

MICROWAVE ROASTING OF PYRITE TAILINGS AND PYRITE ASH FOR SPONGE IRON PRODUCTION

Y I Tosun

Şırnak University, Engineering Faculty, Şırnak,TR

Abstract. Iron ores containing ferrous minerals and sulphide minerals are specifically as several times active in microwave. Pyrolysis of the coal usually requires iron minerals for activation step to both absorption microwave from the matrix of the sulphides and conduct the heat to coal for pyrolysis. In this investigation, the copper pyrite and coal pyrite was microwave roasted to oxidize both the sulphides and even the pyrolysis of coal for reduction iron oxide. The effects were investigated by gravimetric and infrared analysis and the microwave absorption characteristics were quantified by determining the permittivities. The microwave heating behaviour studies showed that the sample temperature increased with increasing incident microwave power, processing time and sample mass. Due to the activity of the iron ore to the microwaves, a low incident power of 600W was found to be sufficient for roasting, as higher powers resulted in sintering and melting of the concentrate. The copper pyrite weight loss values after roasting were over 25% and these were similar to those obtained by conventional roasting. The main advantages of microwave roasting were that both the total pyrolysis rates and the heating rates were higher and the specific energy consumptions were lower than in coal pyrite. In this study; low-grade iron ore and sponge iron pyrite by high production of waste parched areas were carried out. X-ray diffraction analysis of the products mineralogy and grain size in polarizing microscopic description is determined by the nature of the leaching effect on the physical and chemical parameters. Chemical properties making preliminary tests to determine the pellet roasting conditions, reactivity were investigated. This assay has been determined to be advantageous in the metal results in the production of sponge iron with the pyrite ash waste. The feasibility use of low-grade iron ore with microwave roasted pyrite, and pyrite ash in production sponge iron were tested and the physical, chemical properties of the products regarding the results of microwave roasting tests were determined by examining the difference between the textural properties of the different pyrite and ash. The pyrites of Ergani copper concentrator and Siirt were in this study identified as potential iron source in terms of the basic qualifications of sponge iron.

Keywords: Microwave roasting, pyrite ash, pyrite waste, iron ash, sponge iron, microwave treatment

1. Introduction

The effects of electric and magnetic fields in the microwave heater provide a very rapid movement generated with emitting (2.4×10^9 times per second) lead to particle heating [1]. There is a very quick response to this mobilization by a combination of molecules constituting particles [1,2]. Because of this delay movement will consist of a force opposing blocker and the friction which occurs in the particles results will occur at a certain temperature [3]. This event in microwave is based on dielectric heating pass through the particles. Electric field of the microwave, Located in force on charged particle compounds applies. If charged particles are free can move toward the electric field, and heat flow occurs with depending on the compound of charged particles [4].

There is only limited movement and phase movement of the orientation of the electric field in the microwave. It is expressed as dielectric polarization.

Dielectric polarization is installed in substance depending on four different types of particles. It consists of components: electron, nucleus, continuous dipoles and interface loads [5],

$$\alpha t = \alpha e + \alpha a + \alpha d + \alpha i \quad (1)$$

A coal or iron ore specimen located within the microwave field will warm dielectric material to a certain extent regarding the dielectric characteristics of iron mineral content and type, ϵ^* , ϵ^1 and ϵ^{11} to decide.

$$\epsilon^* = \epsilon^1 + j \epsilon^{11} \quad (2)$$

At the very high and very low frequency conditions as happen in the microwave, ϵ^1 is equal to the total dielectric constant of the material. Electromagnetic energy materials ϵ^{11} where the value is converted into heat by the amount of electromagnetic energy converted to heat related. Warming the dielectric field presence with the equation below (3) [5-9], the expressions given by the equation indicated.

$$\tan \delta = \epsilon^{11} / \epsilon^1 \quad (3)$$

The larger the value of a iron material $\tan \delta$ It is high ability to take in that the microwave energy. The values of $\tan \delta$ of the molecules coexisting is connected to the value of the frequency of electromagnetic waves, temperature of the mixture of iron mineral content, composition and physical structure of the iron material.

Iron ores containing ferrous minerals and sulphide minerals are specifically as several times active in microwave. pyrolysis. The coal usually requires an pyrite minerals for activation step to both absorption microwave from the matrix of the coal pyrites and conduct the heat to coal's amorphous carbon that pyrolysed.

