Review Article

Parametric review of microwave-based materials processing and its applications

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\textbf{ABSTRACT}

The realization of microwave’s heating ability is a significant discovery in the history of scientific research. The thermal ability of microwave has led to the invention of devices and processes that could replace conventional heating methods and reduce humankind’s dependency on fossil fuels. In the early days, microwave heating was limited to food processing and drying. Researchers over the years have examined the utility of microwave in materials processing and showed encouraging outcomes. Currently, microwave-based materials processing research is aligned toward exploring the processing of novel materials and achieving greater reliability and control in the existing processes. This, in turn, requires extensive knowledge of the parameters of the microwave heating processes. This review provides insights into microwave-based heating parameters and their effect on the response parameters of major microwave processing applications. Four significant parameters viz., heating mechanisms, dielectric and magnetic properties, load and applicators have been identified and factors influencing these parameters have been critically examined to understand the requirements of efficient microwave-based materials processing. This review analyzes the existing state of research and identifies the future scope of research in this field. It reveals optimization studies, commercialization of the process at large scale, simulation studies for better understanding of heating mechanisms and innovation in processing set-ups as few of the potential areas with a wide scope for investigation.

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### Abbreviations
- MOR: modulus of rupture, psi
- YS: yield strength, MPa
- UTS: ultimate tensile strength, MPa

### Symbols
- $\varepsilon^*$: complex permittivity, $Fm^{-1}$
- $\varepsilon'$: dielectric constant, $Fm^{-1}$
- $\varepsilon''$: dielectric loss factor, $Fm^{-1}$
- $\tan \delta$: magnetic loss tangent
- $\tan \delta'$: dielectric loss tangent
- $\mu_r$: relative magnetic permeability
- $\mu_r'$: relative magnetic loss factor
- $\mu_r''$: relative dielectric constant
- $\mu_r''$: relative dielectric loss factor
- $c$: velocity of light, $ms^{-1}$
- $\varepsilon_r^{\text{eff}}$: effective dielectric loss factor
- $f_0$: permittivity of free space, $8.854 \times 10^{-12} \text{ F m}^{-1}$
- $E_{\text{rms}}$: local value of the electric field, $\text{V m}^{-1}$
- $f$: frequency, $\text{cps}$
- $\omega$: angular frequency, $\text{rad/s}$
- $\varepsilon_r^{\text{eff}}$: effective magnetic loss factor
- $\mu_0$: magnetic permeability of vacuum, $4\pi \times 10^{-7} \text{ H m}^{-1}$
- $H_{\text{rms}}$: local value of the magnetic field, $\text{Am}^{-1}$
- $\Delta L$: change in length of the compact, mm
- $L_0$: initial length of the compact, mm
- $B_0$: collection of material parameters
- $t$: sintering time, $s$
- $D$: particle diameter, $\mu$m
- $R$: gas constant, J $\text{K}^{-1}$
- $T$: absolute temperature, K
- $Q$: activation energy of diffusion, J

### 1. Introduction

Microwaves are electromagnetic radiations having a wavelength between 1 mm and 1 m and are an important constituent of many modern technologies [1]. These radiations are used extensively in the field of network and communications, medical treatments, remote sensing, and food processing applications [2]. Microwaves exhibit unique uniform heating characteristics that have led to the development of applications beyond food processing, which involve thermal energy [1-6]. For example, various materials processing applications, such as sintering, joining, cladding/coating, melting/casting, etc. require high temperature for processing of materials [7]. The unique heating ability of microwaves has inspired researchers to explore avenues for utilizing this source of energy in materials processing and industrial applications [8]. The use of microwaves in these applications have produced encouraging results in terms of shorter processing times, better mechanical properties and superior control over the process [2,8-16].
microwaves is its economic viability and emission-less characteristics. Subsequently, development of microwave-based processing technology is significant as it minimizes dependency on fossil fuels as well as other high-energy based heating systems. As there is an increased awareness of reduced emissions and attempts toward the use of greener technologies in the field of manufacturing, microwave heating presents itself as an effective alternative to conventional heating based processes.

In the context of processes involving metals, microwave-based heating methodologies are still at the preliminary stages of development. It is mostly limited to laboratory experiments. Fig. 1 shows the chronological order of development of microwave-based metal processing [16]. It is evident that microwave-based heating has the potential to replace their conventional counterparts at the commercial level in metal processing applications, such as sintering, surface engineering, joining, melting and drilling.

Large-scale commercialization of microwave-based processing applications is a potential area for research. The major challenge, however, lies in the unique source of energy in the case of microwaves, which differentiates it from the conventional processes and involves an altogether different mode of heating. It requires knowledge of physics involved in the propagation of electromagnetic radiations and its behavior. The lack of synchronization between researchers from physics/electronics domain and materials processing domain is one of the major cause of the slow pace of development in this domain of research. Heating efficiencies can be improved with the design and development of dedicated applicators through collaboration.

