Direct vaporization and ionization of the metals wires using microwave field

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We present a microwave absorption experiment used in the vaporization and ionization process of metal wires. The experiment uses a commercial source having the 2.45 GHz frequency at 800 W microwave power and a cylindrical cavity having the TM_{011} propagation mode. Inside the cylindrical cavity solid state metal wires were placed: indium, lead and zinc. The metallic wires having 0.5 mm diameter are directly vaporized and ionized in direct interaction with the microwave field from the cylindrical cavity. We investigate the dependence between the metal quantity which is vaporized and ionized by the microwave field and the electrical resistivity of the metallic wires. In order to improve the microwave metal absorption we investigate the possibility of using multi-wire metals in the vaporization and ionization processes. The experiment was conducted in air at normal atmospheric pressure and room temperature.

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1. Introduction

Microwave application for heating was discovered in 1946 and has been applied to drying, cooking food and to excitation of chemical reactions such as inorganic/organic synthesis. Microwave heating is a process where by microwaves couple to materials, which absorb the electromagnetic energy volumetrically and transform it into heat. Microwave heating of dielectric materials has been widely investigated and the interaction mechanism between microwave and materials is well documented. The heating is caused by a dielectric relaxation loss due to the rotation and vibration of molecules, which is a result of the interaction with the microwave electric field [1, 2]. In ceramic materials the microwave absorption mechanism is not limited only to dielectric loss, but to ohmic loss as well. At room temperature many ceramics such as: SiO_2, Al_2O_3 etc. do not absorb microwave energy appreciably. One way to improve the microwave absorption is to heat the ceramics before exposure to microwave [3].

In metallic powders the microwave absorption mechanism is characterized only by ohmic loss.

In the history of microwave applications for heating, metal heating has been a minor application area because bulk metals are very good radiation reflectors and cannot be heated. Microwave sintering of metal powders which have high electrical conductivity becomes a new interesting area. The microwave absorption by metal powders was first reported in 1999 by Roy and co-workers [4]. They found that copper powder samples including very complex shaped and large size (100 mm diameter, 1 kilogram) could be fully sintered in 30 min in a 2.45GHz multi-mode cavity. In 2001 J. Cheng and co-workers used a TE_{103} single mode cavity in order to investigate the microwave heating behaviors of various high conductivity materials in different microwave fields. Their studies about the heating behavior of the metallic samples in E and H microwave field showed that metal powder-compact samples can be much more efficiently heated up in the magnetic field [5]. In 2007 Jun Kun Ma and co-workers confirmed that copper powder-compact samples can be much more efficiently heated up in the magnetic field [6].

According to A. Mondal and co-workers when the dimension of the metal powders increases the microwave heating rate decreases and after a certain time the heating rate becomes constant at a particular power setting [7]. The metal powders which have particle dimensions equal to the skin depth of that metal are the best microwave absorbent. The microwave absorption by metal wires was reported in 2010 by G. Mogildea and M. Mogildea [8]. It was demonstrated that lead metal wires having diameters less than 0.5 mm can be vaporized and ionized by microwave from the cylindrical cavity having the TM_{011} propagation mode. In their experiments a commercial source having the 2.45GHz frequency and 800W microwave power was used. Later we investigated the possibility of controlling the quantity of metal (lead wires) which is vaporized and ionized in this manner. In our experiment we used a cylindrical cavity having the TM_{012} propagation mode. We found that when the microwave pulse duration changes, the quantity of vaporized and ionized metal changes as well [9]. In November 2010 G. Mogildea and M. Mogildea investigated the microwave heating behaviors of metal wires (lead) in vacuum conditions. They found that at 10^{-5} milibar pressure the vaporization and ionization process of the metal wires does not occur and the metal wire is only heated up to melting temperature. Because in air at normal atmosphere and room temperature, the metallic wires can be heated up to plasma temperature but in vacuum conditions the metal wires do not exceed the melting temperature, we inferred that air molecules could contribute to the metal microwave absorption process. In order to investigate if the gas molecules have any contribution to the microwave heating process of metallic wires we used a small teflon piece. When the teflon piece was heated in vacuum conditions it decomposes in gases. We found that the metal wire generates a strong electric field when exposed to microwave. This electric field ionizes the gases from the teflon piece. The heat generated by the teflon ion gas will vaporize the metal wire and the metal vapors will be ionized in the microwave electric field from the cavity [10].

