Microwave dielectric heating: applications on metals processing.

El Khaled D[1,2], Novas N[1,2], Gázquez JA[1,2], Manzano-Agugliaro, F[1,2,]*

[1] Dpt. Engineering. University of Almeria, 04120 Almeria, Spain
[2]CIAIMBITAL (Research Center on Mediterranean Intensive Agrosystems and Agrifood Biotechnology), University of Almeria, 04120 Almeria, Spain

*Corresponding author. Tel.:+34 950015396; Fax: +34950015491.

E-mails: dalia.elkhaled@gmail.com; nnovas@ual.es; jgazquez@ual.es; fmanzano@ual.es

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.

Keywords: microwave, heating, metals, sintering, dielectric.

Table 1. Table of Acronyms

Symbol	Concept	Symbol	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 dielectric constant	H-field	Magnetic field
ε''_{eff}	Effective dielectric 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	Resistivity	SLPS	Supersolidus liquid phase sintering
ε'	Dielectric constant	T	Temperature
ε''	Loss factor	TEM	transmission electron

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			microscopy
$\mu''_{eddy\ currents}$	Eddy current magnetic loss	U_a	Energy barrier
$\mu''_{hysteresis}$	Hysteresis magnetic loss	v	Volume fraction
μ''_{r}	Relative magnetic loss	ε''_{d}	Debye dielectric loss factor
$\mu''_{residual}$	Residual magnetic loss	$\varepsilon''_{dipolar}$	Dipolar dielectric loss
μ'_{r}	Relative magnetic constant	$\varepsilon''_{interfecial}$	Interfacial dielectric loss
d	Distance	$\varepsilon''_{polarization}$	Polarization dielectric loss
Dp	Penetration depth	ε_{RMS}	Electric field strength
DSC	Differential scanning calorimetry	ρ	Resistivity of material
DTFD	Finite difference time domain	ω	Angular frequency
E-field	Electric field		

1. A brief overview of microwaves interaction with matter

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). In general, the wavelength of electromagnetic (EM) radiations allows classifying them in a wavelength decreasing order from radio waves to microwaves then infrared radiation passing visible light, ultraviolet, X-ray and ending in Gamma. This order corresponds appropriately to an increasing frequency range [1].

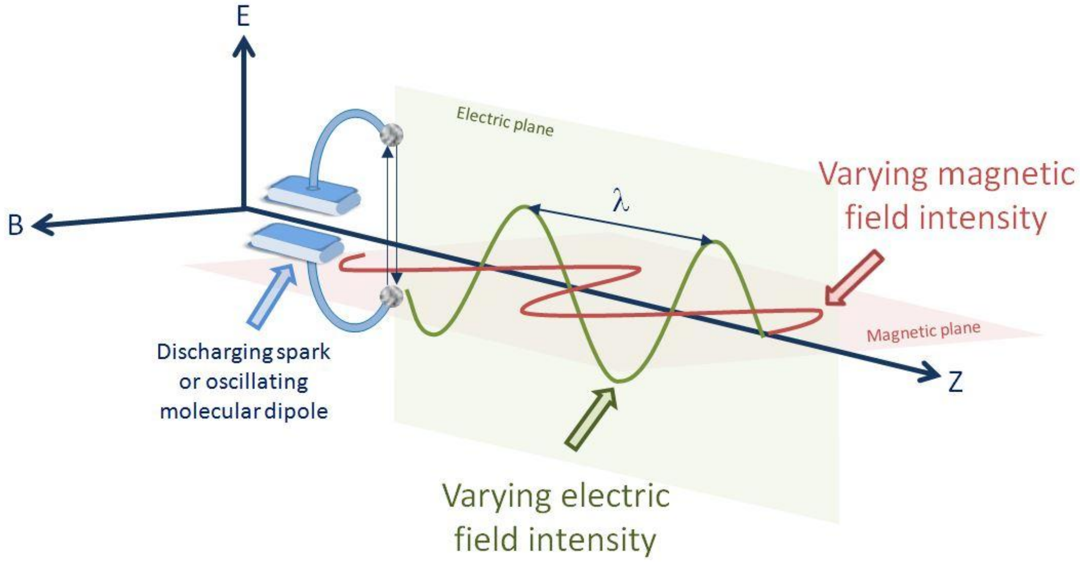

Fig. 1. Schematic representation for the propagation of an electromagnetic wave.

Referring to the electromagnetic spectrum (Fig. 2), the microwave region lying between infra-red radiations and radio frequencies corresponds to microwaves moving at the speed of light in a sequence of frequencies going from 300 MHz to 300 GHz. This spectrum corresponds to wavelengths varying between 1m and 1mm. Further, microwave length is classified into segments nominated as ultra-high frequency (300 MHz to 3 GHz), super high frequency (3 to 30 GHz) and extremely high frequency (30 to 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].

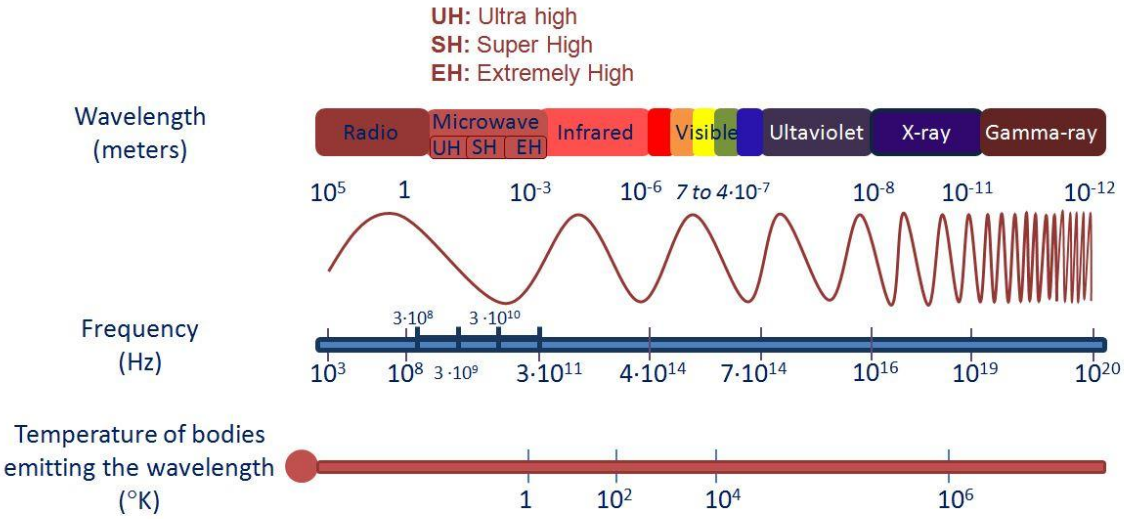

Fig 2. Electromagnetic Spectrum.

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. Differently from the gas phase reactions where a plasma can be created by a microwave discharge with very high temperature and causing recombination and fragmentation reactions, the application of microwave dielectric heating is very attractive to chemists not only for its “in situ” mode but for its magnitude dependence on the material´s properties. In fact, microwave dielectric heating reflects a generic confusion persisting in minds requiring distinction with microwave spectroscopy. Concerning microwave spectroscopy, it can assure a relevant fingerprinting technique for identifying molecules in the gas state and a wide variety of molecules in outer space can be confirmed through this technique. 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).

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

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. On the other hand, when the spectra is considered as broad for possible observation, microwave dielectric heating effect becomes relevant at liquid and solid state where the molecules are not dependent to rotate with freedom. Under high frequency electromagnetic waves, a force is exerted on the charged particles by the electric field, hence producing a heating effect. Microwave heating can result in two phenomenon conduction and dielectric polarization. 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 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].