In this investigation, the copper pyrite and coal pyrite was microwave roasted to oxidize both the other iron sulphide and even the pyrolysis of coal. The effects were

characterized by gravimetric and infrared analysis and the microwave absorption characteristics were quantified by determining the permittivity.

1.1. Microwave Coal Pyrolysis and Pyrite Roasting

Microwave frequencies have been allocated for commercial use in the radio-frequency region of the spectrum. During the past century, materials research has provided many new dielectric materials for application in electronics. As the use of higher and higher frequencies came into practice, new materials, suitable for use in the radio-frequency, microwave wave regions of the electromagnetic spectrum, have been developed. The dielectric properties of these materials are important in the design of electrical and electronics equipment and suitable techniques for measuring the dielectric properties of various materials applications have been developed, as they were needed. The interest in the dielectric properties of rocks and materials and products has been principally for predicting heating rates describing the behaviour of materials when subjected to high-frequency or microwave electric fields in dielectric heating applications. Most of the commercial microwave processing equipment is designed for operation at 2450 MHz, which reflects commercial emphasis on home microwave ovens.

In the past 20 years, the microwave oven has become an essential appliance in most kitchens. Faster cooking times and energy savings over conventional cooking methods are the primary benefits. Although the use of microwaves for cooking food is widespread, the application of this technology to the processing of materials is a relatively new development. The use of microwave energy for processing materials has the potential to offer similar advantages in reduced processing times and energy savings [10-15].

In conventional thermal processing, energy is transferred to the material through convection, conduction, and radiation of heat from the surfaces of the material. In contrast, microwave energy is delivered directly to materials through molecular interaction with the electromagnetic field. In conventional methods, energy is transferred due to thermal gradients, but microwave heating is the conversion transfer of electromagnetic energy to thermal energy through direct interaction of the incident radiation with the molecules of the target material. The difference in the way energy is delivered can result in many potential advantages to using microwaves for processing of materials. As microwaves can penetrate materials and deposit energy, heat can be generated throughout the volume of the material [16-19]. The transfer of energy does not rely on diffusion of heat from the surfaces, and it is possible to achieve rapid and uniform heating of relatively thicker materials. In traditional heating, the cycle time is often dominated by slow heating rates that are chosen to minimise steep thermal gradients that result in process-induced stress. For polymers and ceramics, which are materials with low thermal conductivity, this can result in significantly reduced processing times. Thus, there is a balance between processing time and product quality in conventional processing. As microwaves can transfer energy throughout the volume of the material, the potential exists to reduce processing time and enhance overall quality [19-29].

1.2. Microwave permittivity and Dielectric constant

When microwaves are directed towards a material, part of the energy is reflected, part is transmitted through the surface, and of this latter quantity, part of it is absorbed. The proportions of energy, which fall into these three categories, have been defined in terms of the dielectric properties. The fundamental electrical property through which the interactions are described is the complex relative permittivity of the material ϵ^* . It is expressed as in Equation 2[5-9]:

The absolute permittivity of a vacuum is ϵ_0 and it is determined by the speed of light C_0 and the magnetic constant μ_0 , which are linked together by equation below:

$$C_0 \mu_0 \epsilon_0 = 1 \quad (4)$$

The numerical value for ϵ_0 is about 8.854 pF/m and for μ_0 is 1.26 H/m. In other media (solid, liquid and gaseous), the permittivity has higher values and it is usually expressed relative to the value in vacuum [1]. The relative permittivity ϵ_r of a material is equal to $\epsilon_{abs} = \epsilon_r \epsilon_0$, where ϵ_{abs} is the absolute permittivity of material. Materials which do not contain magnetic components respond only to the electric field.

$$P_{abs} = 5.56 \times 10^{-4} f \epsilon_r^2 E^2 \quad (5)$$

The dielectric properties of materials dictate, to a large extent, the behaviour of the materials when subjected to radio-frequency (RF) or microwave field for the purposes of heating, drying or processing the materials. The characterization of dielectric properties is vital for understanding the response of a material to microwaves, since most useful quantities needed in the design of microwave thermal processes can be described in terms of them. The equations relating dielectric properties to thermal processing parameters are presented in the following section.