The present paper focuses on the investigation of the microwave absorption process for different metal wires such as: indium, lead and zinc, which have melting temperatures below 500˚C and magnetic permeability equal to 1.We aim to study the dependence between the electrical resistivity of the metals and the quantity of metal vaporized and ionized in the microwave field. We will also study if through the use of multi-wires having the same diameter, the microwave absorption by the metal wires will be improved. The experiment is realized in air at normal atmospheric pressure and room temperature. For these studies we use a cylindrical cavity having the TM_{011} propagation mode. The propagation mode of the microwave radiation was selected because in the cavity, the region of half-wavelength of the electromagnetic field has the highest electromagnetic energy density. In the TM_{011} propagation mode the microwave electric field propagates along the axis of the cylindrical cavity in Fig.1, therefore the microwave electric field is responsible for the microwave absorbing process of the metal wires.

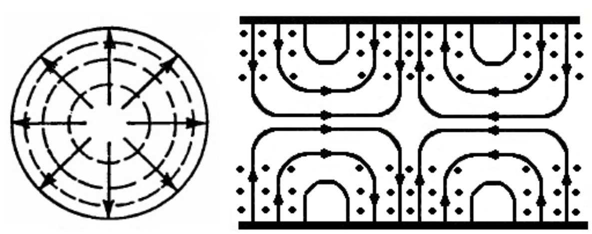

a) b)

Fig.1 Field distribution of TM_{011} mode in the cylindrical cavity a) Cross-Sectional view; b) Longitudinal view E- full lines; H- dashed lines

The dimensions of the cylindrical cavity are 9 cm length and 10.5 cm diameter and were calculated with the following equation:

$$(f_r)_{mnl}^{TM} = \left(\frac{1}{2\pi\sqrt{\mu\cdot\varepsilon}}\right)\cdot\sqrt{\left(\frac{p_{01}}{a}\right)^2+\left(\frac{l\pi}{h}\right)^2}\ ; \qquad (1)$$

where:

a - radius of the cylindrical cavity (m); h - height of the cylindrical cavity (m);

l - longitudinal mode of the cavity; μ - permeability of the medium within cavity (H/m);

ε - permittivity of the medium within the cavity (F/m); p_{01} - first zero of the Bessel function (equal to approx. 2.405); f_r – the resonant frequency of the cavity. The indices *nml* of the *TM* propagation mode refers to the number of half wavelength variations in the radial, axial and longitudinal directions.

The vaporization and ionization process of metal wires is based on the interaction between the microwave electric field and metals. The microwave power in the cylindrical cavity is given by the Poyting equation (2) [11]

$$\vec{P} = \frac{1}{2}\vec{E}\times\vec{H}^* = \frac{1}{2}\frac{|E|^2}{\eta} \qquad (2)$$

where: η is the impedance of the cylindrical cavity; E is the electric field; H is the magnetic field.

When the microwave power from the microwave cavity increases the electric field from the microwave cavity also increases and the interaction between metals and the microwave electric field will be stronger. The microwave electric field will generate electric charges on the surface of metals. The relationship between the microwave electric field and the current density (conduction and displacement current) is:

$$J = (\sigma + j\omega\varepsilon)\vec{E} \qquad (3)$$

These electric charges will generate an electric field having a very high magnitude and will ionize air atoms near the metal wires. The air plasma vaporizes the metal wires and the microwave electric field will ionize the metal vapors. When a multi-wire is introduced in the microwave field, each metal wire will generate its own electric charges. Compared to a single wire, the quantity of vaporized and ionized metal for multi-wires is greater at equal microwave powers.

2. Description of the experimental setup

The experimental setup used for the vaporization and ionization of the metallic wires consists of three main electric (power supply and microwave source) and mechanic (resonant cylindrical cavity) blocks. The power supply feeds the microwave source (the magnetron of 2.45 GHz / 800W) and allows the adjustment of the duration of pulses from the anode magnetron between 1ms – 20ms. When the anode magnetron voltage pulses are modified the microwave pulses in the cavity will be modified and the metal quantity which is vaporized and ionized will be modified as well. In order to know the microwave power inside the cavity we measured the power consumed by the anode magnetron. An ampermeter connected between the grid voltage and the power supply from the anode magnetron recorded the consumed current (Fig 2).