There have been several studies to explore theories, various interaction mechanisms, applications and numerical simulations in different microwave processing domains but there is a need for consolidated information on parametric evaluation for microwave-based metal processing [1,2,8–20]. The objective of this review is to summarize and discuss parameters and corresponding factors affecting microwave processing including discussion on input variables involved in microwave processing and their effect on response variables. The following sections will discuss the process and material parameters related to major applications of microwave heating developed in the past two decades. In addition, the paper summarizes this novel processing concept and methodologies in developing microwave-assisted materials processing.

### 2. Parameters affecting microwave-based heating processes

It is imperative to identify and understand the parameters and the factors that govern these parameters to optimize and control microwave-based materials processing. Since microwaves are electromagnetic radiations, the heating process is primarily influenced by dielectric and magnetic properties of the materials being processed. The authors have identified four significant parameters affecting microwave heating as (i) dielectric and magnetic properties, (ii) heating mechanisms, (iii) load subjected to microwave heating and (iv) applicators used for heating the materials and underlying factors that govern these parameters. Fig. 2 depicts parameters and corresponding factors affecting microwave-based heating processes.

#### 2.1. Dielectric and magnetic properties

Electromagnetic nature of microwaves results in the interaction of inherently present electric and magnetic fields with the electrons, ions, and molecules at micro-levels. In order to understand the microwave-heating phenomenon, a numerical study has also been used [21]. The results have indicated that dielectric properties have a strong effect on heating. The dielectric parameter that characterizes heating ability is known as complex permittivity, $\varepsilon^* [2]$. It is expressed by Eq. (1):

$$\varepsilon^* = \varepsilon' - j\varepsilon''$$  \hspace{1cm} (1)

where the real term, $\varepsilon'$, quantifies the ability to store energy while the imaginary term and $\varepsilon''$, is the measure of the ability to convert the stored energy into useful heat.

The ratio of the imaginary term and the real term is known as loss tangent, $\tan \delta$, which assesses if the material is suitable for microwave-based heating. Several methods for determining dielectric constant and dielectric loss factor have been presented in the literature [22,23]. Table 1 presents the principle of few methods used for characterization of electromagnetic properties.

The magnetic component of microwaves also contributes to heating. Yoshikawa et al. [24] studied the effect of microwave interaction on iron particles and ferromagnetic materials. It has been found that the source of heating in these materials was their magnetic effect. In the case of magnetic materials, the property characterizing loss and storage of magnetic energy is a complex permeability $[25]$. Eq. (2) expresses permeability in real and imaginary terms.

$$\mu^* = \mu' - j\mu''$$  \hspace{1cm} (2)

The real term of complex permeability, $\mu'$ is known as magnetic permeability, while the imaginary term is called magnetic loss factor, $\mu''$. The magnetic properties result in heating due to losses depending on the resonant frequencies corresponding to a given material. For example, the resonant frequency of a water molecule is 2.45 GHz $[26]$. Both complex permittivity and magnetic permeability are variable quantities and are affected by frequency, temperature and material
composition. Complex permittivity is a function of dielectric constant (refer to Eq. (1)). With the increase in temperature, dielectric constant and imaginary part of complex permittivity increases for a particular frequency and drops with the increase in frequency [27].

Fuzerova et al. [28] discussed variation in magnetic permeability in soft magnetic composites. The variation in the real and imaginary part of magnetic permeability using a mixture of Somaloy 700 powder (insulated iron particles) and amorphous Vitroperm (Fe72Cu11Nb3Si2B3) with respect to frequency and sample composition. Thus, by controlling the material composition and frequency of radiations, the magnetic properties of the specimen can be altered.

The chemical nature of a specimen is another factor that affects the rate of microwave heating. Evaluation of the effect of composition, structure, and impurities in the substance was carried out by Yixin and Liu [29]. The experimental investigation revealed that microwave absorption is a function of the chemical state of the material subjected to microwaves and thus, it plays an important role in heating efficiency.

In conclusion, the factors such as frequency of radiations are governed by the standards laid down by governing bodies [2,25] and temperature of processing is limited by the application and control available. Therefore, the only factor that can be controlled by the researcher is the material being used and its composition. In cases where the material to be processed do not have required dielectric or magnetic properties, the use of hybrid heating is devised [15]. Refer Section 2.2.3 for detail discussion on this mechanism.

### 2.2. Mechanism of heating

Prediction and control over the response of the material subjected to the microwave environment are significantly affected by mechanisms involved in heating. Researchers, such as Hao et al. [30], Sun et al. [20], Mishra and Sharma [19], have studied microwave-heating mechanisms. Hao et al. [30] specifically developed a model termed as “flat-ball” to express the relationship between sintering time and density. It is clear that microwave heating is primarily due to the electric field and magnetic field heating. Subsequent sections discuss the various aspects of the two heating modes and the advent of a hybrid-heating concept.