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 diverging the biodiesel production from conventional fossil fuels to environmental friendly biofuels [31]. Thus, microwave heating technique is viewed as a potential technology with unique commercial and scientific advantages in retaining environmental sustainability and assuring energy efficiency. In this regard, the review proposes an energy efficient heating of material processing through microwave dielectric heating. In the objective of reducing time processing and improving product quality, new techniques are developed to replace the old conventional techniques of metal processing. This purpose meets appropriately the objective of encountering relevant sustainable energy methods especially that microwave heating targets primarily reducing material and energy waste [32] where new environmental regulations are satisfied with the latest dielectric heating applications. For our knowledge, no reviews are published recently that tackle the heating of metallic powder metal materials.

The objective of this review is to define and explain the basics of microwave dielectric heating as an advanced heating tool satisfying energy requirements and environment sustainability recommendations. It aims to build a guided strategy for the use of microwave heating into several metallic applications by charactering the interactions mechanisms of electric and magnetic fields with metal types of materials to develop comprehensive understanding of the mechanisms developed and introducing some recent applications in the metallurgy.

2. Theory and Mechanisms: Microwave heating

Microwave heating effect resulting from polarization or conduction depends on the power applied as well as the frequency. For metal based materials interaction, featured effects are outlined by reflection, heating and discharge. It is often said that bulk metals are ready to reflect the incident waves instead of coupling with microwave energy to heat effectively. In fact, resonance causes the constructive interference which alters the distribution of the electromagnetic field intensity spatially through constructive interference. This helps and thus improving the absorption of power and nondestructive interferences suppressing it. In this concern, the role of the metallic coating highly studied in single or multiple cavity mode might be doubtless and efficient thermal process can be achieved through constructive resonance. The penetration of electromagnetic waves results in the concentration of electrons at the surfaces and edges. As a consequence, the energy is discharged in form of arcing where the penetration depth is a major parameter; the thickness of material to be heated under microwaves is limited by this skin depth. Another consequence is the Eddy current induced at the superficial of the metal by heating effect [9].

2.1 Electric field Component (E-field)

2.1.1 Dielectric polarization

Microwave heating occurs when charges in a material are polarized by an electric field and polarization is unable to chase the quick reversals of an electric field. Electronic, atomic, dipole and interfacial are the individual components that are summed together to form the total polarization. Electrons realigned in the neighbor of a particular nucleus create electronic polarization. Charges distributed non-uniformly within a molecule lead to an allied displacement of the nucleus which is defined by atomic polarization. Orientation of permanent dipoles by the electric field results in dipolar polarization. When charges are built up at interfaces, interfacial polarization occurs and it is recognized as well by the Maxwell Wagner effect. However, due to their fast timescales of polarization and depolarization (faster than microwave frequencies with 10^{-9} s), electronic and atomic polarizations do not contribute to dielectric effect. With the oscillation of an electric field under the radiation of electromagnetic waves, time scale associated with the orientation and disorientation phenomena is reliant on the response time of the material under test. Time scales of the permanent dipole moments on the molecules and interfacial processes, reflected by dipolar and interfacial components, are compared to microwave frequencies, which put them under focus of the dielectric characterization [10].

A- Dipolar

Having differences in their electronegativities, oxygen and hydrogen atoms cause the occurrence of dipole moments and therefore lead to dipole polarization often exciting in liquid water. Being in phase with the dielectric polarization at low frequencies, the electric field changing its direction requires a duration correspondent with the response time of the dipoles.

In order for the molecules to rotate into arrangement, the needed energy is provided by the field where a part of this energy goes to realign a dipole being knocked out alignment randomly. However, a rapid change of the electric field oscillation will provoke the dipole to acquire a faster response time. As a matter of fact, dipoles do not rotate and water does not heat up if there is no energy absorption. With a small energy transfer, the temperature increase is hard.

In fact, dipoles at microwave frequencies experience torques pushing them to rotate because the field changes appropriately with their response time. Polarization keeps growing meanwhile the field fades; this falter is a sign that water is heated due to energy absorption from the field. The interesting parameters in the dielectric properties are the dielectric constant (ε') reflecting the polarization of dipoles, this value reaches its maximum at low frequencies where the maximum amount of energy is stored, whereas the dielectric loss factor (ε'') reflecting the ability of the manner to transform electromagnetic radiation into heat increases to its maximum with the decrease of dielectric constant. Fig. 3 is a schematic graph presented to show the dependence of permittivity components (ε' and ε'') with frequency [33]. The time required by dipoles to reach polarization and returning back depolarized is defined by relaxation time (τ). Becoming closer to the excitation time constant (inverse of excitation frequency), the polarization mechanisms become more important [5]. Whenever the power falls to 1/e of its initial superficial value (0.368), this specific distance at which this occurs is defined as penetration depth (D_p): another important parameter in the design of a microwave experiment. Dp is approximated by Eq. 2 where λ_0 is the wavelength of the microwave radiation.

$$D_p \cong \lambda_0 \sqrt{\left(\frac{\varepsilon'}{\varepsilon''}\right)} \qquad (2)$$

Debye equations [2] are derived in order to examine the dependence of both dielectric constant and loss factor on frequency in Eq. 3 and 4 respectively as follows.

$$\varepsilon'_d = \varepsilon'_\infty + \frac{(\varepsilon'_0 - \varepsilon'_\infty)}{1+\omega^2\tau^2} \qquad (3)$$

$$\varepsilon''_d = \frac{(\varepsilon'_0 - \varepsilon'_\infty)\omega\tau}{(1+\omega^2\tau^2)} \qquad (4)$$

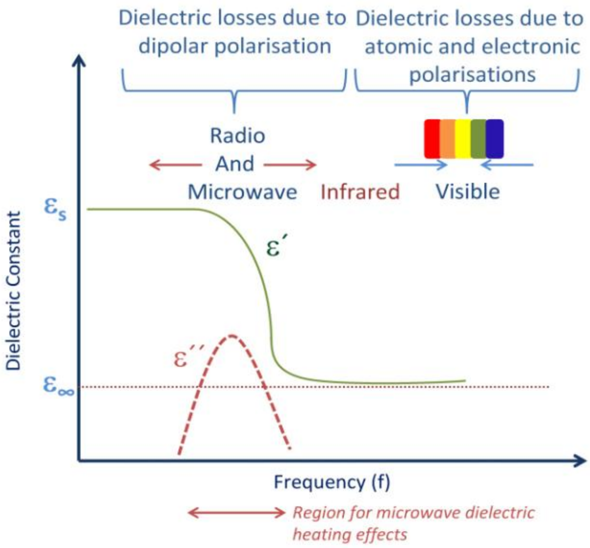

Fig 3. Real and Imaginary dielectric components.

Where ε'_∞ is the high frequency dielectric constant and ε'_0 the static dielectric constant. ω is the frequency and τ the relaxation time characterizing the build up and decay of polarization. Whenever dielectric loss reaches its maximum, it is interesting to notice that both dielectric constant and loss factor in Debye´s equations $(\varepsilon''_{max}, \varepsilon'_d)$ are independent of this high frequency specific frequency at which this phenomena occurs and the relaxation time is as such (Eq. 5).

$$\varepsilon''_{max} = \frac{(\varepsilon'_0 - \varepsilon'_\infty)}{2} \qquad (5)$$

Results of Debye can be derived through various models to be applied for liquids and solids. At 25°C, the dielectric properties of distilled water are plotted in Fig. 4 [34] where appreciable values of dielectric loss appear at high frequency ranges. It is assumed in liquids that dipoles due to thermal agitation change continuously and can point to any direction [4].