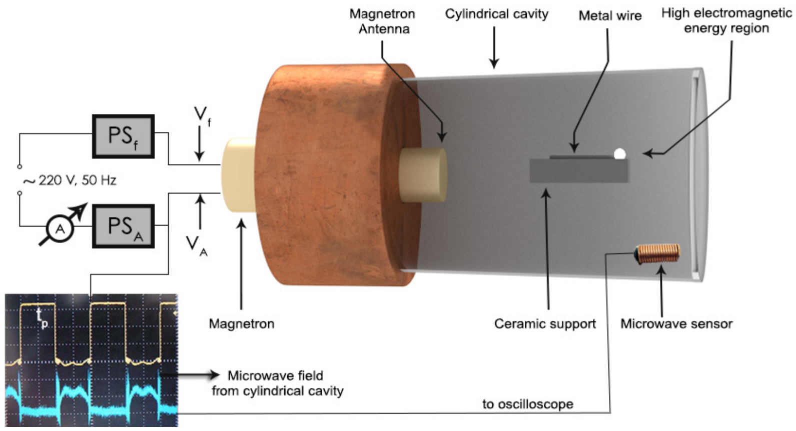


Fig.2 Schematic of the experiment used for the vaporization and ionization of the metallic wires.

where,

- power supply of the filament, - power supply of the anode, - electric potential of the filament,

- electric potential of the anode

The total power used in the vaporization and ionization process of the metal wire is:

(4)

where:

is the electric power used for powering the magnetron anode and is the electric power used for powering the magnetron filament. The magnetron emits frequency modulated microwave pulses that have lengths between 1ms and 20 ms. The power of the anode magnetron can be calculated using equations (5) and (6):

(5)

(6)

where is the duty factor; is the pulse duration in seconds; n is the pulse repetition rate in Hz;

= 800 W is the power of a pulse from the anode magnetron;

The experiment takes into consideration the efficiency of the magnetron (conversion of electric power to microwave field) which is estimated at 75 %.

To compare the vaporization and ionization process of a single metal wire and multi-wires by microwave we made several tests using metal wires such as: indium, lead and zinc. These high conductive materials have different electrical proprieties and different melting temperatures. All samples (the metal wires) have a 0.5mm diameter and a 45 mm length. Each sample was weighed before it was introduced in the high density energy region of the cylindrical cavity. Each sample was placed on a ceramic support and was introduced in the cavity (Fig. 2).

Because in the TM_{011} propagating mode, the electric field propagates along the axis of the cavity, the solid metal wire and the multi-wires must be positioned along and as close as possible to that axis. All samples were exposed to the same microwave power for 10 seconds and were vaporized and ionized during the interaction with the microwave field. For the 2.45 GHz frequency, the high density energy region is located at 6.3 cm distance from the magnetron antenna. In Fig. 3 a zinc wire is vaporized and ionized when exposed to 150 W microwave power. In Fig. 4 two lead wires are vaporized and ionized when exposed to 150 W microwave power.

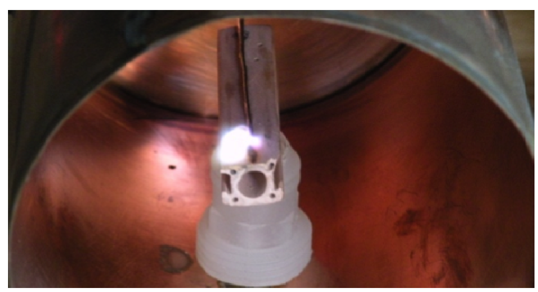


Fig. 3 The zinc sample is vaporized and ionized at 150W microwave power

Fig. 4 Two lead wires are vaporized and ionized at 150W microwave power

In Fig. 5 two lead wires are presented before and after being introduced in the high electromagnetic region of the cylindrical cavity. The marked area represents the high density electromagnetic energy region.

Fig.5 Lead sample before and after exposure to the microwave field from the cavity.