The power dissipated inside a material is proportional to ϵ''/ϵ' . The ratio, ϵ''/ϵ' , called the loss tangent or dissipation factor, a descriptive dielectric parameter, is also used as an index of the material's ability to generate heat [10-12];

Sometimes, d_p is defined as the distance at which the microwave power has been attenuated to 50% of P_{trans} . The penetration depth is a function of ϵ'' and ϵ' [5,6]:

$$d_p = c \lambda_0^2 P f \frac{\sqrt{\epsilon''}}{2\pi \epsilon'} \quad (6)$$

Where λ_0 is the free space microwave wavelength (for 2.45 GHz, $\lambda_0 = 12.2$ cm).

As the wave travels through a material that has significant dielectric loss, its energy will be attenuated. If the attenuation is high in the material, the dielectric heating will taper off quickly as the wave penetrates the material. Attenuation is often expressed in decibels per unit length in meters (dB/m). In terms of power densities and electric field intensity values, The rate of heating can be expressed by the power equation [11]:

$$P_v = 2\pi f \epsilon_0 \epsilon'' E^2 \quad (7)$$

where P_v is the energy developed per unit volume in Wm^{-3} , f is the frequency in Hz; and E is the electric field strength inside the load in V/m

The electric field inside the load is determined by the dielectric properties and the geometry of the load, and by the oven configuration. Therefore, this equation is generally impractical since the determination of the electric field distribution is very complex.

2. Materials and Method

The produced high frequency (2.45 GHz) microwaves and the incident power could be varied continuously from 0 to 1000 W. A quartz crucible (about 120 g) containing the pyrite was placed on an alumina platform. The power was varied from 600W to 1000 W. The sample mass ranged from 5 to 50 g. In all experiments, the temperature was measured at the base of the sample, and this is referred to as the sample temperature. A type K thermocouple (wire diameter of 0.20 mm) was employed and the temperature was measured immediately after turning the power off. The variables studied were: incident microwave power, processing time and sample mass. For the microwave roasting tests, samples weighing about 15–20 g, were placed in fireclay roasting boats and heated. (Figure 1 and Figure 2)

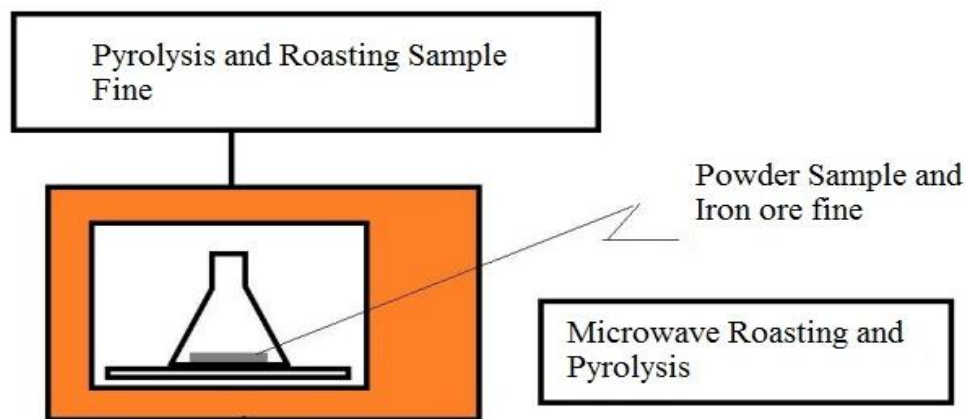


Figure 1. Microwave Experimentation Flowsheet

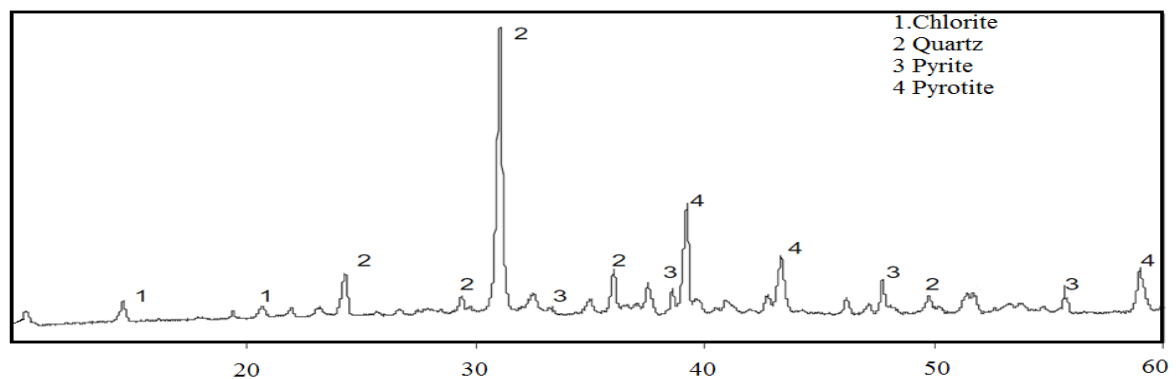


Figure 2. The XRD 2θ Pattern of Şirnak Coal Pyrite Sample used in Microwave Roasting