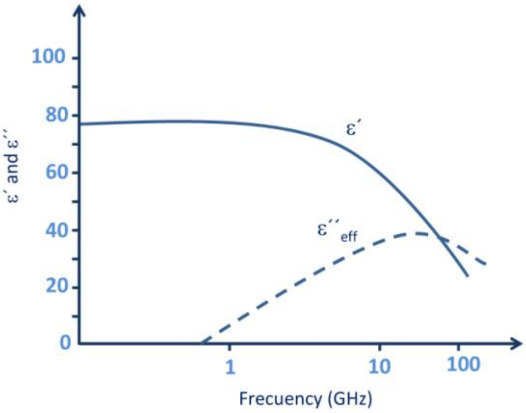

Fig 4. Dielectric properties of water as a function of frequency.

In terms of the frictional forces in the medium and using the theorem of Stokes [35], Debye has interpreted and derived the relaxation time of spherical dipoles as such in Eq.6.

$$\tau = \frac{4\pi r^3 \eta}{KT} \qquad (6)$$

Where η, r and K refer to the viscosity of the medium, the radius of the dipolar molecule and Boltzmann´s constant respectively.

For solids, dipoles with several equilibrium positions changing directions should pass over barriers separating them. Fig. 5 illustrates two equilibrium positions with dipoles of opposite directions separated by an energy barrier U_a. Since the transitions from state to state are proportional to (1-$e^{t/\tau}$) according to Boltzmann statistics [36], the time associated with a single oscillation is referred by 1/n and the following relationship (Eq. 7).

$$\tau = \frac{e^{Ua/kT}(\varepsilon'_0+2)}{n(\varepsilon'_\infty+2)}\pi r^2 \qquad (7)$$

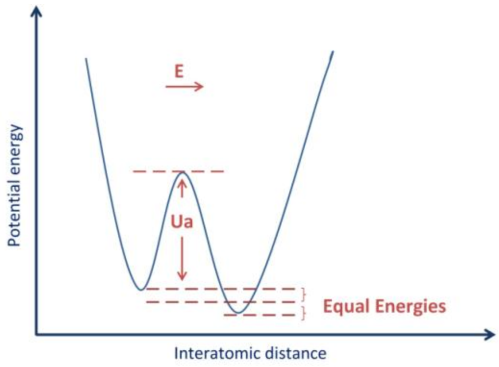

Fig 5. A dipole potential energy diagram.

Frohlich [4] concluded as well that this model can be equivalent to be applied for liquids. Onsager applied successfully the following equation on various liquids and solids (Eq. 8) [37-39], where the number of molecules is referred by N and their mass by m. It is important to note that in a similar system, temperature is increased with the decrease of the magnitude of the dielectric absorption.

$$\varepsilon'_0 - \varepsilon'_\infty = \frac{4\pi N m^2 \varepsilon'_0\,(\varepsilon'_\infty+2)^2}{9kT(2\varepsilon'_0+\varepsilon'_\infty)} \qquad (8)$$

B- Interfacial

In a conducting medium, the dielectric constant of an inhomogeneous material with suspending particles is dependent on frequency. Charges between the interfaces are built up relating to that loss in a phenomenon known as Maxwell-Wagner effect. Wagner has developed a simple model to feature this polarization type. Through a non conducting area, conducting spheres were distributed and the dielectric loss factor of a material with a volume fraction, v, is presented as in Eq. 9 where the conductivity of the conductive phase is given by σ in Sm^{-1}. Up to 3% of spherical particles of semiconducting copper phtalocyanine into paraffin wax [40] were incorporated to come up to approximate Wagner´s model with an experimental system and agreed with the theory as shown in Fig. 6.

$$\varepsilon'' = \frac{9v\varepsilon' f_{max}}{1.8*10^{10}\sigma}\,\frac{\omega\tau}{(1+\omega^2\tau^2)} \qquad (9)$$

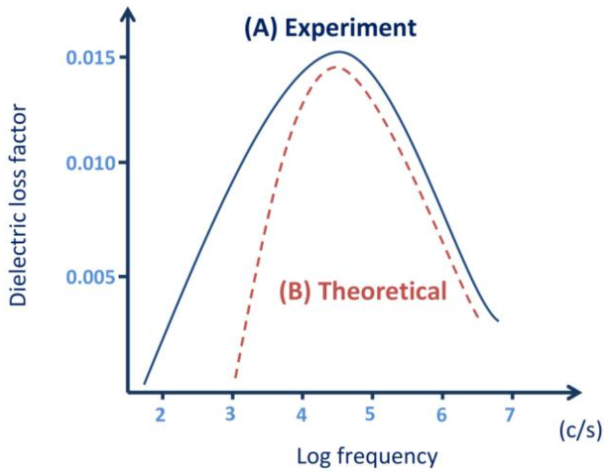

Fig. 6. Maxwell Wagner system of dielectric absorption.

2.1.2 Conduction

Conduction effect generating dielectric heating is returned to the free movement of the electrons known as free charges carriers back and forth in the material thus creating an electric current. Due to the electrical resistance of the present charge species, the induced current produces heating in the sample [9]. As an expansion of the simple Wagner theory, considerations are taken on the interactions between each conducting area [41,42]. Interfacial polarization is given by a model of two layer capacitor and is considered by Maxwell and Wagner as such in Fig. 7 and complex permittivity is presented as in Eq. 10.

$$\varepsilon^* = \varepsilon'_\infty + \frac{(\varepsilon'_0 - \varepsilon'_\infty)}{(1+j\omega t)} - \frac{j\sigma}{\omega\varepsilon_0} \qquad (10)$$

While the real part is very similar to the one given by Debye model, the loss term shows an additional relaxation time response that is due to DC conductivity on which depends the total loss of the extra conductive part. The loss effects caused by conductions can be larger from those of dipolar relaxation effects when it comes to highly conductive and especially liquids and solids with high content of salts. Considering the dielectric heating expression, the effective dielectric loss factor (ε''_{eff}) can be expressed as in Eq. 11, where interfacial polarization, ionic conduction and Maxwell-Wagner polarization are summed up [9].

$$\varepsilon''_{eff} = \varepsilon''_{polarization} + \varepsilon''_{dipolar} = \varepsilon''_{interfacial} + \frac{\sigma}{\omega\varepsilon_0} + \varepsilon''_{dipolar} \quad (11)$$

Berteaud and his coworkers illustrated the dielectric loss of sintered alumina [43] as a function of temperature and showed that the loss effects due to conduction are only important at lower frequencies and that dipolar relaxation dominate the losses at microwave region. With the increase in temperature, the conduction losses rise very quickly to play a major role as the dipolar relaxation loss.

2.2 Magnetic field component

The fact that magnetic field component brings about significantly to microwave heating becomes undoubtful for various types of materials especially conductors and semiconductors. In the first years of the twentieth century, efficient results published by Cheng and his coworkers proved that some magnetic dielectric materials are more efficiently heated by the microwave magnetic field rather than the electric field [44-46]. In 2012, Zhiwei and his coworkers have given a relevant importance to the magnetic component of the electromagnetic field as well and presented its major advantages over electric field heating described earlier in a larger number of publications [47]. Other researchers have confirmed practically the same reported results [48-49]. Up to recent findings, multiple losses mechanisms contribute to the microwave magnetic field heating; among which are cited eddy current losses (Fig. 8), hysteresis, magnetic resonance and residual losses.

Under the valuable benefaction of the magnetic field, eddy current is regarded as constitutional mechanism for the microwave heating of a wide range of conductors and semiconductor. During microwave processing, field variations with time or an external changing magnetic field being in relative motion with a conductive material such as metals is principally responsible of generating Eddy currents that induce the alternating magnetic field and produce losses consequently [50-51]. Eddy current is highly dependent of the electrical resistivity of the materials which is translated in its density equation.