#### 2.2.1. Electric field heating

Heating due to the electric field is attributed to various mechanisms, namely polarization of dipolar molecules, ionic conduction and Maxwell–Wagner effect [20]. The mechanisms involved in the electric field and magnetic field heating are presented in Fig. 3.

The polarization of dipolar molecules occurs under the effect of the applied electric field, which is an inseparable part of any electromagnetic radiation. The heat generated through this phenomenon is because of frictional interaction due to “to and fro” movement of these molecules under the effect of a time-varying electric field [2].

In the mechanism involving ionic conduction, the charge carriers, such as electrons and ions, undergo forward-reverse movement when the electric field is applied [20]. This leads
Fig. 3 – Mechanisms of electric and magnetic field heating.

to the induction of currents which releases heat. In materials that consist of excess electrons like carbon, a cause of electric field heating is attributed to the Maxwell–Wagner effect [20]. Here, the heat is generated due to interfacial polarization. The excess electrons also termed as α electrons available in carbon, are unable to couple with the changing phase of the electric field component of the microwave, thereby, resulting in dissipation of energy [31]. In the context of microwave-based materials processing applications, there are quite a few materials that do not interact with microwaves or reflect the microwaves altogether. This is quite prominent in the case of metals. Therefore, susceptors such as charcoal, graphite, and silicon carbide are used due to their heating capability as a result of the Maxwell–Wagner effect. These susceptors are used as per the requirement of the set-up as described in detail in Section 2.2.3.

2.2.2. Magnetic field heating

The magnetic field component of microwaves also causes heating under the effect of microwave irradiation. Several loss mechanisms have an effect on temperature rises, like in the case of magnetic materials and conductors. These are losses due to eddy current, Hysteresis, magnetic resonance and residual losses. Sun et al. [20] and Mishra and Sharma [19] discussed this in detail. Table 2 is a comparison between the two modes of heating under the influence of microwaves.

Mathematical modeling of heat transfer and generation mechanisms in microwave-based materials processing is an area that needs further investigation to achieve greater reliability and reproducibility of experimental results.

### Table 2 – Comparison between electric field heating and magnetic field heating.

<table>
<thead>
<tr>
<th>Particulars</th>
<th>Heating-electric field</th>
<th>Heating-magnetic field</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mechanisms</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polarization due to dipolar effect</td>
<td>Losses due to eddy current</td>
<td></td>
</tr>
<tr>
<td>Conduction of ions</td>
<td>Conduction of ions</td>
<td></td>
</tr>
<tr>
<td>Maxwell–Wagner polarization</td>
<td>Maxwell–Wagner polarization</td>
<td></td>
</tr>
<tr>
<td>Magnetic resonance losses</td>
<td>Magnetic resonance losses</td>
<td></td>
</tr>
<tr>
<td>Residual losses</td>
<td>Residual losses</td>
<td></td>
</tr>
</tbody>
</table>

### Table 3 – Susceptor material properties at different temperatures [32].

<table>
<thead>
<tr>
<th>Material</th>
<th>tan δ (25 °C)</th>
<th>tan δ (500 °C)</th>
<th>tan δ (900 °C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al₂O₃</td>
<td>0.0005</td>
<td>0.002</td>
<td>0.01</td>
</tr>
<tr>
<td>ZrO₂</td>
<td>0.0002</td>
<td>0.04</td>
<td>0.25</td>
</tr>
<tr>
<td>AlN</td>
<td>0.004</td>
<td>0.004</td>
<td>&gt;0.01</td>
</tr>
</tbody>
</table>

2.2.3. Microwave hybrid heating

Energy generated in electric and magnetic field heating is inadequate to achieve desired heating effects. This is primarily due to the inability of materials to interact with microwaves effectively. In microwave hybrid heating, high microwave absorbent material, known as susceptors are used, such as carbon, silicon carbide and alumina for rapid heating. This absorption property is a function of temperature [32]. The loss tangent increases with increase in temperature thus enhancing the microwave heating characteristics. Table 3 shows the value of loss tangents at different temperatures for selected materials that are used as susceptors. The loss tangent (tan δ) value >0.01 suggests good absorption capacity.

Owing to the in microwave hybrid heating, applications, such as sintering, coating and joining have attracted the attention of several researchers. Table 4 summarizes research on powder metals and their use in microwave-hybrid heating.