In the microwave system pyrolysis were managed at the period of 3–5 min. It was found that it was necessary to disperse the particles as a thin layer in order to minimize local overheating. Consequently, pyrolysis and roasting was not uniform and the sections that were not fully calcined were separated and recycled. The chemical analysis of pyrite samples are given in Table 1.

Table 1. The chemical analysis of different type of pyrites used in the experiments.

Component Type,%	Siirt copper pyrite	Şirnak coal pyrite	Şirnak pyrite shale
CuFeS ₂	0,69	0,91	0,47
FeS ₂	75,5	85,5	8,7
PbS	2,92	0,72	0,21
SiO ₂	14,4	6,23	48,5
FeO.SiO ₂	9,56	1,84	17,4

3. Results and Discussion

3.1. Porosity and Matrix(air/water) Content

The dielectric properties depend on the frequency of the applied alternating electric field, the temperature of the material, and on the density, composition, and structure of the material. In granular or particulate materials, the bulk density of the air-particle mixture is another factor that influences the dielectric properties. The dielectric properties of materials are dependent on their chemical composition and any other molecules (Table 2) [9,10]. With the exception of some extremely low-loss materials, i.e., materials that absorb essentially no energy from microwave fields, the dielectric properties of most materials vary considerably with the frequency of the applied electric fields. The phenomenon contributing to the frequency dependence of the dielectric properties is the polarisation arising from the orientation with the imposed electric field, of molecules, which have permanent dipole moments.

Table 2. Microwave Temperature Effect on Minerals [9]

Mineral Type	Maximum Temperature, °C	Time,min
Albite	69	7
Chromite	155	7
Chalcopyrite	920	1
Cinabarite	144	8,5
Galenite	956	7
Hematite	1082	7
Magnetite	1258	2,75
Marble	74	4,25
Molibdenite	192	7
Ortochalse	67	7
Pyrite	1019	6,75
Pyhrotite	586	1,75
Quartz	79	7
Sphalerite	88	7

The microwave roasted pyrite led to relatively low pyrolysis of only 12% extraction. After application of recycling, the pyrolysis extraction increased to about 11,7%. Extraction from the samples pyrolysed in the conventional furnace at 600 °C and 700 °C yielded values of 15% and 17%, respectively.

Microwave treatment could find application in the minerals industry as a pretreatment method for iron ores. Many bio-processing plants treated the bio-wastes by microwave for torrefaction. Microwave roasting could be integrated into such a system in order to make pretreatment faster and more economical. The proposed process that includes even microwave roasting in the pyrolysis circuit is determined in heating by microwave oven. The test results in this method are shown as permittivity loss and heat absorbance as temperature change as seen in Figure 3 and Figure 4.