For ferrous magnetic materials under the influence of the alternating magnetic field, hysteresis losses are substantial. A relevant fact to notice is that on top of the Curie temperature (about 700°C), the heating from hysteresis loss becomes insufficient so that steel can become nonmagnetic and loose its magnetic properties [9]. For some magnetic materials and ferrites metal oxides, magnetic resonance that is persuaded by electron spin resonance and domain wall resonance are also to be veritably considered next to eddy current and hysteresis [45,50,52]. Buschow concedes the magnetic resonance loss as residual loss that can be illustrated by rotational resonance and domain wall resonance [53]. Determinately, heating of selective conductive magnetic materials such as ferrites in alternative magnetic field is owed to adjusted losses from eddy current, hysteresis and residual losses. Thus, the three losses make up the imaginary part of the effective magnetic permeability (μ''_{eff}) as follows in Eq. 12

$$\mu''_{eff} = \mu''_{hysteresis} + \mu''_{eddy\ current} + \mu''_{residual} \qquad (12)$$

As a comprehensive manner, since power loss is owed to the microwave heating, the following equation (Eq.13) that sums up the power dissipated by both magnetic and electric field respectively, can be attributed to the power dissipated due to magnetic field per unit volume in the sample where μ_0 and ε_0 are the permeability and the permittivity of vacuum respectively

$$P = \omega\left(\mu_0 \mu''_{eff} H_{rms}^2 + \varepsilon_0 \varepsilon''_{eff} E_{rms}^2\right) \qquad (13)$$

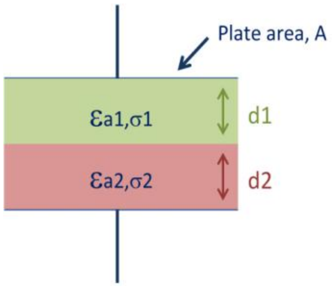

Fig. 7. Two layer capacitor (Maxwell-Wagner)(ε is the dielectric constant and σ the conductivity, d the distance).

2.2.1 Penetration depth of microwaves

In order to realize a uniform and effective heating process, the determination of the adequate penetration depth into the material is highly relevant so that the sample into test can be fully emerged into the microwaves to reach optimal heating rate. In fact, the uniformity of microwaves penetration into a sample is an essential parameter to quantify the efficiency of heating to avoid some shallow penetration in large samples. Similarly to dielectric parameters, μ'_r is the relative magnetic constant measuring the ability of a material to accumulate magnetic energy and μ''_r the relative magnetic loss measures its ability to lose magnetic field energy. Generally, loss low materials tend to have bigger penetration depth than other materials with higher capabilities of converting microwave energy into heat. Penetration depth is known to be decreased with ascending frequency and both dielectric and magnetic loss factor. The penetration depth of selected metals at 2.45 GHz is listed in the table 2 [9].

Table 2. Penetration depth of cited metals (2.45 GHz).

Metal	Penetration Depth (Dp)
Fe	1.3
Mg	2.2
Ni	2.5
Cu	2.7
Zn	3.2

The resistance for most of the metals is limited due to the defects present, which makes the total reflection of microwaves impossible. Penetration depth of a conductor is expressed as in Eq. (14) where ρ is the resistivity of the material [1].

$$d = \frac{1}{\alpha} = \sqrt{\frac{2}{\omega^2 \mu_0 \mu' \varepsilon''_{eff} \varepsilon_0}} \qquad (14)$$

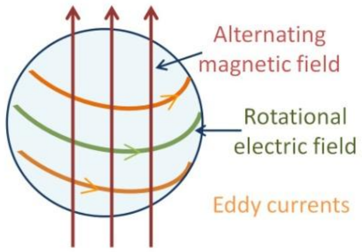

Fig. 7. Eddy current loss.

3. Metal Heating

In recent years, an efficient energy tool has emerged in a large number of successful applications tackling the interaction of metals and microwaves. By saving up to 80% of the energy used in conventional sintering processes, microwaves have succeeded in sintering applications for a large variety of metal compacts with improved properties [1].

An erroneous assumption used to believe that metals cannot be heated; metallic materials reflect microwave radiations which cause the formation of plasma in the cavity of microwave at room temperature. This relation is only valid for room temperature and bulk or sintered metals, but not for powdered materials or higher temperatures [54]. In 1999, Roy and his coworkers published the very first successful microwave metallic application in literature. Roy et al. [55] and Cheng et al. [44] have shown that due to multiple scattering, microwave energy can heat efficiently finely divided metal powder and distinctly high conductivity samples by the magnetic field component. Further, the efficient absorption of microwave by powder metals has been proved [56]. Although the mechanisms of energy loss are not completely enlightened [57], it is suggested that eddy current, hysteresis and magnetic resistance are bonded to the magnetic loss mechanism next to the domain wall oscillation [45]. The chronological success of metallic applications developed under the processing of microwave field is shown in Fig. 9.

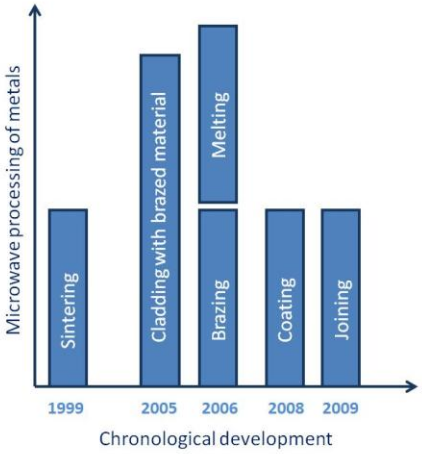

Fig. 9. Chronological microwave processing of metals.

Interpretation of the microwave–metal interaction mechanisms gains more significance nowadays in the technological investigations due to the emergence of the fashionable microwave processing in the scientific community for the realization of successful applications in catalytic pyrolysis and powder metallurgy [9].

The heating interaction of metals and their alloys is more complicated; bulk metals do not couple directly with microwave energy. Instead, they are ready to reflect the incident waves, which urges the use of sufficiently small size particles for heating in a microwave field [1]. Whether at micro or submicroscopic flaws, abundant kinetic energy is accumulated by charges at the metal surface which produce ionization and breakdown in the enclosing medium**.** Hence, when microwave fields manipulate the submicroscopic irregularities, electric discharges that are induced by microwave can take place in the form of arcs, coronas or sparks. During the transient discharge process, local hotspots, detected to be plasmas at the microscopic level are formed at high temperature [58]. Considerable implications may be involved due to the concentrated generation of such plasmas [59-60]. From what comes, it is considered that the effects caused by the interaction of metal and microwave are considered significant and cannot be ignored [9].

Microwave radiations may have distinctive effects not only with the variations of the metal type but structural and size difference in the metallic materials lead to altered performance under the same radiations conditions. For the microwave power absorption within 2D sample, various shapes of metal objects can have a significant role [61]. Upon the progress of the research, discharge phenomena in microwave metals interaction depend on the size of the metal, their number, morphology, dielectric loss tangent and the surrounding medium [9].

3.1 Processing of metals

3.1.1 Scientometric analysis

The search on microwave metal heating on Scopus database comes out with more than two thousands results dating back to the sixties, with a pretty slow increase in the investigation process with an average of 19 publications per year. The subject topic reveals a significant interest in the new millennium with continuous increase in research published every year with 148 articles in 2013 and an average of 150 articles in 2015 and 2016. With more than 32 published works, Aslan leads the metal assisted microwave studies. Practically, Gupta, M. Yoshikawa, N. Peng, J. and Leonelli, C are pioneers in this scope equally. On another hand, the majority of the published work is signed by the Japanese "Tohoku" University, Pennsylvania State University and Central South university in China.

