# The Influence of Dielectric Properties on Heating of Sulphide Ores in Electromagnetic Field

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*Abstract*

*Microwave heating is a form of high-frequency electromagnetic radiation. The heating of primary and secondary mineral raw materials in the microwave field depends primarily on their dielectric and thermal properties. The condition is the absorption of microwave radiation. Dielectric heating of materials occurs immediately after placing them in an electric high-frequency field. Knowledge of the dielectric characteristics of mineral raw materials is an important assumption for the use of electromagnetic radiation at the intensification of technological treatment methods. Most mined minerals consist of several mineral components that have different dielectric properties. Most sulphides are well heated in a microwave field. Conversely, tailings components of ores, such as quartz, are transmission materials. The study of dielectric properties involves measurements of the complex relative permittivity ε*, which consists of a real and an imaginary part. The imaginary part of permittivity "loss factor" represents the measure of dielectric losses in the material. Microwave heating of sulphide ores and concentrates such are chalcopyrite, tetrahedrite, galena depends on their chemical composition and content of impurities. The article describes the influence of dielectric properties on heating of chalcopyrite in microwave field. SEM analyses of studied samples are presented.*

*Keywords: dielectric properties, heating, sulphide ores, electromagnetic field*

**Introduction**

The use of electromagnetic radiation in the processing of mineral raw materials and waste has received considerable attention in the world in recent years [1, 2, 3]. Rapid and selective heating of the useful components of ores in a microwave field represents an interesting aspect in the metals extraction. Sulphide ores and minerals belong to the economically important mineral raw materials containing copper, iron, antimony, zinc, lead, and in smaller amount silver and gold. In nature, they usually occur together in the form of multicomponent sulphide ores containing tailings components. The most widespread is chalcopyrite, other sulphide minerals include tetrahedrite, galena, sphalerite, arsenopyrite, pyrite and others. The processing of complex refractory ores is energetically and ecologically difficult, including the flotation, cyanidation, roasting, leaching and electrolysis processes. One of the possibilities of innovation and intensification of technological procedures for the treatment of ores and their concentrates is the use of microwave radiation [4]. Application of microwave energy in the treatment of mineral raw materials at the Institute of Geotechnics SAS in Košice is paid long-term attention. The positive influence of electromagnetic radiation in the processing of siderite ores in magnetization roasting processes, in the pre-treatment of magnesite, dolomite and limestone ores, in the processes of drying and melting of minerals and rocks, desulfurization of coal, pyrolysis and processing of biomass, eternite and waste from metallurgical and mining activities has been confirmed [5, 6, 7]. An essential assumption for the use of electromagnetic radiation in the processing of mineral raw materials is knowledge of their dielectric properties. Several research teams deal with the measurement of dielectric properties of mineral raw materials in the microwave band of electromagnetic radiation. Methods for permittivity measurement of various materials are gradually being developed and improved, e.g. rubber, waste, biomass, rocks, coal and others. Tikhonov et al. deal with determination of complex dielectric permittivity of selected minerals. They presented the results of reflectivity and transmittance measurements of chalcopyrite, magnetite, sphalerite and labradorite samples in the frequency range 77 - 300 GHz [8]. The permittivity measurement of Pittsburgh coal was carried out using a coaxial line at frequencies of 0.2 - 20 GHz [9]. At frequency of 11.7 GHz, they found that the real part corresponded to a value of 4.21 and the imaginary to 0.156. From the measured data, it was found that the depth of microwave penetration during heating of studied coal sample will correspond to a value of ≈ 10 cm at a given frequency.

At the Institute of Radio Electronics, Faculty of Electrical Engineering an Communication, Brno University of Technology, Czech Republic, the research is aimed at measurement of the dielectric properties of various materials. The attention is focused on the study of new microwave structures and the development of modelling and optimization methods for prospective communication systems operating in the centimetre and millimetre wave bands [10, 11]. The attention is paid to measurements of relative permittivity of materials using various methods [12, 13]. The measurement methodology is focused on determination of procedure for calculation of the sought quantity from the data obtained by measurement. The emphasis is placed on the samples preparation, arrangement and necessary mechanical properties of the individual elements of the measurement device for given measurement method.

