 6.17, 6.18, 6.19 and Table 6.20. From these results it is seen that after 20 seconds microwave radiation of particles, chalcopyrite concentrate can be increased to the 2.6% and more importantly around 60% of the feeding material can be separated as waste material. Other possibilities of separation with different heating time are also shown at the tables.



**Figure 6.17:** Temperature change as a function of heating time

**Table 6.17:** Results of 20 sec microwave heating following with 48°C separation

	%	% CuFeS <sub>2</sub>	CuFeS <sub>2</sub> recovery
Concentrate	39.39	1.60	86.67
Waste	60.61	0.16	13.33
Feed	100.00	0.73	100.00

**Table 6.18:** Results of 20 sec microwave heating following with 46°C separation

	%	%CuFeS <sub>2</sub>	CuFeS <sub>2</sub> recovery
Concentrate	45.45	1.41	88.33
Waste	54.55	0.16	11.67
Feed	100.00	0.73	100.00

**Table 6.19:** Results of 40 sec microwave heating following with 60°C separation

	%	%CuFeS <sub>2</sub>	CuFeS <sub>2</sub> recovery
Concentrate	24.24	1.45	48.33
Waste	75.76	0.50	51.67
Feed	100.00	0.73	100.00

**Table 6.20:** Results of 50 sec microwave heating following with 73°C separation

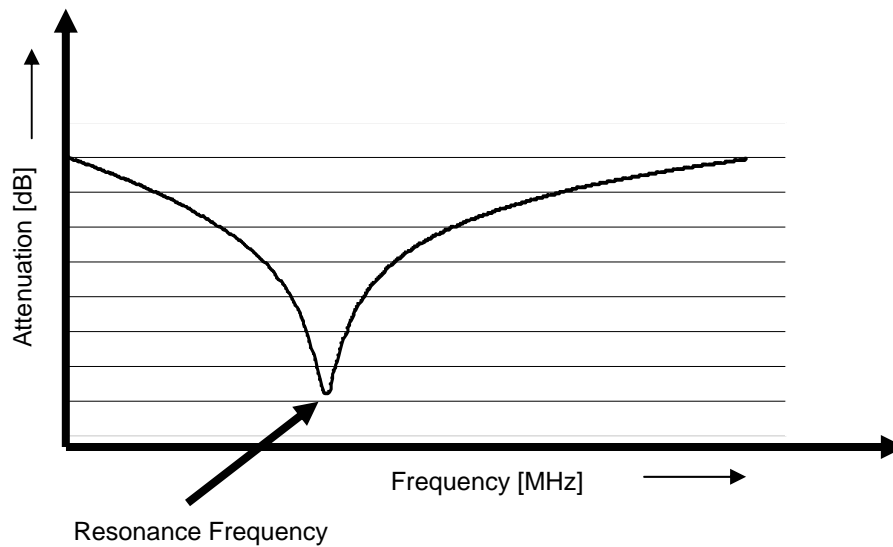
	%	%CuFeS <sub>2</sub>	CuFeS <sub>2</sub> recovery
Concentrate	75.76	1.50	50
Waste	24.74	0.48	50
Feed	100	0.73	100

## 6.2 Microwave Attenuation

Differing of microwave heating results for different materials and different ore properties bring a question; “do different samples also absorb low power microwaves differently?” Microwaves used in microwave heating techniques are 2.45 GHz and are not easily useful in the application.

In order to determine the application possibility of these waves, microwave attenuation experiments has been carried out and change of resonance frequency measured for each sample.

From attenuation results it is seen that the attenuated value increases with the increasing applied frequency (Figure 6.18).



**Figure 6.18:** Relation between attenuation and applied microwave frequency

Results of attenuation experiments are shown in Table 6.21, 6.22, 6.23 and table 6.24-. Two results are shown in different tables; attenuation and resonance frequency. From these results it could be said that more microwave energy are attenuated by samples having less mineral grade and also waves are attenuated more by the samples, having bigger particle range.

Resonance frequency is higher for the samples, which have less mineral grade and also it is higher for samples having bigger particle range.

Because of the measuring conditions and heterogeneous particle distribution in the samples, results are not always same for all samples. During the experiments samples measured where they are placed between spools without any cover, protecting from affect of outside which changes absorbed wave energy so that attenuation and resonance frequency changing depending on the affect.

**Table 6.21:** Attenuation results of pyrite samples

		Attenuation [dB]			
size range	Mineral Grade	0.4%	0.8%	1.6%	3.2%
	-250+125 $\mu$	-63.9100	-60.1046	-60.3014	-60.4163
	-500+250 $\mu$	-67.9488	-63.1372	-61.7927	-63.1237
	-1000+500 $\mu$	-62.2375	-64.9885	-58.1008	-64.1793
	-2+1mm	-62.6732	-66.7724	-64.9784	-68.2685

**Table 6.22:** Resonance Frequency results of pyrite samples

		Resonance Frequency [MHz]			
size range	Mineral Grade	0.4%	0.8%	1.6%	3.2%
	-250+125 $\mu$	115	110	120	113
	-500+250 $\mu$	119	114	116	114
	-1000+500 $\mu$	117	118	117	118
	-2+1mm	118	119	115	120