3.1.2 Recent review

Including steel, copper, iron, aluminum, cobalt, tungsten carbide and tin, nickel and molybdenum, alloys of these different compositions were under investigation of metal powder component. These alloys rated as green parts-metal powders prepared in the laboratory or obtained from the Keystone Powdered Metal Company show that they 10 to 30 min. are enough for sintering in an appropriate microwave apparatus (Fig. 10) to obtain microwave processed samples with higher densities. Iron particles look to have excellent sintering as shown in microstructure photographs and confirmed by X-ray. Fe-Cu solid solution is formed after the copper is melt and dispersed within the boundaries of the iron particle where only α-iron solid solution single phase is contained in the sintered sample. Varying temperatures in range of 900°C to 1200°C for about 10 min, the density of Cobalt metal sintered varied between 8.70 g/cm^3 and 8.88 g/cm^3 at 900°C and 1050°C respectively and get to approximately a theoretical density of 8.89 g/cm^3 at between 1100°C and 1200°C [55].

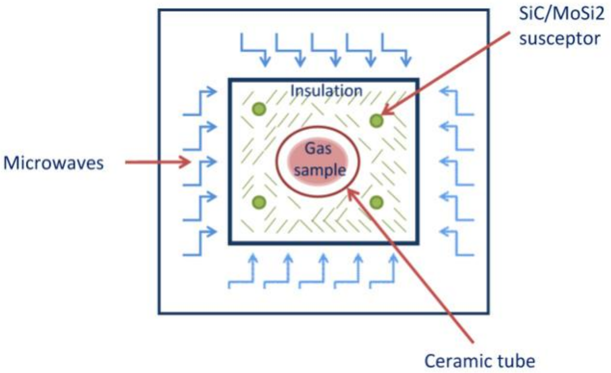

Fig. 8. Microwave sintering diagram of powdered metals.

Over the past years, some metal objects have been under test experiments inside the microwave cavity [62]. Shayeganrad and Mashhadi confirmed theoretically the sparking basis of metal objects under microwaves. Although arcing occurs evidently, no analytical interpretation is introduced on this phenomenon. They state that metal, as any conductive object under microwaves will act as an antenna and is, up to certain point, a heating element resulting electric current that passes through the vapor to forma plasma; a conductive loop is formed as result of the metal and the plasma [63].

The past two decays have witnessed successful applications of sintering powder metal materials and alloys [55,64-67]. A systematic study based on experiments in electromagnetic theory with establishing series of mathematical formulas presented the process of powdered materials microwave heating in a physical process where experiment and theoretical results were in a pretty agreement [68]. Various techniques are followed depending on the material state; at the liquid state are applied melting and induction melting, from solid state are applied powder metallurgy and mechanical alloying from the solid state and electrochemical process from the gas station [69]. In a diversity of engineering fields tackling microwave assisted applications of sintering, pyrolysis and material synthesis, microwave discharge has proven to have great potentials; however instability and uncontrollability of this process requires further research [70] .Due to the fact that higher densification can be accomplished in the liquid persistent phase, temperature of sintering is considered as a major parameter in the process of variation of solid and melting ratio [71].Various metallic systems particulate have been under investigation to produce materials with considerably improved densities and mechanical properties [55, 72-76].

The main scope of research was the use of the hybrid heating technique to realize sintering of metallic powders. Applications of sintering of multiple metallic powders were described in a review article by Agrawal. Agrawal reported the latest findings on successful sintering applications and processing of metallic powder of iron, steel, Cu, Al, Ni, Mo, Co, Ti, W, WC, Sn and their alloys, and described pure microwave technology as a potential processing technique for a clean steel making technology by releasing 50% less CO_2 in comparison with conventional routes [72].

In the microwave heating of particulate metals electromagnetic and thermal heating models are developed by Mishra and his coworkers where electric and magnetic components are calculated to come out with the power absorbed by the compact. Radiative and connective losses are incorporated through the electromagnetic model that can predict the heating profiles through the temperature dependence on the dielectric properties of materials, as well as the physical and thermal properties. With a multimode microwave furnace operating at 2.45 GHz, the predicted heating profile is experimentally validated through measurements of tin, copper and tungsten particulates compacts [23].

In the field of microwave and spark plasma sintering today, a substantial attraction is directed towards heating rates in microwave sintering [77]. In powder metallurgy fabrication, sintering is considered to be time consuming; it requires periodic isothermal holding, balanced heating rate (approximately 10°C/min) and long time soaking at peak temperatures [78]. Today, it is found that microwave sintering can be applied successfully to metal powders used in a diversity of synthetics in the industry. Only minor penetration of microwaves occurs at the order of some microns depth in the bulk materials. As proven by a theoretical model, the degree of absorbance of microwave depends highly on temperature, frequency and electrical conductivity and microwaves will be absorbed at 2.45 GHz if the particle dimension of the metal powder is less than 100 μm. In a multimode microwave system, sintering applications have been applied on a variety of powder metals and metals at a 2.45 GHz frequency. These applications are not limited and cover some alloy compositions such as nickel, aluminum, iron, steel, Sn, Mo, Ti, Co…In this section, sintering applications of metal composites with practical advantages are presented.

Although most of the published reviews on microwave processing of materials describe the fundamentals of microwave dielectric heating, the basic concepts of microwave processing of materials and their microstructural characteristics, novel applications are not well documented in the review unless recently in "Microwave processing of materials and applications in manufacturing industries: a review" by Singh and his coworkers [15]. Because the applications of microwaves in joining and sintering bulk metals and allows are not well classified in the literature, this review takes into responsibility to provide a database on the various applications specialized with metal matrix composites and processing of metal powders.

3.2 Sintering applications

3.2.1 Si-modified $Mn_{25}Fe_xNi_{25}Cu_{(50-x)}$

After the empiric work of Roy and his coworkers [55], many applications are executed in the field of metallurgy. Recently, a rapid synthesis technique is applied through microwave heating of metallic powder compacts. At 2450 MHz, microwave absorption by the powder compacts of $Mn_{25}Fe_xNi_{25}Cu_{(50-x)}$ alloy directly or indirectly via the auxiliary SiC absorbers is studied by Veronesi and his coworkers to prepare HEA from the liquid state. Despite the occurrence of a little damage of the oxygen reactive elements, the Si-modified $Mn_{25}Fe_xNi_{25}Cu_{(50-x)}$ alloy proves its ability to preserve the stoichiometry. Both mechanical properties and microstructure are affected by the Si content with the acicular structures formed and the micro hardness trend increases with the rise of Si respectively [79].

3.2.2 W-Ni-Fe alloys

While conventional sintering requires higher time and produces undesired grain growth with some brittle intermetallic precipitations, several researchers have conducted investigations on the microwave heating of tungsten (W) and its alloys earlier [80-82]; sintering response of 92.5W-7.5(Ni-Fe) alloy was studied [74]. Further, the effect of heating rate raging between 10°C/min and 112 °C/min of 90W-7Ni-3Fe heavy alloys were under study by Zhou et al. who prove that smaller size of W grain and larger W-W contiguity are obtained with faster heating; a decrease from 13.6 to 96 μm in the grain size and W-W contiguity increase from 0.25 to 0.35. For instance, the rate of 80°C/min looks to be the optimum combination that enhances the mechanical performance of tensile strength and elongation reaching 1020 MPa and 21% respectively [78]. The disposal of separate elements in tungsten grains is analyzed by Dzykovich at the matrix phase during the sintering of W-Ni-Fe alloys where the solubility of W in Ni is decreased with addition of Fe with formations of an intermetallic phase [83]. Concurrently, the strength of the W-Ni-Fe alloys was correlated with microstructure to conclude that the ductility of the alloys declines with the rise of tungsten content and a maximal strength is accomplished at a combination with 93 wt% tungsten. The inversely proportional between tungsten and ductility is confirmed as well by Belhadjhamida and his coworkers who found out that increasing the properties of the W-Ni-Fe alloys are affected by the temperature and sintering time, and that the content of tungsten result in boosting the strength of W-Ni-Fe alloy (93 wt.%) [84]. When sintering temperature rise from 1465 to 1580, a proportionally larger fraction of matrix phase between the grains was achieved due to the increased tungsten grain growth. This was accompanied with a ductility increase (from 14% to 27%) and a decrease in the strength from 924 Mpa to 899 Mpa [84-85]. Matching results of the temperature influence on strength and ductility were addressed by Bose and his coworkers [86]. On the other hand, prolonged heating time leads to microstructural coarsening which diminishes the mechanical properties of tungsten heavy alloys [87]. In this concern, variations in the microstructure and thermodynamics that occur during the heating process result in attenuation of free energy [88]. Mondal and his coworkers evaluate the sintering temperature and heating mode of 90W-7Ni-3Fe alloys in solid state and liquid phase up to 1500°C. Results are obtained with 80% decrease in processing time where solid state sintering results in a valuable densification exhibited prior to melt formation. Moreover, lower heating rate contribute more intensely to densification and microwave sintered compacts show 22% improvement in bulk hardness and have approximately 23% lower tungsten grain size. Microwave sintered compacts at lower temperature (50°C) with a well developed liquid phase are more interesting for authors than those of conventional sintering where conclusions come out that a significant improvement has been realized in terms of "transverse rupture strength" from 782 Mpa to 1800 Mpa [65].