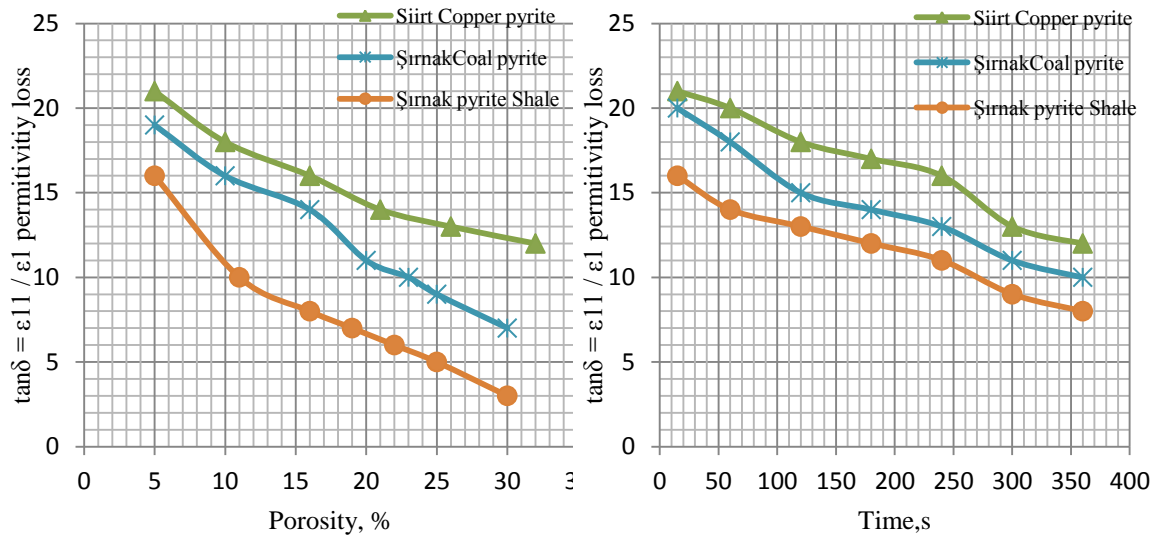


Figure 3. Porosity effect on permittivity loss in Microwave Roasting

Figure 4. Time effect on permittivity loss in Microwave Roasting

3.2. Pyrite Type

The advantages of such a procedure are that coarse coal particles have a lower heating rate than fines, thus, temperature control during pyrolysis would be enhanced. Additionally, there will be improved coal dust control during pyrolysis and the specific energy consumptions required for complete pyrolysis by microwave heating and conventional pyrolysis were about 0,18 and 4,4 kW h/kg, respectively. Typically, the energy consumption in ball milling is between about 4,5 and 9 kWh/kg. Therefore, the combined energy consumption for microwave roasting plus regrinding would still be lower than conventional.

The two major causes of pyrite and iron ores are the presence of ferrous ions and magnetic attenuation of waves in carbonaceous matter and ultra-fine sulphide particles, pyrite and pyhrotite in coal matrix. When less permittivity is due to the presence of both sulphides in coal matter, the shale, silicate clay matrix is called transparent and reflects

through under the microwaves. The carbonaceous matter in the ore adsorbs heat. The most important matter are the organic carbon and coal carbon. The constituents of the organic carbon are amorphous.

Such ores require pretreatment to break down the matrix of the sulphides and oxidize or passivate the carbonaceous matter before pyrolysis. The microwave treatment methods include roasting, chlorination, pressure oxidation, drying, torrefaction, pyrolysis and also digestion and gasification of waste. Microwaves could be utilized as an alternative source of energy for the treatment of ores in some of the unit operations such as drying, calcining, roasting and smelting. Carbon and metal sulphides are known to be very good microwave absorbers and they can be rapidly and selectively heated. Some researchers may improve heat it was indirectly heated by microwaves, therefore using magnetite as a susceptor.

In the present study, the microwave pyrolysis of a coal sample with coal pyrite and copper pyrite was investigated. The concentrate was very responsive to microwave heating and this resulted in almost complete roasting and in some cases sintering of the material as seen in Figure 5.

The changes in the heat absorbing behaviour of the copper pyrite were monitored and the optimum conditions for leaching the pyrolysis rate were established as seen in Figure 6.