2.3. Load

Load in the context of microwave hybrid heating refers to the material being heated inside the chamber. The factors that affect this parameter selection are size, penetration depth – a factor dependent on the electrical conductivity of the material – and load positioning in the applicator [2].
Table 4 – Microwave direct/hybrid heating applications.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Material</th>
<th>Powdered/bulk</th>
<th>Susceptor/direct</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gupta and Sharma [33]</td>
<td>Austenitic stainless steel (SS-316)/EWAC powder as clad material (40 μm)</td>
<td>Bulk substrate and powder as clad material</td>
<td>Graphite</td>
<td>Cladding</td>
</tr>
<tr>
<td>Gupta and Sharma [34]</td>
<td>Austenitic stainless steel (SS-316)/WC10Co2Ni Clad material (40 μm)</td>
<td>Bulk substrate and powder as clad material</td>
<td>Graphite</td>
<td>Cladding for wear resistance</td>
</tr>
<tr>
<td>Gupta et al. [35]</td>
<td>Austenitic stainless steel (SS-316)/EWAC (Ni-based) + 20% Cr23C6 Clad material (40 μm)</td>
<td>Bulk substrate and powder as clad material</td>
<td>Graphite</td>
<td>Cladding for wear resistance</td>
</tr>
<tr>
<td>Sharma and Gupta [36]</td>
<td>Austenitic stainless steel (SS-316)/EWAC + 20% WC10Co2Ni Clad material (40 μm)</td>
<td>Bulk substrate and powder as clad material</td>
<td>Graphite</td>
<td>Cladding for wear resistance</td>
</tr>
<tr>
<td>Pathania et al. [37]</td>
<td>Mild steel/EWAC + 20% WC10Co2Ni Clad material (40 μm)</td>
<td>Bulk substrate and powder as clad material</td>
<td>Charcoal</td>
<td>Cladding for wear resistance</td>
</tr>
<tr>
<td>Zafar and Sharma [38–60]</td>
<td>SS304/WC-12Co</td>
<td>Bulk substrate and powder as clad material</td>
<td>Charcoal</td>
<td>Cladding for wear resistance</td>
</tr>
<tr>
<td>Roy et al. [41]</td>
<td>Al, Cu, Co, W, Ni Fe and steel Mo, WC and Sn and their alloys</td>
<td>Powder</td>
<td>SiC powder</td>
<td>Sintering</td>
</tr>
<tr>
<td>Saitou [42]</td>
<td>Ni (99.8%, 45 μm), SUS316L (45 μm), Co (99.5%, 5 μm) Cu (99.5%, 75 μm) and Fe (99.5%, 45 μm)</td>
<td>Powder</td>
<td>SiC powder</td>
<td>Sintering</td>
</tr>
<tr>
<td>Agrawal [7]</td>
<td>Copper-steel</td>
<td>Powder</td>
<td>Direct</td>
<td>Sintering</td>
</tr>
<tr>
<td>Prabhu et al. [43]</td>
<td>W (99.95%, 5–7 μm)</td>
<td>Powder</td>
<td>Direct</td>
<td>Sintering</td>
</tr>
<tr>
<td>Xu et al. [44]</td>
<td>Al (purity: 96%, average diameter: 120 μm)</td>
<td>Powder</td>
<td>Direct</td>
<td>Sintering</td>
</tr>
<tr>
<td>Shannigrahi et al. [45]</td>
<td>Ferrite</td>
<td>Powder</td>
<td>SiC</td>
<td>Sintering</td>
</tr>
<tr>
<td>Bykov et al. [46]</td>
<td>Al2O3–Ni (2–2.5 μm)</td>
<td>Powder</td>
<td>Direct</td>
<td>Sintering</td>
</tr>
<tr>
<td>Thuault et al. [47]</td>
<td>Kaolin bowls</td>
<td>Bulk</td>
<td>SiC</td>
<td>Sintering</td>
</tr>
<tr>
<td>Yang et al. [48]</td>
<td>SiC</td>
<td>Fiber bundles</td>
<td>Direct</td>
<td>Sintering</td>
</tr>
<tr>
<td>Li et al. [49]</td>
<td>SiC (125 μm)</td>
<td>Powder</td>
<td>Direct</td>
<td>Sintering</td>
</tr>
<tr>
<td>Ghobadi et al. [50]</td>
<td>Al2O3 nanocomposites</td>
<td>Powder</td>
<td>Direct</td>
<td>Sintering/composites synthesis</td>
</tr>
</tbody>
</table>

2.3.1. Penetration depth

Selection of a load for microwave interaction is based on an understanding of the parameter known as penetration depth. A material with all other parameters constant would behave differently under the microwave environment when the dimensions change. Penetration depth is defined as: “The depth at which electric field component drops to 1/e times the magnitude of electric field intensity at the surface” [20]. Mathematically, it is expressed by Eq. (3):

\[
d = \frac{\sqrt{\varepsilon} \cdot \varepsilon_{r}}{\varepsilon_{r} + \mu_{r}} \left[ \left( 1 + \tan^{2} \delta_{0} \right) + \left( \tan^{2} \delta_{0} + \tan^{2} \delta_{0} \right)^{1/2} \tan \delta_{0} \right]^{-1/2}
\]  

(3)

where \( \tan \delta_{0} = \mu_{0}/\mu_{r} \) and \( \tan \delta_{0} = \varepsilon_{r}/\varepsilon_{r} \).