3.2.3 W-Ni-Fe alloy (Tungsten powder)

The fabrication of tungsten heavy alloys by microwave processing is not investigated tremendously in the literature. The mechanical properties and microstructure 92.5W-6.4Ni-1.1Fe alloy are studied under the heating mode effect. In a radiatively heated microwave furnace, Upadhyaya and his coworkers sintered the green compacts at 1500°C. Under a heating rate recorded as 20°C/min inside the microwave furnace, the process time of W-Ni-Fe compacts were processed with a 75% reduction in time while the heating rate was recorded to be slow with 5°C/min, leading less tungsten W grain coarsening. Moreover, the problem of brittle intermetallic phases that used to precipitate in W-Ni-Fe alloys was avoided with microwave heating that did not require a long sintering time. The potency of volumetric heating in microwave sintered samples was underscored by the absence of micro or macro-cracking observations [74]. The microstructure evolution of 93W-4.9Ni-2.1Fe (wt%) alloys was investigated in a recent study by Liu and his coworkers through microwave sintering to observe the mechanical properties that are found out to improve with rising the temperature of heating from 1250°C to 1500°C. Also, pore are reduced with temperature increase and eliminated gradually. Sintered alloy records a relative density of 98.8%, 16.4% elongation, 1185.6 MPa as tensile strength and 42.1 HRC as hardness respective to Rockwell scale measuring metals strength. The mass fraction of tungsten increases to 35.79% in 5 min sintering at 1500 °C. It is undeniable that not only the tungsten grains but the matrix phase as well become more homogeneous with microwave sintering that stimulates the diffusion and dissolution of tungsten grains in the matrix phase [89]. Because tungsten grains are dissolved in the matrix phase and their diffusion is simulated in microwave sintering, it is undeniable that tungsten grains and become more homogeneous in matrix phase.

3.2.4 Tungsten powder

High sintering temperature (above 2773 ºK) and long soaking times (above 2773 ºK) are required for the conventional sintering of tungsten powder. Prabhu and his coworkers achieved microwave sintering at 2073 ºK of 99.95% pure particle of tungsten with a size of 5-7 μm where powder compacts are sintered under the same conditions as well. The density of the compact reached 93% of the theoretical density with 85% densification. Process time of the operation reached 6 to 7 hours with a maximum power consumption recorded to be 20 KW for the whole process [80].

3.2.5 Al-Al_2O_3 Aluminum powder

While Das et al. reported in 2003 and 2006 [90,91] about Al-Al_2O_3 composite formed by microwave heating, Ghosh and his coworkers aimed to form this core shell composite by microwave processing and confirmed the formation of Al phases in the AL treated powder after being exposed to radiation for 45 min [57]. The obtained spectrum of pure α-Al_2O_3 is confirmed by the one obtained earlier [92]. Due to the presence of powder, the absorption peaks characterize the aluminum oxide in the range of 450-1000 cm^{-1}, the OH stretching vibration might have leaded to some weak bands at 2339 cm^{-1} and 2362 cm^{-1}, same for the hydrogen bonded surface that is considered mainly responsible of the broad band at 3448 cm^{-1} [93]. In comparison with peaks of the pure α-Al_2O_3, only few wavelength absorption peaks were shifted. As the formation of amorphous silica coasting on ultrafine α-Al_2O_3 was demonstrated by Wang [94], a coating layer was revealed by the transmission electron microscopy (TEM) micrograph at the surfaces of Al particles [35].

In 1991, Cheng and his coworkers presented a set of empirical data to investigate the issue of the microwave interaction with matter and encourage the development of new models that come out with systematic samples data. A metallic powder composition sample (Fe-2%Cu-0.8%C) was hardly heated in the electric field with occurrence of some arcing around the sample edges. The same sample was heated instantly and rigidly by the magnetic field where the decrease in heating rate was returned to thermal losses. In the same concern of the magnetic field, cobalt (Alfa) and copper (alfa) were tested with observations of high heating rates. The temperature of the copper powder compact rises in a couple of minutes to 700 °C then drops down to 500 °C for the rest of the heating. Hence authors refused the ignorance of the effect of the magnetic component leading the induction of eddy current [44].

3.2.6 Austenitic (316L) and ferritic (434L) stainless steel

Using 316L austenitic and 434L ferritic of stainless steel, the influence of heating mode on the microstructure, strength, the hardness, densification, and sintering time of stainless steel was compared by Panda and his coworkers. Sintering stainless in microwave furnace recorded a 90% time reduction with the conventional one with isothermal holds and very slow heating rate (5 °C/min). Also, pore size distribution is notably smaller and narrower which can be explained that coarsening of pores is very low in the diminished sintering time. Microstructural coarsening is restricted by microwave sintering for both types of stainless steel where grain coarsening occurs at 1400 °C. However, the differences in microwave sintering of 316L and 343L are returned to the composition influence on the microwave metal coupling [73].

3.2.7 WC/Co composite

The sintering of WC/Co samples is intrinsically different from the conventional sintering where no WC grain were remarked to grow in the former which reflects better mechanical properties with a finer distribution of Cobalt in microwave sintering. Results prove that grain growth inhibitor does not need to be practically used. While a large amount of tungsten (about 20 wt%) is dissolved in the cobalt binder during conventional heating, a cobalt binder phase is encountered during microwave heating with no significant amounts of tungsten. Microwave sintering is as well marked with a three dimensional uniform shrinkage resulting from the dominance of capillary forces over gravity forces. Sintered samples are twice more resistant against erosion, 6 times more resistant to corrosion and are harder than conventional samples with 1-5 GPa [95].

3.2.8 Metastable (AL/Ti) and hybrid (Al/Ti +SIC) composites

Takhur and his coworkers carried a two directional rapid sintering of Al/Ti metastable composites and Al/(Ti+SiC) hybrid composites. Uniform distribution of Ti particles and SiC nanoparticulates in Al matrix was revealed by the microstructural characterization accompanied with reduced porosity and reinforcement of interfacial integrity [96]. Results found out that production of hybrid composite materials is possible with microwave sintering coupled with PM technique. Moreover, providing an extra source of heat to AL powders and TI particles through the incorporation of SiC as susceptor material is assumed to reinforce sintering and improve their bonding [97].