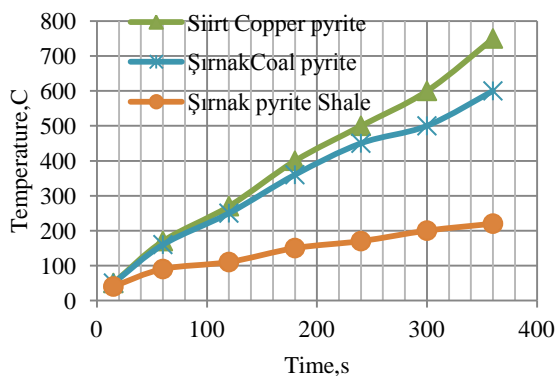


Figure 5. Time effect on temperature in Microwave Roasting

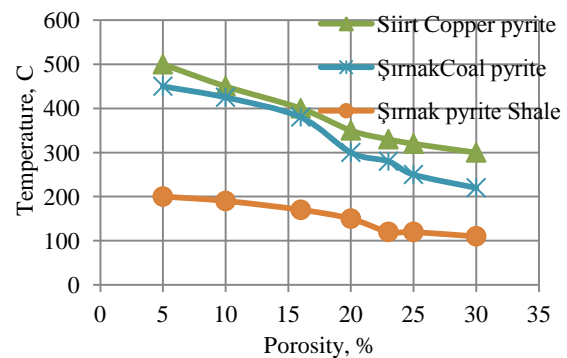


Figure 6. Porosity effect on temperature in Microwave Roasting

800 W, the 15 g sample reached a temperature of about 500 °C while the 25 g sample reached 600 °C. When 50 g of sample was used, the temperature rose to about 700 °C. Generally, in laboratory scale microwave processing, the sample temperature increases with sample mass. In contrast to conventional heating, in microwave systems the heat is generated internally and thus the heat loss from the sample is a major factor that controls the heating behaviour. For samples with a relatively low mass, the high surface area to volume ratio restricts the rate of temperature rise and also the maximum attainable temperature. As a result, the permittivity values are relatively low and the sample cannot effectively couple with the microwave field. On the other hand, for the same cross-sectional area of the crucible, as the sample mass is increased, there is a reduction in the surface area to volume ratio and this reduces the heat loss

from the interior, leading to a higher bulk sample temperature. Additionally, as the sample mass increases, there is more material to interact with the electric field. For comparison purposes, oxidation of the sulphides and the carbonaceous matter in the refractory concentrate was carried out in both the microwave system and a conventional resistance furnace. At an incident microwave power of 800 W, the heat generated was enough to cause melting of the sample and thus further tests were conducted at a lower incident power of 600 W. At 600 W, appreciable oxidation was achieved, without excessive rise in temperature. However, with some samples, sintering was observed. As shown by the results in Figure 3 the roasting process is almost complete at about 600 °C and therefore the conventional roasting tests were performed at 600 °C. Since the permittivity decreased above 700 °C, additional roasting was carried out above 700 °C. Figure 4 shows the effect of roasting time on the carbon content of the concentrate as a function of processing time for both conventional and microwave roasting. It can be seen that the carbon content decreases significantly faster in the microwave tests than in conventional roasting. More than 75% of the carbon was removed within minutes with microwave roasting, while in conventional roasting the same degree of carbon removal would require hours. The behaviour of the coal pyrite is presented in Figure 5. For both microwave and conventional processing, the rate of temperature at the end was higher than that of coal pyrite, which likely reflects the larger amount of iron in the sample. After 30 min, 85% of the sulphur was removed by conventional roasting, while for microwave heating about 65% of the pyrite sulphur was removed at the end of 3 mins. In microwave processing the pyrolysis of coal and pyrite content of coal particles (Figure 6), which are excellent microwave absorbers, are at higher temperatures than in conventional pyrolysis and this leads to higher pyrolysis rates.

4. Conclusions

The specific energy consumptions required to achieve oxidation of the refractory concentrate by microwave heating and conventional roasting were about 0,128 and 4,58 kW h/kg, respectively. In conventional roasting, the specific energy values are higher since the surroundings also have to be heated, while in the microwave process only the sample and the sample carrier are heated.

The oxidation reactions of sulphides are exothermic and if heating is not controlled, there is the tendency for sintering and/or melting to take place. In microwave heating it is more difficult to control the temperature, than in conventional roasting. As a result, some local melting occurred and there was some sintering and formation of some glassy material.

The roasting of copper pyrite and iron ores, the pyrites of coal and shale using microwave radiation has been investigated. The test results showed that there was a continuous mass loss from room temperature to 700 °C with a total mass loss of 12%. The major mass loss of over 10% occurred between 400 °C and 600 °C in coal pyrolysis. This occurred due to the sulphur combustion of and reaction of exothermic heat release from pyrite from the sample. The real and relative permittivities were very high and increased significantly with decreasing frequency. Beyond 400 °C the permittivity decreased and this was attributed to the removal of most of the combustion

of pyrite. The copper pyrite could be heated rapidly and temperatures of over 600 °C were attained with a 50 g sample after microwave heating for 3 min.

For microwave roasting, both the heating rate and the roasting rates were higher with depending on porosity and the specific energy consumptions were lower than the corresponding values for conventional roasting. In roasting and pyrolysis processes, the pyrite content was readily effective in accomplished amount of the reacted matter. Due to the high temperatures generated in microwave heating, sections of the carrier had sintered in which pyrite oxidation of about 65% completed in microwave were roasting.