**Heating of materials in electromagnetic field**

The use of electromagnetic radiation in the processing of mineral raw materials has significant importance, especially in the processes of their pretreatment and extraction of metals. The conversion of electromagnetic energy into heat depends primarily on the dielectric properties of the irradiated minerals, as well as on their thermal properties and chemical composition. The intensity of thermal heating of complex mineral raw materials in the microwave field can be assessed by the degree of absorption and the depth of radiation penetration. When non-conductive materials are heated, transmission occurs, i.e. radiation transition. Conversely, when electrically conductive materials are heated, radiation is reflected. For heating in the microwave field, those materials are suitable that absorb radiation, i.e. dielectrics.

The influence of dielectric properties on the heating of mineral samples in electromagnetic field can be evaluated by measurement of the parts of complex permittivity.

The complex electrical permittivity is expressed:

$$\varepsilon^* = \varepsilon' + i.\varepsilon'' \quad (1)$$

where: $\varepsilon'$ - real part of the permittivity (dispersion factor),
$\varepsilon''$ - imaginary part of the permittivity (loss factor),
$i$ - imaginary unit.

The penetration depth of microwave radiation was calculated according to the relationship:

$$D = \frac{\lambda\sqrt{\varepsilon'}}{2\pi\varepsilon''} \quad (2)$$

where: $\lambda$ - wavelength of microwave radiation.

The real and imaginary parts of permittivity describe the interactions of microwaves with materials. The real part characterizes the material in the microwave band of electromagnetic radiation. It represents the material energy in the electric field. The imaginary part represents the measure of dielectric losses in the material. The depth of radiation penetration directly depends on the dielectric properties of heated material. Metals have low values of complex dielectric permittivity and reflect electromagnetic waves. The penetration depth is very low. When heating dielectrics with high complex permittivity, electromagnetic waves are absorbed by the materials and the penetration depth is high.

**Material and methods**

The samples of chalcopyrite from Slovinky, Slovakia were used for the research. The studied samples on measurement of dielectric properties and microwave heating were prepared by classic preparation methods of disintegration and sieve analysis. The overview morphologies and sizes of the samples were obtained by field emission scanning electron microscope TESCAN MIRA 3 FE SEM with an accelerating voltage of 20 kV (Figure 1).

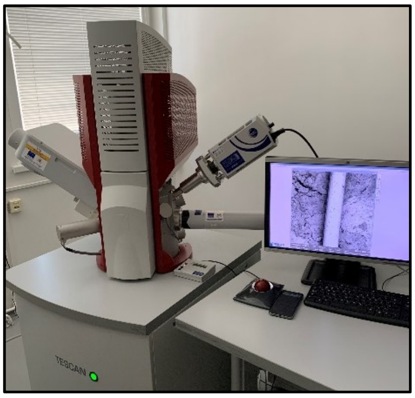


Fig. 1. Scanning electron microscope TESCAN MIRA 3 FE SEM

Dielectric properties were measured using the resonance method at a frequency 2216 MHz at the Faculty of Engineering, School of Electrical & Electronic Engineering, University of Nottingham, Great Britain. The grain size samples 1-2 mm were placed in a silica tube and then inserted into the cavity of the resonator. The initial measurement temperature was 150 °C, the temperature increase was 5 °C/min, the measurements were carried out after 50 °C. Microwave heating was realized in a Whirlpool AVM 434 microwave oven at a power of 900 W.

Chalcopyrite samples with a grain size of 1-2 mm, 0.5-1 mm and a weight of 100 g were irradiated at a frequency of 2450 MHz. The heating time was 15, 30, 45, 60, 75 and 90 s. Magnetic susceptibility was measured on a Kappabridge KLY 2, Geofyzika Brno, Czech Republic.

## Results and discussions

The presence of elements in chalcopyrite: 26.3 % Cu, 26.4 % Fe, 23.5 % S (Figure 2b) was confirmed by Energy-dispersive X-ray spectroscopy (EDX). EDX spectra of selected plots light and dark colour (Figure 2c, 2d), as well as point EDX analysis (Figure 2e) confirmed the content of interesting strategic metals. It was confirmed the presence of 0.7 % Mg.