3.2.9 Al-Mg-Si-Cu alloy

A successful application of liquid phase sintering (LPS) on Aluminum alloys was executed between 460°C and 610°C on Al-Mg (3-32 wt.%) [98]. Aluminum alloys present some considerable advantages in reason of their elevated compressibility, distinguished strength and economical processing; this creates wide opportunities for powder metallurgical processing of Aluminum alloys in the recent years [99-100]. During sintering of Aluminum alloys, densification is shortened by oxide layers formed at the surface which decreases the mechanical properties, however LPS succeed in removing this oxide [101]. Through the formation of MgAl2O4 structure with surface oxide, sinterability is enhanced with the presence of Magnesium (0.1-1 wt%) (5,7). Sintering of 6061 prealloyed powders were reported by Youseffi and his coworkers where supersolidus liquid phase sintering (SLPS) mechanism resulted in the formation of a liquid phase above solidus temperature [102,103]. Adjustable properties of vacuum degassed properties were studied as well for their sintering behavior by Ziani and Pelletier [104]. Although the expansion in other Al alloys is returned to the unbalanced diffusion rate known as Kirkendall effect, the Al-Mg-Si-Cu alloys are found to be quite variating with formations of various eutectics [105].

Firstly, Le Paroux and his coworkers reported the microwave sintering of Al-SiC composite as Al based materials [106] The transformation of Al-Fe-Cu alloys during the process of microwave heating was investigated by Vaucher et al. in 2008 [107]. Although other researches were conducted further on various AL based composites [18,94,108].

Al-Mg-Si-Cu alloys are not reported heavily in the literature, until microwave consolidation of Al-1Mg-0.8Si-0.25Cu (6711) through its sintering response is studied by Wong and Gupta [109,110]. The study, comparing the mechanical properties, densification and phase changes of the microwave sintered compacts with conventional ones focuses on the effect of heating mode in function of the temperature during sintering. The in situ dimensional changes and the phase transformations are studied through the dilatometric studies and differential scanning calorimetry (DSC). Results were obtained with a significant reduction in processing time (about 58%); rapid heating results in an inhomogeneous structure where alloying elements do not have sufficient time to diffuse or to form precipitations at an intermetallic phase (Mg2Si). In contempt of the energy time savings, 6711 microwave sintered compacts are lead to distortion in vacuum with a noticeable high observation of ductility (19%). The retention of ductility was considered among the unique results of the conducted studies on the naturally aged T4 samples [66].

3.2.10 Mg and Mg composites

Tun and Gupta applied microwave sintering on Mg and Mg composites using heating rates between 20°C and 59°C/min where extensible strength and average hardness obtained prove to be higher than conventional cones [111]. Environment friendly microwave sintering is accentuated in another study where magnesium composites materials are synthesized to obtain Mg-MMCs nanosized ceramic/metal particles and mechanical properties of the nano-particles emphasize Mg composites [112].

3.2.11 Green metal parts

Under the presence of organic binder, green parts obtained by polymer junctions are sintered by Leonelli and his coworkers without any auxiliary absorber addition. The feasibility of the process was increased by avoiding the addition of microwave auxiliary absorbers. Achieving an optimal thermal insulation that is concerned with insulating the sample properly is the core of the study since sintering only a thin layer under the surface and melting took place while for less and excessive heating respectively. By producing a hydrostatic tension state on the sample, sintering AL_2O_3 powder restrains any distortion in the shape. And maintaining the temperature for an efficient diffusion ensures a good joining among the particles to produce uniformly sintered samples where unsintered shell is reduced in a 20 min heating as the heat is transmitted from the internal to the external zone. Electric discharge between particles is responsible of the joining mechanism and presence of the dendritic structure proves that temperature reached the metal to a melting point. For instance, obtained resulted are comparable to the ones obtained in the literature with a difference in the short time that prevents the segregation of unwanted chromium [25].

3.2.12 Precious metals

In industrial application, microwave is used as a green heating process in the field of precious metals known for their distinctive properties of corrosion and oxidation resistance. Beside being fast and highly efficient, microwave technology proves to have a low energy consumption and high speed utilization rate. Moreover, authors considered new opportunities of applications in precious metal industry [113].

3.3 Melting applications

Used as a susceptor material, Chandrasekaran and his coworkers took advantage of the silicon carbide to provide practical finding on melting of a variety of metals such as tin, lead, and copper and aluminum with multiple levels of microwave power; which proves that microwave melting assures an efficient and safer process that requires less energy with faster results. For instance, microwave melting of Aluminum is reduced by a 2.5 factor when compared with the conventional heating technique [114]. Other experiments used lumped parameter model and come out with similar results [15]. It is expected in the near future, that casting industries will be targeted by the time and energy savings of microwave metals melting.

Despite that possibility of melting aluminum, stainless steel and copper is reported by, no relevant heating characteristics are published so far [54]. Using a limped parameter model, Chandrasekaran and his coworkers realized experiments on successful microwave melting of lead, tin, copper and aluminum with twice faster time, safer handle and less energy consumption [114].

With very few microns skin depth, most metals are acknowledge for reflecting microwaves which causes sparkling of metallic materials; a direct interpretation of the difficulty of microwave to heat countless materials [1]. Microwave sintering in the conducted research yields fast heating rates, shape retention and uniform microstructure [25], elevated sintered density, uniform distribution of pores and bigger flexural retentions [115]. Among the techniques used for microwave heating, the finite difference time domain (FDTD) is well cited for metal particles applications [23]. For metal matrix composites, finer microstructure were resulted for the copper-graphite composite [116], and for other composites as Al/SiC, and Ti/C at elevated temperatures (>933 ºK) [103]. Van der Ejik reported a rewarding microwave brazing of nickel-titanium alloy [117].

Researchers of "Oak Rodge Y-12 National Security Complex" (TN, USA) have extended investigation to melting processes and casting of masse ranging from few Kg to 350 Kg of titanium, zirconium, uranum, copper, bronze, steel, aluminum [118].

4. Results and Discussions

The findings carried out by the research investigation hold a wide relevance in the powdered metal field technology. A various range of industrial products and applications are based on metal powders. While a process is involved in the traditional powder metallurgy, sintering metals implies compacting the alloys as a green body under elevated temperature to obtain a determined clear shape. Although it is does not require large laboring, this process consumes pretty much energy to introduce a genuine technology. Most of the published works agree that sintering is considered an effective process producing high quality components and well conserved materials with high integrity for advanced engineering applications. However, it is still somehow challenging to get to some theoretical densities in special powdered metal components in concern of the high cost related which is offered easily by the microwave sintering.

Today, Microwave processing is committed to come out with finer microstructures and improved properties at a lower cost and this is returned mainly to two basic issues: the grain size and the form (shape) of the porosity. An illustrative graph of the microwave heating functionality is presented in Fig. 11. Compared to conventional heating, powdered metal samples processed though microwave are more ductile and though due to the round edge porosities. It is inevitable that the form and size of the object are a major factor in the microwave heating of materials but other factors have a tremendous effect as well. First, due to reflected power and the magnetron that generates microwave field, the cut off mechanism ensures prohibition of possible burn out. Next comes the existence of SiC susceptor rods that occupy a little fraction from the total space. At room temperature, the cylindrical insulation package is transparent to the 2.45 GHz radiation. Moreover, it is made of alumin-osilicate fibres surrounding an alumina tube also affects microwave heating. Last but not least, the nature, size and the shape of the sample under test in the center of the alumina tube [55].

The work of Demirskyi and his coworkers objects to look further in the influence of microwave heating on sintering of metal powders compacts. Under typical profile temperatures of sintering applications experimented in multimode furnaces, results show that copper takes up to 10 min to heat up. The intense energy concentrated around the specimen during microwave processing contributes to immediate heating marked at single-mode quick heating. Controlling the power at single mode and multimode heating lead to a temperature set; a soaking period constant temperature is reached through suitable reduction of power levels.