The microwave heating behavior studies showed that the sample temperature increased with increasing incident microwave power, processing time and sample mass. Due to the hyperactive response of the iron ore to the microwaves, a low incident power of 600W was found to be suitable for roasting, as higher powers resulted in sintering and melting of the concentrate. The copper pyrite values after combustion in roasting were over 25% and these were similar to those obtained by conventional roasting. The main advantages of microwave roasting were that both the total roasting rates and the heating rates were higher and the specific energy consumptions were lower than in coal pyrite.

In the Southeastern Anatolian Region of Turkey, in Ergani Elazığ and Siirt Şirvan copper ore concentrators, containing the pyrite and the high pyrite content discarded is received as pyrite concentrate from concentrating copper by flotation swept and waste products. Ergani Concentrator produce the pyrite concentrate by product about 350 thousand tons for sulfuric acid production and about 1,700 thousand tons of pyrite waste sent to dispose, Siirt Şirvan copper pyrite is not also evaluated. These pyrite waste products both should mainly be evaluated by the iron and copper content and the other metals such as, Au, Ag, Co, must be evaluated in terms of high valuable metal contents. In this study, samples are subjected to microwave roasting of pyrite tailings, ash and subsequently pelletized and subjected to reductive roasting by coal at 1000°C. Sulfur-containing complexes in Southeast Anatolia pyritic copper ores rich hydrothermal ore deposits is 2-4% Cu constitute the vessels. Ergani, Siirt Şirvan and Hakkari copper, lead, zinc Fe sulfide deposits demonstrates the wide disseminated distribution of low and high quality sulphide ore reserves. Ergani copper concentrate are produced by several million tons of ore concentrate processed at least 100.000 tons. Every year about a few million tons of pyrite tailings are discarded to waste. Siirt Şirvan is 400.000 tons per annum of crude ore concentrate produced 300 thousand tons of waste are produced pyrite. Therefore, it is becoming clearer common waste product of pyrite in the region. Occurs in a particle size of these wastes usually occurs below 100 microns in size may be advantageous for the evaluation. In our country, especially in Siirt and Hakkari region that includes reaching 15 m thick seams spread over a large area. The disseminated copper and lead pyrite ores is evaluated for copper production and this ore waste or pyrite tailings, pyrite ash and Fe silicates may greatly discarded. The evaluation of those waste sources in sponge iron production was prompted regarding as chemical properties in the microwave process, and feasible production of sponge iron was managed in this study.

5. References

- [1] Chen TT, Dutrizac JE, Haque KE, Wyslouzil W, Kashyap S. 1984, The relative transparency of minerals to microwave radiation. *Canadian Metallurgical Quarterly*, 123, 3, s. 349–51.
- [2] Amankwah, R.K., Pickles, C.A., 2005. Microwave calcination and sintering of manganese carbonate ore. *Canadian Metallurgical Quarterly* 44 (2), 239–248.
- [3] Amankwah, R.K., Pickles, C.A., Yen, W.T., 2005b. Gold recovery by microwave augmented ashing of waste activated carbon. *Minerals Engineering* 18 (2), 517–526.
- [4] Gabriel C., Gabriel S., Grant E.H., Halstead B.S.J., Mingos D.M.P., 1998, Dielectric parameters relevant to microwave dielectric heating. *Chemical Society Reviews*, 27, s.213–23.
- [5] Datta A K; Sun E; Solis A (1995). Food dielectric property data and their composition-based prediction. In: *Engineering Properties of Foods* (Rao M A; Rizvi S S, eds), Chapter 9, 457–494. Marcel Dekker, Inc., New York
- [6] Datta A K; Nelson S O (2000). Fundamental Physical Aspects of Microwave Absorption and Heating in *Handbook of Microwave Technology for Food Applications*. CHIPS Publications, USA
- [7] Decareau R V (1985). *Microwaves in the Food Processing Industry*. Academic Press, Orlando, FL, USA
- [8] El-Shami S M; Selim I Z; El-Anwar I M; Hassan M M (1992). Dielectric properties for monitoring the quality of heated oils. *Journal of the American Oil Chemists' Society (JAOCS)*, 69(9), 872–875
- [9] Walkiewicz JW, Kazonich G, McGill SL., 1988, Microwave heating characteristics of selected minerals and compounds. *Minerals and Metallurgical Processing* , 5, 1, s.39–42.
- [10] Walkiewicz J.W., Clark A.E., McGill S.L., 1991, Microwave assisted grinding. *IEEE Transactions on Industry Applications* ,27, 2, s.239–43.
- [11] Haque KE. Microwave energy for mineral treatment processes—a brief review, 1999, *International Journal of Mineral Processing*, 57, 1, s.1–24.
- [12] Jacob J., Chia L.H.L., Boey F.Y.C., 1995, Review—thermal and non-thermal interaction of microwave radiation with materials. *Journal of Materials Science*, 30, 21, s.5321–7.
- [13] Kelly RM, Rowson NA., 1995, Microwave reduction of oxidised ilmenite concentrates. *Minerals Engineering*, 8, 11, s.1427–38.
- [14] Metaxas, A.C., Meredith, R.J., 1983. *Industrial Microwave Heating*. Chapter 10, Peter Peregrinus, London, UK.
- [15] Hutcheon, R.M., De Jong, M.S., Adams, F.P., 1992. A system for rapid measurement of RF and microwave properties up to 1400 °C. *Journal of Microwave Power and Electromagnetic Energy* 27 (2), 87–92.
- [16] Hutcheon, R.M., De Jong, M.S., Adams, F.P., Lucuta, P.G., McGregor, J.E., Bahen, L., 1992a. RF and microwave dielectric measurements to 1400 °C and dielectric loss mechanisms. In: *Materials Research Society Symposium Proceedings (Microwave Processing of Materials III)*, vol. 269, pp. 541–551.

