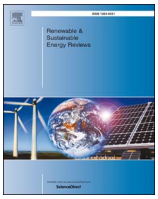
ARTICLE IN PRESS

Renewable and Sustainable Energy Reviews xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser



Microwave dielectric heating: Applications on metals processing

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ARTICLE INFO

Keywords:
Microwave
Heating
Metals
Sintering
Dielectric

ABSTRACT

Microwave material processing is a novel energy efficient technology with improved mechanical properties, minimized defects and economical and environmental advantages making it a convenient application for various types of materials. Although, microwave interaction with matter has been largely investigated and published in food processing, ceramics and chemistry, no particular work has been involved in collecting the interactions of microwaves with metals and placing a special emphasis on their interaction with metals and metal-based formulations, and here resides the aim of the review: consolidating the fundamentals of microwave heating applications as a time and energy saving application and addressing its various applications and mechanisms with metal interactions seeking a more sustainable environment. This review reports the latest literature findings on microwave processing fundamentals and highlights the advanced technological improvement applied on metals in this field. It focuses on the relevant industrial applications related to the development of microwave technology on metals and its possible future processing in this specific scope of investigation.

Table 1

1. Theory and mechanisms: microwave heating

Energy radiated in a wave traveling at the speed of light, is the electromagnetic radiation presented by Maxwell as the electromagnetic theory. It comprises both electrical and magnetic fields oscillating in the direction of propagation at right angles (Fig. 1) [1].

Referring to the electromagnetic spectrum (Fig. 2), microwave length is classified into segments nominated as ultra high frequency (300 MHz to 3 GHz), super high frequency (3–30 GHz) and extremely high frequency (30–300 GHz) (Check Fig. 2). However RADAR transmission uses extensively wavelengths up to 25 cm and telecommunication applications are used for the rest of the wavelength. In order to ensure no occurrence of radiation losses, domestic and industrial microwave heaters do not have to interfere with these uses and their operations frequencies are designated by 900 MHz and 2.45 GHz corresponding respectively to 33.3 cm and 12.2 cm wavelengths. Microwave usage is significantly diverse; it is not largely used for heating applications only, but for power transmission, radar, communication industry and many other successful medical and scientific appliances [1]. Many workers have been contributing to the development of microwave heating theory among which are cited Debye, Cole and Cole, Frohlich, Daniel, Hill and Hasted [2–7].

An alternative to the conventional conductive heating resides in the conversion of the electromagnetic energy into heat. This ability characterizing some liquids and solids and driving major chemical reactions is defined as microwave dielectric heating. Molecules studied in the gas phase, show a spectrum of sharp bands [8] from 3 to 60 GHz. The equation of rotational energy defines the arising transition between the rotational state of the molecule (Eq. (1)).

$$E_j = \frac{J(J+1)h^2}{8\Pi^2 I} \tag{1}$$

J, *I* and *h* refer to the rotational quantum number, the moment of Inertia and the Planck´s constant respectively. For a pure rotational spectrum to be observed, the molecular rotation has to be associated with an oscillating dipole. Microwave spectroscopy results from discrete quantized energy that are not well spaced. Conductive losses occur if a current is induced by the particles free to move in a substance and will result in magnetic loss heating or Joule heating [9]. Whenever they are restricted to only defined regions, the charge carriers will keep moving until they are balanced by a counter force and producing dielectric polarization [10]. However, most of the research evading from dielectric heating is still insufficient and dielectric heating is the soul of the microwave matter interaction investigations in multiple technological fields going from food processing to medical waste treatment, pyrolysis processes, sintering of metals, drying processes and other physical and chemical fields [11–14]. In these fields, microwave dielectric heating is cited for the distinguished advantages; microwave

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http://dx.doi.org/10.1016/j.rser.2017.10.043
Received 10 December 2016; Received in revised form 13 July 2017; Accepted 26 October 2017

Please cite this article as: El Khaled, D., Renewable and Sustainable Energy Reviews (2017), http://dx.doi.org/10.1016/j.rser.2017.10.043

Table 1
Table of Acronyms.