The magnitude of penetration depth is used to categorized materials as transparent, reflectors and absorbing. Due to inherent properties, conventionally processed materials such as plain carbon steels, alloy steels, aluminum and copper have low penetration depths and therefore, microwaves do not effectively heat these materials. These are termed as transparent materials. This might be a reason for the slow rate of progress in microwave-based processing technologies. Eq. (3) shows that frequency has an inverse relationship with penetration depth. Since the frequency band for industrial heating is limited to specific values such as 915 MHz, 2.45 GHz, etc. [25], the penetration depth is fixed for a given operational frequency of the applicator.

A typical value of penetration depth (at 2.45 GHz) for conductors (opaque/reflecting materials), absorbing materials and transparent materials is shown in Table 5 adapted from [51]. This categorization helps in understanding load attributes and facilitates selection of crucible materials.

2.3.2. Size

Size of the load under treatment affects the uniformity in heating. Maximum efficiency is attained only when load dimensions are close to the order of penetration depth. In the case of materials with unfavorable di-electric and magnetic properties, powdered materials have exhibited superior ability to interact with microwaves. Studies have attempted to understand the behavior and utility of powdered metals in microwave-based applications. Whitaker and Mingos [52] found that powder metals show good coupling characteristics with microwaves. Experiments were carried out in a power controlled 2.45 GHz microwave oven. The study revealed that there was no morphological change compared with conventional syntheses after microwave syntheses. To understand the nature of heat absorption in a powder sample, Mondal et al. [53] examined the influence of microwave field on the
thermal profile of copper powder with different particle sizes and porosity under the condition of constant power. A thin layer of graphite was used as a susceptor. It was observed that particle size inversely affects the heating rate that is, the heating rate increases with reduced particle size while higher porosity provides higher heating rates. Ghosh et al. [54] combined powdered aluminum, alumina, to synthesize composites. The results were quite effective owing to the exposure of each powdered particle to radiation. All these studies revealed that the size of the sample is an important factor in the processing of materials and therefore, a key component of process effectiveness.

2.3.3. Load positioning in the applicator

Several studies have attempted to identify the optimum location for the positioning of the load. Microwaves form a standing wave pattern inside the chamber due to the interference phenomenon. The location with maximum amplitude has the maximum possible energy for conversion into thermal energy. Therefore, it is important to know these locations for load positioning.

2.4. Applicators

Applicators are chambers in which microwave processing is carried out. The applicator type i.e., single mode or multimode and cavity design and size have a direct effect on microwave heating efficiency. It influences the availability of power for processing [55]. Researchers have for long been finding ways to customize applicators for improving power concentration and in turn heating efficiencies. It has led to the development of various industrial microwave heating systems and customized set-ups. Based on the modes of microwave frequencies generated by the source, the applicators are classified as single mode and multi-mode. Rana and Rana [18] discussed in detail microwave reactors. The following sections discuss the applicator types and their impact on applications.

2.4.1. Single mode applicators

These applicators operate at single mode microwave frequency. The radiations propagate through waveguides. These waveguides are transmission media, similar to that of an electrical cable used for passing electricity and can be circular or a rectangular cross-section. In rectangular waveguides, either a transverse electric mode or a transverse magnetic mode of wave propagation can exist depending on the boundary conditions. These applicators provide better control over the microwave process parameters due to the predictability of the field across the load. The challenge with the single mode applicators is the proper selection of system components and precise impedance matching to avoid loss of power. A typical single mode applicator configuration is shown in Fig. 4. The microwave is generated by the magnetron and passed through a series of components placed inside a transmission line known as waveguides, analogous to electrical transmission lines. The isolator protects the generator from cutting off the reflected microwave transmission back to the source [8]. Sometimes circulators are also used to perform the task of directing microwaves to desired space using multiple ports. In order to enable the transfer of waves without obstruction and reversal, which will damage the source, it is important to have a matching of impedance. Stub tuners are used for impedance matching and minimizing reversal of waves [56]. Maximum heating in the cavity or the heating zone is achieved when the standing waves developed after interference with the reflected wave are constructive in nature. Constructive interference is achieved by having a movable shorting plunger. The load or the material to be processed has to be placed in this heating zone [57].

Researchers have designed single mode applicators for various heating applications to achieve closer process control. For instance, Gower [58] developed a beam applicator for melting of ceramics and Uhm et al. [59] fabricated a unique microwave torch to synthesize carbon nanotubes. A single mode applicator prototype developed by Pavuluri et al. [60] was 10 times faster in heating the integrated circuit packages required for electronic components. The single-mode applicator with a cylindrical cavity developed by Prapuchanay et al. [61] exhibited superior heating performance compared with multi-mode microwave ovens. Customized single-mode applicators have been developed for microwave drilling applications [62–68]. These applicators have provided novel means for drilling concrete, silicon, glass [65], bones [66] and Litz wire [68].