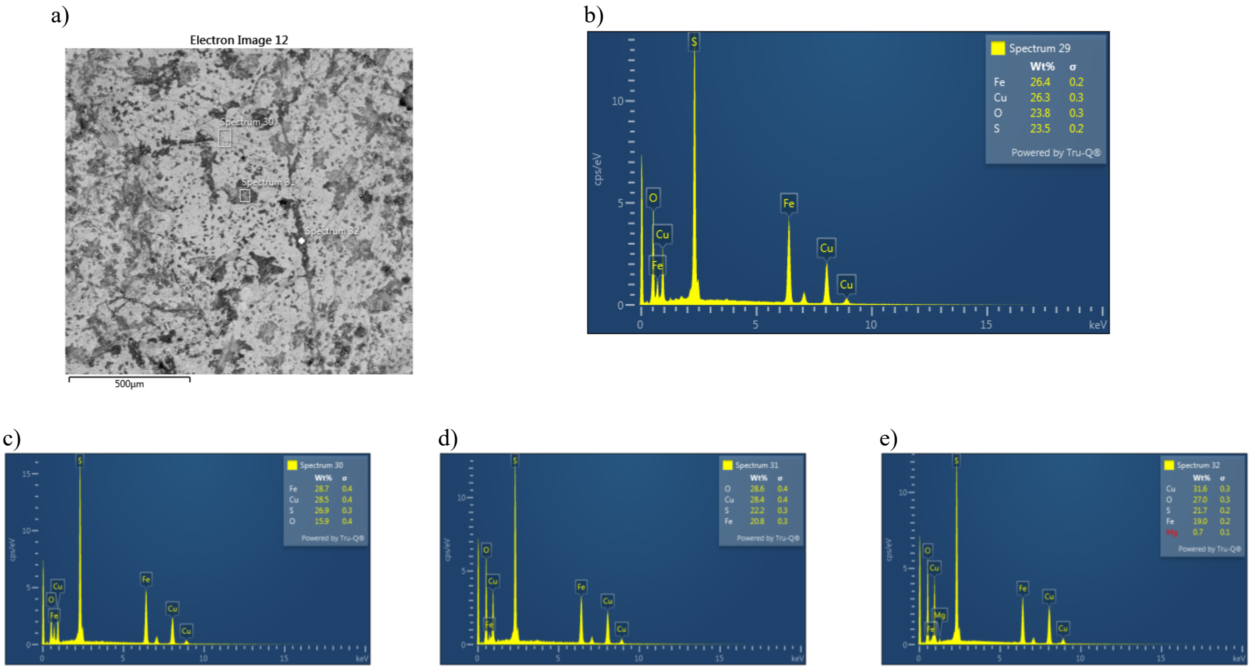


**FIGURE 2.** Scanning electron micrographs of chalcopyrite; a) micrograph of chalcopyrite, b) EDX spectrum of chalcopyrite (matrix), c) EDX spectrum (light colour), c) EDX spectrum (dark colour), c) EDX spectrum (point analysis)

The assumption of use of microwave heating in the processing of sulphide ores was evaluated by measurement their dielectric characteristics and the rate of radiation absorption. Effect of temperature on the real (ε') and imaginary (ε'') part of the permittivity of chalcopyrite is on Figure 3 and Figure 4.

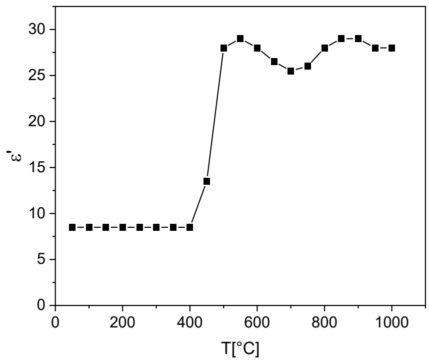


**FIGURE 3.** Effect of temperature on the real part of the complex permittivity

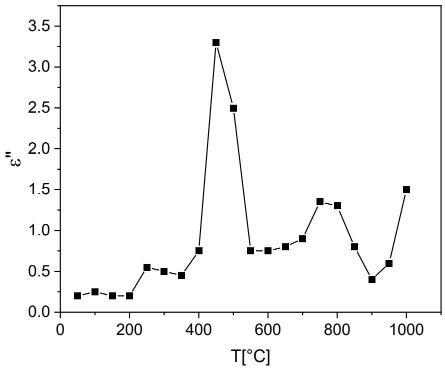


**FIGURE 4.** Effect of temperature on the imaginary part of the complex permittivity

Based on the measurements, it was found the increase of the real part of the permittivity around a temperature of 500°C. When measuring the imaginary part of the permittivity, the highest value was also found at a temperature of 500°C, then a sharp decrease was observed. With increasing temperature, the values of ε'' oscillated ~1. Changes in the measured values are related to thermal decomposition of samples. Based on the experimental measurements of ε' and ε'', the penetration depth of electromagnetic radiation was calculated (Figure 5). An increase of radiation depth values as a function of temperature was observed. A significant increase was detected at temperatures of 500 and 900 °C.