**Table 6.23:** Attenuation results of chalcopyrite samples

		Attenuation			
size range	Mineral Grade	0.4%	0.8%	1.6%	3.2%
	-250+125 $\mu$	-63.7584	-59.9746	-63.4010	-61.7988
	-500+250 $\mu$	-58.0009	-57.5818	-57.8776	-57.9258
	-1000+500 $\mu$	-66.1007	-64.0681	-63.3308	-59.0860
	-2+1mm	-64.7423	-63.5976	-62.2262	-60.2028

**Table 6.24:** Resonance Frequency results of chalcopyrite samples

		Attenuation			
size range	Mineral Grade	0.4%	0.8%	1.6%	3.2%
	-250+125 $\mu$	117	112	112	113
	-500+250 $\mu$	109	106	104	107
	-1000+500 $\mu$	118	112	113	109
	-2+1mm	117	117	115	112

## 7 CONCLUSION

In this investigation, the correlation between microwave absorption and mineral grade as well as the microwave absorption and grain size were investigated. Experiments with high power microwaves for heating and low power microwaves for measuring attenuation were carried out on former prepared artificial samples.

As expected sulphides adsorb microwaves while the gangue material does not, and the samples are heated by microwave radiation. The maximum temperature was obtained about 30s after the heating. In some cases there seems to be a direct connection between mineral grade and measured temperature

However, the variation in the temperature in the other experiments can be due to the measurement principle being a point measurement of the temperature. It could be obtained that the temperature distribution slightly varies over the sample surface and hence cause noisy measurements. This can be overcome applying area scanning by using an infrared line scan camera on the belt. Another reason for the irregular heating may be caused by an inappropriate grain distribution inside the samples. This effect can only be determined by supplying a much larger set of samples to avoid systematic errors. Finally, this effect may also rely upon different grade of contained water in the samples which was considered constant during this study.

Produced heat increases with the increasing power level of microwaves. With the same energy level which is 2.45 GHz, produced heat by ore increase with increasing sulphide grade of the ore and with same energy level and sulphide grade, heat also increase with the decreasing particle size distribution because of increasing surface of particles in the ore material.

As in the heating case, there is a certain variation in the results. Nevertheless, the results indicate that with decreasing mineral grade and increasing grain size, the attenuated microwave energy increases. While the latter one could be expected the first correlation seems contradiction. This can be caused by the too sensitive

experimental setup in which even small perturbations may have a major impact on the measurements.

The results of certain microwave heating time and different separation temperature show that chalcopyrite particles are heated more than pyrite particles. Chalcopyrite particles can be fed into separator after 20 sec microwave heating and separated of a temperature value of around 48 °C.

Using this information, it is possible to produce a sorting machine which has a microwave heater over the belt and a detection unit that scan the material surface temperature, after certain time transporting and an applied force unit separate accepted and rejected materials.

After this possible separation process chalcopyrite concentrate will be increased in the pre-concentrate, more important that considering a grinding and other processes after pre-concentration unit, this 60% decrease of the feeding of following processes will decrease the installing and operation cost of the process especially grinding costs.

Another solution of sulphide ores production is that using low power microwaves. Low power microwave beams could be produced under the belt and over the belt there will be a sensor which detects the microwave after passed through the material and separation unit will sort materials.

Application of a sensor based sorter in the low grade metalliferous sulphide ores for a pre-concentration production will decrease throughput of processing plant which lets grinding costs and other operation costs decrease, lets the production capacity increase in a plant, already been installed, and lets investment costs decrease for new plant.

Another advantage is that a near mining operation installed sorter will decrease transport costs and in the case of underground mining production, pre-concentration process in underground and storing the pre-separated gangue material in underground will also lets waste treatment cost decrease.

## **8 RECOMMENDATIONS**

This study is on a very elementary level and hence further experiments have to be carried out to investigate the effect of microwave heating and attenuation. Because of the variations in the results, future experiments will have to be based on a much larger set of samples to overcome statistical variations.

For the heating, a microwave device for heating on the belt is desirable to simulate heating under real-world conditions. The lack in accuracy of the point measurement can be overcome using an infrared line scan camera. However, it should be noted that such a test setup is quite expensive as even a simple infrared camera usually costs about 25,000€.

Especially in the case of attenuation, the used test setup turned out to be too sensitive even for the laboratory level. A more robust test procedure will have to be found in cooperation with people from electrical engineering.

As a result, using both, high and low power microwaves for sorting sulphide ores seems a promising alternative to traditional mineral processing even if there is quite a lot of work to do.

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## **BIOGRAPHY**

Tevfik Serhat ÖNOL was born in Turkey in 1980. After graduated from high school, he studied mining engineering in Osmangazi University Eskisehir (1998-2002). In 2003 he started to Master of Science education in Istanbul Technical University and in 2004 he went to Germany through a double diploma program between Istanbul Technical University and Aachen Technology University and he has done his Master of Science thesis in Aachen in 2007.