Saitou [42] carried out series of experiments in a single mode applicator using selected metal powders, such as iron, cobalt, nickel, copper and stainless steel to investigate the mechanism of microwave sintering. Sintered SiC tube was used as a susceptor. The applicator had the provision for establishing a controlled atmosphere (nitrogen gas for nickel and cobalt and hydrogen gas for other materials). It was achieved by providing two ports to the applicator chamber: one for creating a vacuum which in turn, created space for the gas to be introduced while the other port acted as an inlet to the gas; H2/N2 mixture in this case. Nitrogen was used as it is one of the best low-cost alternative to argon for creating inert atmosphere to avoid the formation of undesired compounds during
the sintering process [69]. However, there is a tendency for nitrogen uptake by the material and formation of nitrides [70]. Therefore, to ensure sinter quality, hydrogen is used for iron, copper and stainless steel. It develops a reducing atmosphere in the furnace and absorbs the oxygen from the oxide layers between the particles formed under the high temperature of the furnace. This improves bonding and reduces porosity [71]. Yoshikawa et al. [24] carried out a similar experiment using a 1.5 kW single mode applicator. This enabled easier prediction of the locations with higher strength of magnetic fields and electric fields. The area with higher strength magnetic field showed greater efficiency in heating ferromagnetic materials while nickel-oxide, another material used here, showed better heating results at the location with higher strength of the electric field. The factor that limits the utilization of single-mode applicators is its inability to support larger size specimen.

2.4.2. Multi-mode applicators
Multi-mode applicators, shown in Fig. 5 are designed to accommodate multiple modes of microwave radiations emitted from a microwave source such as a magnetron. This leads to the distribution of energy in a larger cavity. Eventually, the energy efficiencies obtained in these applicators are lower compared with that achieved in single-mode applicators. For the material processed in multi-mode applicators, the position of the load is insignificant as the uniformity in heating is obtained by rotating the load or by using a mode stirrer, i.e. a component that reflects the microwaves to desired locations.

Multi-mode applicators are the most commonly used test chambers for microwave treatment. The domestic ovens are a prime example of a multi-mode set-up. Vollmer [26] described the physics of how these ovens operate while the use of simulations has been reported in applications involving multi-mode applicators as well. For instance, Ju and Zhao [72] used a simulation software (HFSS) in the designing of applicators while Srinath et al. [73] used simulations to predict microwave-heating behavior in a multi-mode setup. There was a good agreement between the experimental and simulation results. These simulation results revealed the distribution of electric and magnetic fields along with thermal losses and the temperature distribution in the applicator. Thus, favorable results obtained using experiments and simulation of microwave-based heating can be used for development of large-scale furnaces for industrial applications.

2.4.3. Design modifications and accessories in applicators
In order to understand the effects of process variables, several researchers have done modifications in multi-mode applicators, such as provision for temperature measurement, gas supply and vacuum creation. The set-up used by Roy et al. [41] was an industrial one with a maximum power rating up to 6 kW, working at frequency 2.45 GHz. Facility for mounting susceptors was also available to enable hybrid heating. The temperature at 1400 °C was suitable for achieving sintering of all the combinations of metal and alloy samples. Various metal powder components were successfully sintered. On evaluation, these sintered components exhibited superior metallurgical properties. Agrawal [74] also used an industrial batch type microwave furnace with a high power rating (up to 6 kW) at 2.45 GHz to sinter copper-steel powdered components. Temperature, to the order of 1260 °C, was achieved in this experiment. These studies suggested that judicious usage of multi-mode applicators could lead to a significant magnitude of temperature. A significant investigation in this context has been carried out by Prabhu et al. [43]. Sintering of high melting point material, tungsten was performed in a multi-mode microwave furnace with variable power input facility at 2.45 GHz. The furnace had the facility of creating a vacuum. Even using domestic ovens at different power ratings yielded desired results in cladding and coating processes [14]. Although there was no clear mention of the temperature levels achieved in these experiments the quality of clads and their properties reveal that complete melting of the clad materials, such as EWAC (Ni-based) +20% Cr23C6, WC10Co2Ni and EWAC, etc. have taken place. Table 6 shows the temperature achieved in different applicators.

An important component of the microwave applicator design is the selection of microwave source. Generally, commercial ovens use a magnetron. Apart from this, other generators, such as power grid, gyrotron, traveling wave tube and klystron are available [25]. The selection of the generator is factorized by power. Gyrotron and klystron are high power devices with a frequency range greater than the one used for domestic heating (2.45 GHz) while power grids exhibit very
high-power characteristics at lower frequencies [25]. Thus, one can choose these microwave sources as per the requirement of the application.