- [17] Hutcheon, R.M., Hayward, P., Smith, B.H., Alexander, S.B., 1995. High-temperature dielectric constant measurement – another analytical tool for ceramic studies. *Microwaves: Theory and Application in Materials Processing III*, vol. 59. *Ceramic Transactions*, American Ceramic Society, pp. 235–241.
- [18] Karmazsin, E., 1987. Use of low – and high-power microwave energy for thermal analysis. *Thermochimica Acta* , 110, 289–295.
- [19] Lu, T., Pickles, C.A., Kelebek, S., 2007. Microwave heating behaviour of a gibbsite type bauxite ore. In: Bekguleryuz, M.O., Paray, F., Wells, M. (Eds.), *Proceedings of Symposium on Light Metals in Transport Applications. MetSoc (CIM)*, Toronto, Ont. Canada, pp. 421–449 (August 25–30).
- [20] Ma, J., Pickles, C.A., 2003. Microwave segregation process for nickeliferous silicate laterites. *Canadian Metallurgical Quarterly* 42 (3), 313–326.
- [21] Veasey TJ, Fitzgibbon KE., 1990, Thermally assisted liberation—a review. *Minerals Engineering* , 3, 1/2, s.181–5.
- [22] Xia D.K., Pickles C.A., 2000, Microwave caustic leaching of electric arc furnace dust, *Minerals Engineering*, 13, 1, s.79–94.
- [23] Kılıç Ö., 2009, Mikrodalga ile Isıl İşlem Uygulamanın Kireçtaşı Kalsinasyonuna Etkisi, *Madencilik*, 48, 3, s 45-53.
- [24] Kingman S.W., Vorster W., Rowson N.A., 1999, The influence of mineralogy on microwave assisted grinding. *Minerals Engineering*, 3,3, s.313–27.
- [25] Marland S, Han B, Merchant A, Rowson N., 2000, The effect of microwave radiation on coal grindability. *Fuel*, 79, 11, s.1283–8.
- [26] Salsman J.B., Williamson R.L., Tolley W.K., Rice D.A., 1996, Short-pulse microwave treatment of disseminated sulphide ores. *Minerals Engineering*, 9, 1, s.43–54.
- [27] Standish, N., Worner, H.K., Gupta, G., 1990. Temperature distribution in microwave heated iron ore–carbon composites. *J. Microwave Power Electromagnet Energy* 25 _2., 75–80.
- [28] Standish, N., Worner, H.K., Obuchowski, D.Y., 1991. Particle size effect in microwave heating of granular materials. *Powder Technology* 66, 225–230.
- [29] VanWyk EJ, Bradshaw SM, de Swardt JB., 1998 The dependence of microwave regeneration of activated carbon on time and temperature, *Journal of Microwave Power and Electromagnetic Energy* ,33, 3, s.151–7.