3. Results of the study and their analysis

The experiment reveals that the dimension of the high density electromagnetic energy region from the cylindrical cavity is about 5 mm. Only the part of the metal wire in the high density electromagnetic energy region was vaporized and ionized, while the rest of the metal wire from the cavity was found in solid state (Fig. 5). After the interaction between the microwave field and the metal samples, the quantity of vaporized and ionized metal was different for each metal wire, due to the fact that the metal wires have different electrical resistivities. When the metal wire is heated by plasma air which is found around the metallic wire, according to formula 7, the electrical resistivity will increase and therefore the loss factor (formula 8) will increase as well. In graph 1 the dependence between the loss factor of each metal sample and temperature is presented.

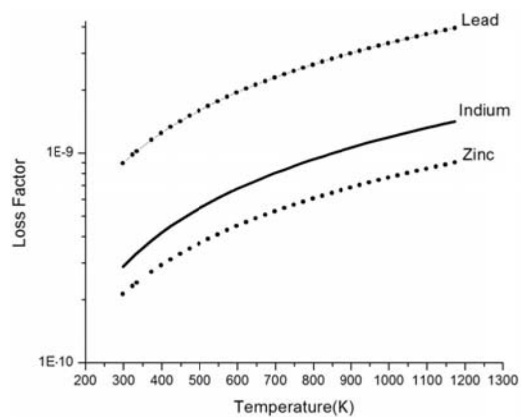
$$\rho(T) = \rho_0[1+\alpha(T-T_0)] \tag{7}$$

Where ρ is the resistivity value adjusted to T, ρ_0 is the electrical resistivity at 20 , is the temperature coefficient, T is the temperature at which the electrical resistivity value needs to be known, = 20 .

The loss factor of metals (formula 8) depends on their electrical resistivity. Therefore each metal wire will be heated differently in the microwave field and the vaporized and ionized quantity of metal will be different.

$$\varepsilon^{"}(T) = \frac{\sigma(T)}{\omega\cdot\varepsilon_0} = \frac{1}{\omega\cdot\varepsilon_0\cdot\rho_0[1+\alpha(T-T_0)]} \tag{8}$$

Where is the loss factor, is the conductivity of metals, is the vacuum permittivity, , f = 2.45GHz, f is the frequency of the electromagnetic radiation.



Graph1. Dependence between the loss factor of each metal sample and temperature.

The metal samples with high electrical resistivity will have higher loss factors and will couple better to the microwave field from the cylindrical cavity. Table 1 presents how the vaporized and ionized quantity of metal depends on the microwave field from the cylindrical cavity.

Table 1. Dependence of the vaporized and ionized quantity of metal at different microwave powers

The metal wire (0.5 mm diameter)	The microwave power (W) inside the cavity	The quantity of vaporized and ionized metal (mg/s)	Melting point ( )	Electrical resistivity (Ω·m) at 20°C
indium	150	2,4	156.6	$8\cdot10^{-8}$
	300	5,2		
	600	30		
lead	150	3.6	327.46	$2.5\cdot10^{-7}$
	300	38		
	600	43		
zinc	150	1.44	419.53	$5.9\cdot10^{-8}$
	300	2.88		
	600	9.72		

If in the cylindrical cavity the microwave power will increase according to equation (2) the microwave electric field will increase as well, which will lead to the increase of the charge density on the metallic wire surface (equation 3). Because the charge density from the metallic wires is responsible with the generation of the electric field for the ionization of air molecules, we expect to be able to vaporize and ionize metallic wires with diameters larger than 0.5 mm if we use microwave powers greater than 800W.

Because the metal wires in solid state can be converted directly to vapors and plasma state, this method could be further used in different scientific applications, such as deposition of thin layers and metallic coating.

4. Conclusions

We found that the quantity of vaporized and ionized metal depends on the electrical resistivity of each metal. For metals with small electrical conductivity the vaporization process starts at smaller microwave powers.

We also found that if we use two wires (multi-wires) in the vaporization and ionization process (the wires having the same diameter) the quantity of vaporized and ionized metal increased with approx. 25%. The metal wires having diameters lager than 0.6 mm become radiation reflectors when exposed to 800 W microwave power.

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