The parameters discussed above are the basis for the successful implementation of microwave heating in materials processing. This field of research has much to offer in terms of exploring materials for processing, the design of applicators, controlling factors, such as frequency, the atmosphere inside the furnace, analyzing mechanisms of heat generation among others for getting desired experimental outcomes.

平

Table 6 – Applicator type and temperature attained.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Temperature °C</th>
<th>Power/frequency</th>
<th>Applicator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Das et al. [75]</td>
<td>1310</td>
<td>800 W/2.45 GHz</td>
<td>Multi-mode</td>
</tr>
<tr>
<td>Gupta and Sharma [33]</td>
<td>Melting point of WC10Co2Ni Cr23C6</td>
<td>900 W/2.45 GHz</td>
<td>Multi-mode</td>
</tr>
<tr>
<td>Gupta et al. [35]</td>
<td>Melting point of EWAC (Ni-based) + 20%</td>
<td>900 W/2.45 GHz</td>
<td>Multi-mode</td>
</tr>
<tr>
<td>Gupta and Sharma [34,76]</td>
<td>Melting point of EWAC + 20% WC10Co2Ni</td>
<td>900 W/2.45 GHz</td>
<td>Multi-mode</td>
</tr>
<tr>
<td>Puthania et al. [37]</td>
<td>Melting point of EWAC + 20% WC10Co2Ni</td>
<td>900 W/2.45 GHz</td>
<td>Multi-mode</td>
</tr>
<tr>
<td>Roy et al. [41]</td>
<td>Fe: 775–1250</td>
<td>1.4 kW/2.45 GHz</td>
<td>Multi-mode</td>
</tr>
<tr>
<td>Saitou [42]</td>
<td>Co: 900–1200</td>
<td>1.5 kW/2.45 GHz</td>
<td>Multi-mode</td>
</tr>
<tr>
<td></td>
<td>Ni: 900–1300</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>SS316L: 900–1200</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cu: 600–1000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Agrawal [7]</td>
<td>1260</td>
<td>6 kW/2.45 GHz±2 kW/2.45 GHz</td>
<td>Multi-mode-Batch furnace</td>
</tr>
<tr>
<td>Prabhu et al. [43]</td>
<td>1600, 1700, 1800</td>
<td>3 kW/2.45 GHz</td>
<td>Multi-mode</td>
</tr>
<tr>
<td>Shanigrahi et al. [45]</td>
<td>900–950</td>
<td>0.5–3 kW/2.45 GHz</td>
<td>Multi-mode</td>
</tr>
<tr>
<td></td>
<td>(1400-capacity of furnace)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bykov et al. [46]</td>
<td>1250</td>
<td>5 kW/24 GHz</td>
<td>Multi-mode</td>
</tr>
<tr>
<td>Thuault et al. [77]</td>
<td>1200</td>
<td>6 kW/2.45 GHz</td>
<td>Multi-mode</td>
</tr>
<tr>
<td>Yang et al. [48]</td>
<td>1200</td>
<td>4 kW/2.45 GHz</td>
<td>Multi-mode</td>
</tr>
<tr>
<td>Li et al. [49]</td>
<td>1800</td>
<td>3 kW/2.45 GHz</td>
<td>Multi-mode</td>
</tr>
<tr>
<td>Hassan et al. [78]</td>
<td>1300</td>
<td>5 kW/30 GHz</td>
<td>Multi-mode</td>
</tr>
<tr>
<td>Gobadi et al. [50]</td>
<td>1520</td>
<td>900 W/2.45 GHz</td>
<td>Multi-mode</td>
</tr>
</tbody>
</table>

Gradually, it was understood that apart from drying microwave energy could be used in efficient sintering of ceramics [74]. For instance, sintering of WC/Co composites through microwave led to a drastic reduction in processing time and offered superior mechanical properties [7,10,74]. Similar advantages have also been reported in the case of metal powders [41,42].

The outcome of the sintering process is measured in terms of three distinct parameters: mechanical properties, sintered density, and porosity. In order to understand the effect of microwave heating on mechanical properties, Roy et al. [41] used components of varied alloy compositions, such as iron, nickel, molybdenum, aluminum, tungsten, tungsten carbide and tin, manufactured through powder metallurgy route on a commercial basis. The applicator had controlled environment and provision for single mode as well as multi-mode operations while susceptors (SiC and MoS2) were used to enhance heating efficiency. The results indicated the superiority of microwave sintering process, which boosted toughness and ductility of the materials.