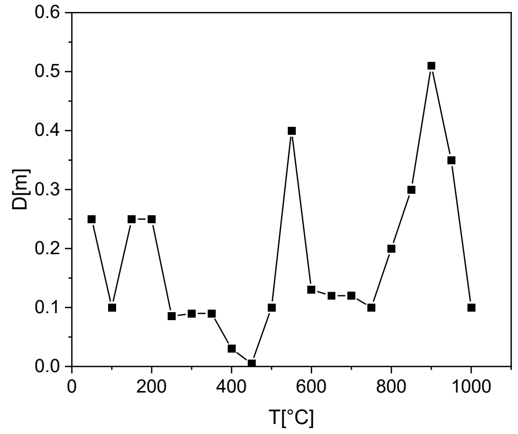


Fig. 5. The effect of radiation depth depending on the heating temperature of chalcopyrite

When heating investigated of chalcopyrite samples, reflection of electromagnetic radiation was observed. It was experimentally confirmed that significant thermal effect occurs in the surface layer of irradiated mineral raw materials containing metals, i.e. „conductive“ useful components (Cu, Fe in the case of heating chalcopyrite) during the reflection of microwaves. In addition, "hot spots" with a very high temperature could also occur inside the heated samples. The magnetic properties were evaluated based on the measurement of magnetic susceptibility of investigated samples. After a very short time there was the significant change in the magnetic properties, which is related to the formation of new phases (Figure 6).

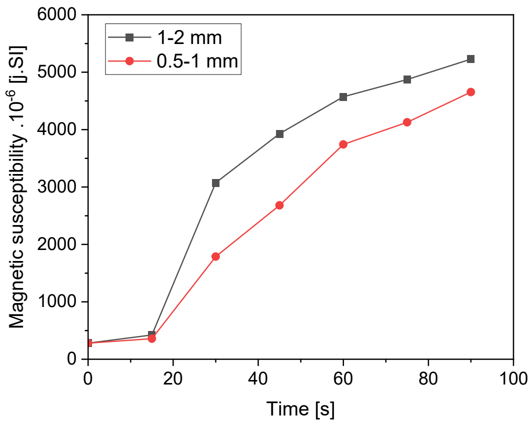


Fig. 6. Effect of microwave heating on the change in magnetic susceptibility of chalcopyrite

The higher values of magnetic susceptibility were observed after heating of chalcopyrite samples with grain size 1-2 mm. The increase of magnetic properties by selective heating of useful components of ore has the significant importance in the intensification of separation processes.

**Conclusions**

In the paper, attention was paid to the use of electromagnetic radiation in the microwave band when heating chalcopyrite ore. The main advantage of heating of sulphide ores in the microwave field is the immediate transfer of energy, the speed and selectivity of the ongoing process based on the different dielectric properties of useful and non-useful mineral components. A sufficient level of radiation absorption predetermines the potential of using microwave energy in the ore processing. The positive influence of electromagnetic radiation on the heating of chalcopyrite was confirmed by the increase of magnetic susceptibility, suitable for magnetic separation. It was confirmed the influence of temperature on the real and imaginary part of the complex electrical permittivity of chalcopyrite, which is related to its thermal decomposition and the formation of new phases. It was experimentally confirmed that sulphides are good absorbers of microwaves. The pretreatment of Cu, Fe-containing ores and concentrates in electromagnetic field has potential importance in the recovery of strategic metals. However, measurements of the dielectric properties before heating of mineral raw materials are only a prediction of their behavior in high-frequency electromagnetic field. However, complex refractory ores often have different chemical compositions and significant content of impurities. When they are irradiated, occur the "hot spots", which are characteristic only for microwave heating. In some hot centers, higher temperatures are expected compared with heating of the same material in conventional oven. For this reason, it is not entirely possible to predict the behavior of materials in the microwave field only by permittivity measurement before their irradiation. In cooperation with Faculty of Electrical Engineering an Communication, Brno University of Technology, the subject of further research will be the development of methodology for measurement of dielectric properties before and after microwave heating of fine-grained mineral raw materials at specified intervals and conditions based on DTA analyses. To determine the dielectric properties, an apparatus will be made for permittivity measurement by the reflection method in the microwave area. The emphasis will be focused on the possibilities and character of measurement not only solid, but especially granular mineral samples from the point of view obtaining optimal knowledge of the behavior of real samples during heating in the microwave field. The measurements of dielectric properties at several frequency ranges will also be beneficial.

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