Siglas	Concept	Siglas	Concept
λ_0	Wavelength	Ej	Rotational energy
ε'_∞	High frequency constant	EM	Electromagnetic
ε'_0	Static dielectric constant	f_{max}	Maximum frequency
ε''_{max}	Maximum dielectric loss	H	Planck´s constant
ε'_d	Debye dielctric constant	H-field	Magnetic field
ε''_{eff}	Effective dielctric loss factor	H_{RMS}	Magnetic field strength
μ''_{eff}	Effective magnetic loss	I	Moment of inertia
μ_0	Vacuum permeability	J	Rotational quantum number
ε_0	Vacuum permittivity	K	Boltzmann´s constant
μ'_r	Relative magnetic constant	LPS	liquid phases sintering
μ''_r	Relative magnetic loss	M	Mass of molecules
τ	Relaxation time	N	Number of molecules
η	Viscosity	P	Power dissipated
σ	Conductivity	R	Radius
ρ	Resitivity	SLPS	Supersolidus liquid phase sintering
ε'	Dielectric constant	T	Temperature
ε''	Loss factor	TEM	transmission electron microscopy
$\mu''_{eddy\ currents}$	Eddy current magnetic loss	U_a	Energy barrier
$\mu''_{hysteresis}$	Hysteresis magnetic loss	ν	Volume fraction
μ''_r	Relative magnetic loss	$\varepsilon''_{\mathrm{d}}$	Debye dielectric loss factor
$\mu''_{residual}$	Residual magnetic loss	$\varepsilon''_{\mathrm{dipolar}}$	Dipolar dielectric loss
μ'_r	Relative magnetic constant	$\varepsilon''_{\mathrm{interfecial}}$	Interfacial dielectric loss
D	Distance	$\varepsilon''_{\mathrm{polarization}}$	Polarization dielectric loss
Dp	Penetration depth	$\varepsilon_{\mathrm{RMS}}$	Electric field strength
DSC	Differential scanning calorimetry	ρ	Resistivity of material
DTFD	Finite difference time domain	ω	Angular frequency
E-field	Electric field		

dielectric heating is recognized for being selective, it is a rapid process with a considerably quick start up and stop, it can treat waste in-situ with portable processes and equipments and most importantly of all is that it does not require contact heating [9]. While transparent materials do not absorb microwaves, conductor materials reflect them back causing plasma formations. Only microwave coupled materials absorb these radiations and convert them into heat [15].

1.1. *Microwave interaction with matter*

The electromagnetic field is constituted essentially by the electric field (E-field) and magnetic (H-field) field. These two components making up electromagnetic field have different mechanisms in their interaction with materials which is significantly important for the design and development of any microwave heating application. For instance, common ceramic phases show radical heating differences depending on which component of the field is used, sintering of ceramic shows successful applications for the reason that microwave radiation absorption is possible at room temperature and diffusion is enhanced with lowering the temperature [16–21]. Reflection, absorption and transmission are the three interactions that can occur in single or combination fashion whenever a medium is encountered by an electromagnetic field due to determined mechanisms responsible of the microwave interaction with a matter. These mechanisms are recognized as losses whether dielectric, conductive or magnetic [9].

The fact that electromagnetic energy is converted to thermal energy makes microwave heating different from conventional heating involving heat generation. Whenever microwaves penetrate into the material to supply energy, heat is generated in the whole volume and volumetric heating occurs [11,22,23]. Volumetric heating minimizes the processing time, lowers the consumption of power and improves the diffusion rate [24–26]. Moreover, heat is converted from electromagnetic energy within the material. Thus the outer surface of the materials will receive heat produced from the core of the sample in a direct manner towards it providing selective and uniform heating [15]. At high frequencies, polar molecules with electric dipoles are under the effect of the electric component of the electromagnetic radiation then microwave heating is most often assigned to dielectric heating as well. In such cases, magnetic field is coupled to some materials beside the electric field inducing heating [9]. Microwave ovens are massively used and available at low prices and they constitute a major component in most common chemical undergraduate courses. However, microwave dielectric heating is a neglected subject that has been selectively used in the applications at chemical laboratories.

On a worldwide interest, contribution to energy consumption reductions are arising essentially in the production of renewable energies whether solar, wind, biomass or geothermal [27], and is not limited to bioclimatic architectural systems implementations [28] or the development of models for high heating values of residues [29]. Recently, Mariprasath and Kirubakaran reviewed some edible oils as alternative to liquid dielectrics to motivate their research and possible utility in dielectric transformers replacing the mineral less biodegradable oil for environmental purpose [30]. Additionally, El Khaled et al. reviewed the dielectric properties of alcohols and alcohols mixtures though microwave heating characterization which owes a great potential in

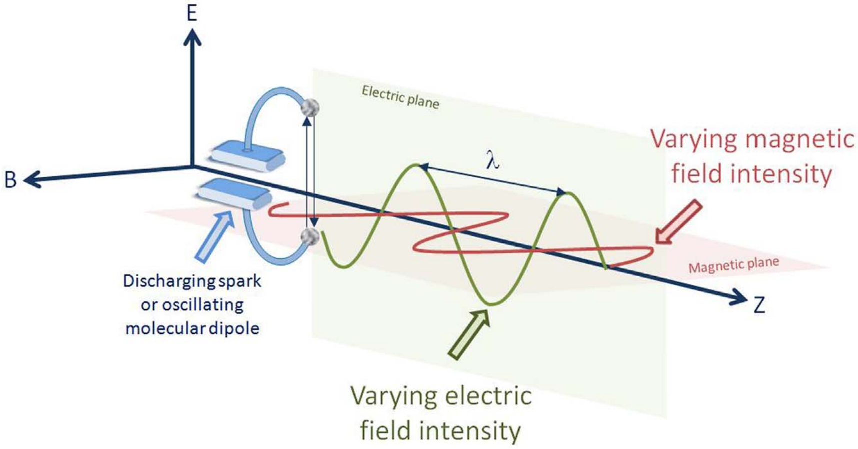

Fig. 1. Schematic representation for the propagation of an electromagnetic wave.