Moreover, in order to allow the observation of size change, the distribution of narrow particle size was considered desirable for sintering experiments where the formation and interpretation of contact areas or fracture surfaces of sample sintered are characterizing for the initial stage sintering at both single mode microwave and multimode furnaces. However, strong EM field in cavity are proved to be resulted at a single mode furnace with a better efficiency in energy transfer. In this concern, the eddy current at the surface and possible charging and discharging at the surface increase the possibility of having plasma ignition among the individual particles [64]. Because non thermal interaction of material with electromagnetic field affects the mass transport, microwave sintering processes report a mass transport enchantment where non-thermal interaction of electromagnetic field due to the high diffusion rate accompanied with microwave heating [119]. In fact, the temperature doesn't increase quickly in contact zone therefore the diffusion growth in set to a non thermal nature and contribute in consequence to the "microwave effects" reported for metallic materials [120].

On another hand, greater eddy currents are developed with a stronger applied magnetic field and faster field changes exposed on the conductor presented in microwave heating through frequency. In a similar fashion, a magnetic field of 2.45 GHz generates eddy current which induces the heating of green copper samples and reduction on the fractional volume of the compact subject is inevitable [121].

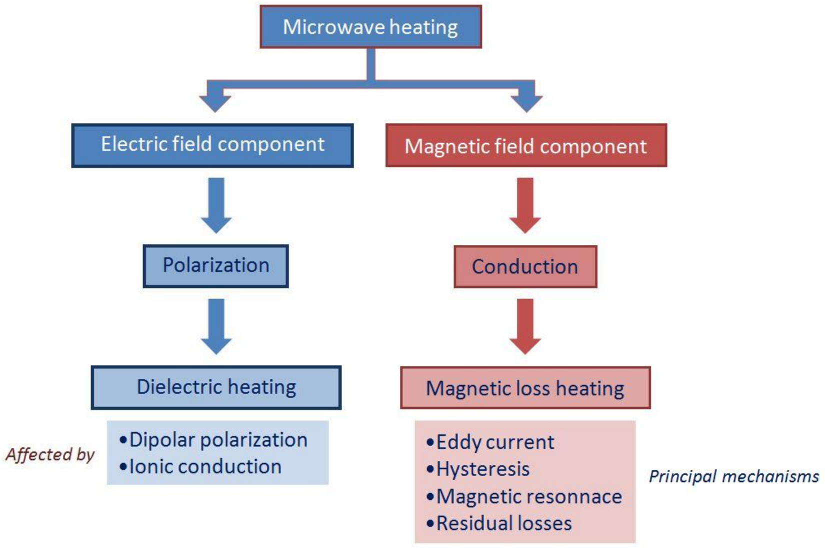

Fig. 9. Microwave processing functionality.

During microwave heating, electric field between distinct powder particles is relatively high and the skin effect is dominant. Hence, heating of the superficial area at the top of the powder particles might provoke micro plasmas inside the pores or at the grain boundaries. Higher sintering activity made possible at relatively low temperatures is brought through a sufficient decrease in the size of particles in contact. Hence, neck formation and growth supported by these tiny particles at the surface shorten the initial sintering stage [122].

Majority of the valuable work exploring heating mechanism in the process of microwave interaction and material absorption of heat attribute heating of metals under microwave fields to the losses resulting from the magnetic field loss effects. During the microwave-material interaction, heating generation taking place inside the materials at the atomic level are mainly due to the electromagnetic fields of microwaves. The characteristics of energy absorption are determined by the properties of material into interaction whenever the matter is submitted to the electromagnetic field effects. Hence the primary issue in microwave heating of metals resides in determining the physics of interaction phenomena in dependence of the materials properties. Maxwell equations govern the phenomenon of a material microwave coupling inside an applicator; analytical and numerical solution of these equations analyze the contribution of both electric and magnetic field and their distribution in a microwave applicator with known geometry which enhances the positioning of the sample material and fastens the processing [123]. Microwave properties of selected metals at 2.45 GHz are shown in Table 3. While one resonant mode is enough to design a single mode applicator, trial and error, intuition and experience are behind the design of a multi-mode applicator requiring high electromagnetic intensity points presented by diverse constructive hotspots [124]. Experiments prove that uniform heating is better ensured in a multi-mode cavity design due to the homogeneous electromagnetic field provided by a stirrer or turn table, Moreover, a unit volume of a material under test absorbs a specific amount of energy which depends on the material property itself, that is, in its turn, influenced by the electric component of the electromagnetic field. While the variations of absorbed energy is linear with loss factor for thin materials, the strength of the electric field decreases with thick materials under the penetration depth matter. In fact, it is observed that with decrease of energy conversion inside the material, penetration depth decreases; these values correspond to highest records of loss factor. Thus metals that reflect microwave with a negligible penetration depth have the highest loss factor [125].

In virtue of a more efficient mass transport mechanism, microwave sintering proves to proceed at a higher speed in presence of a liquid or vapor phase. Microwave heating results are more volumetric and can be more penetrating in less dense green metal parts [126]. In concern of penetration depth, dielectric properties measurements at 2.45 GHz report a value of 131.3 mm as penetration depth in green part metal power which is interpreted as an entire penetration in green part thickness. In comparison with the initial particles dispersion, the areas of electromagnetic field concentration are reduced with self regulating microwave sintering [25].

The information collected in the review show that microwave magnetic heating contributes largely to the microwave heating of conductive powder metals. Because microwave technology is considered as expensive in terms of capital cost, industrial applications of microwave heating are limited so that this technology is not as competent as the conventional techniques economically. Thus, optimization of energy is ultimately necessary in order to achieve minimal energy consumptions requirements in the energy process. Some important strategies are proposed by Sun and his coworkers to an efficient energy conversion such as enhancing the energy conversion with a microwave absorber or a microwave induced discharge effect, the use of a specific set of reactor that takes into account the constructive interference of wave propagation and penetration depth. Another suggested strategy is the numerical modeling in the optimization processing of the microwave thermal heating [9]. Future research scope is concentrated on the possibility of indentifying diffusion mechanism to measure surface area reduction specifically during sintering processes. And it is important to mention finally that Mishra and Sharma have concluded in their recent review that new processes can be popular with better understanding of their physics such as microwave joining, cladding, drilling and casting and that these processes are a must for industries to adopt them with optimized control [127].

Table 3. Dielectric properties of particular metals (Mishra and Sharma, 2016).

	Dielectric constant	Dielectric Loss	Penetration Depth
Diamagnetic			
Ag	0.9999998	1.6	1.29
Cu	0.9999992	7.72	1.33
Paramagnetic			
Pt	1.0000210	11.1	3.39
Al	1.0000016	2.78	1.70
Ferromagnetic			
Ni	600	8.7	0.12
MS (0,2%C)	2000	13	0.08
Fe (0,2% impurity)	5000	10	0.05

5. Conclusions

A better investment of microwave technology is conditioned by a fundamental understanding of the microwave-matter physical interactions and mechanisms. By offering its specific energy, speed and simplicity advantages, microwave heating is gaining with days a large and international approval as a novel method for sintering and heating a wide range of materials through an efficient process that produces finer microstructures and lowers the environmental hazards. Owing to its challenging advantages in the energy efficiency track from cleanness to time saving and cost effectiveness, microwave dielectric heating is worth the exploration as a veritable environmental friendly metal processing technique. Taking into consideration the reflectivity of bulk metals under microwaves, the results obtained can be investigated in automotive industries where metal sintering is highly demanded. Ability of sintering wide ranges of waste products from commercial sources at industrial frequency of 2.45 GHz to yield products with better mechanical properties and dense is worth the research in further studies. Moreover, the review directs towards further promising research possibilities in advance microwave heating of metallic materials where most of the challenge is highlighted.

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