For materials with high melting points (such as tungsten – about 3683 K), these characteristics are relevant as it is processed primarily through powder metallurgy route. Prabhu et al. [43] carried out sintering of tungsten powder and activated tungsten powder. Activation of the tungsten powder was achieved using the ball milling process. The experiment was carried out with three different experimental conditions based on variable sintering temperatures (1873 K, 1973 and 2073 K) and varying power input in a 3 kW, 2.45 GHz-controlled atmosphere (5% H2 and 95% N2) multi-mode microwave furnace. It was observed that activated tungsten showed better properties in terms of sintered density as shown in Fig. 6. This enhancement is due to the increased surface area, smaller particle sizes and increased strain energies developed during activation using the ball milling process.

3. Applications of microwave processing

The extent of control over the parameters discussed above determines the effectiveness of the microwave processing applications. The following sections discuss the development in microwave-based heating applications and the relationship between corresponding response parameters and input parameters discussed in previous sections.

3.1. Microwave sintering applications

The conventional methods of sintering use resistance heating or heating through conventional modes of heat transfer that is, conduction, convection and radiation. These methods have limitations such as slow heat transfer rate and uneven heating. The development of microwave heating attracted attention when it was observed that microwave sintering offered several advantages over conventional sintering. The energy transfer from microwaves to materials is achieved by absorption. This heating is uniform in nature and therefore yields superior characteristics of the processed material quantified as response parameters [79].
A unique output parameter identified by Saitou [42] for evaluating the sintering process effectiveness is “Shrinkage Measurement” [80]. The shrinkage parameter can be measured using Eq. (4).

\[
\left( \frac{\Delta L}{L_0} \right)^n = B_0 t (2^D)^{mRT} \exp \left( -\frac{Q}{RT} \right)
\]  

(4)

Values of numerical constants, \( n \) and \( m \), depending on the sintering mechanism:

- \( n = 2, m = 1 \) for viscous or plastic flow;
- \( n = 5, m = 3 \) for volume diffusion;
- \( n = 6, m = 4 \) for grain boundary diffusion; and
- \( n = 7, m = 4 \) for surface diffusion.

The samples used in the study consisted of several metal powders, viz. copper, cobalt, iron, nickel and stainless steel subjected to sintering in single mode applicator within a controlled environment. It was observed that microwave-heating process has an impact on shrinkage, which is dependent on material parameters as expressed in Eq. (4). It was also pointed out by the author that the reasons for shrinkage are still unknown and further studies are required to understand it [42].

Ferrite is an important component in many engineering applications, especially in electrical and electronic devices due to its magnetic properties. It is processed through powder metallurgy route and requires sintering. Conventional sintering causes a loss in fineness of the particles as a result of high temperatures [45]. Microwave sintering of the ferrite powders led to superior properties [45]. Microwaves, exhibit selective heating characteristics due to different interaction abilities of materials as discussed in Section 2.3.1. This ability of microwaves was used in the sintering of Ni-Al₂O₃ functionally graded material [46]. The samples obtained were free from defects, such as cracks and delamination. Fig. 7a–c compares a few response parameters of microwave sintering with conventional sintering of selected samples [41,74]. Microwave sintering resulted in a greater degree of hardness, modulus of rupture (MOR) and reduced processing time.

In short, the response parameters in sintering are sintered density, hardness, flexural strength and toughness in general and magnetic properties and shrinkage in particular. The superior properties of microwave-sintered components are attributed to the following reasons [41]:

- Bulk heating characteristics of microwaves resulting in heat transfer in dual directions (from penetration depth to both the sides of the sample).
- Fast processing speed leading to microstructure-dependent property enhancement such as finer grain size and development of round edge porosities. It also minimizes the formation of undesired compounds and at the same time, provides energy advantage due to low consumption of power.

Sintering is a well-known application in microwave processing wherein a lot of development in design and development of dedicated microwave furnaces has taken place. There is very little understanding of the mechanisms involved in sintering. Large-scale commercialization is also yet to be realized. At the same time, the optimization of the process parameters and predictable control over the process is still a challenge and demands extensive research.

### 3.2 Cladding and surface coating applications

Many engineering applications require materials that exhibit strong resistance to chemical attacks and wear with an ability to perform intended function even in hostile environments and operating conditions [81]. Marine applications, aeronautical applications, oil and gas refineries and drilling applications, agricultural applications, and defense applications are few of those applications that involve extreme as well as adverse environments [82,83]. The materials used in these applications also need to have sufficient strength, hardness and toughness to withstand the various structural and thermal loads experienced by them [84–88]. The effects of adverse

**Fig. 6 – Sintered density versus temperature for activated tungsten and as received tungsten [43].**
environmental and severe operating conditions are primarily limited to surfaces.

There are different ways to modify or enhance surface properties, such as modification of chemical composition by surface nitriding, surface cyaniding, carburizing, vanadizing and modification in the surface characteristics by mechanical and thermal processes and development of layers or overlays on the surfaces using coating and cladding processes. Conventional surface modification methods are thermal spraying [82], high-velocity oxyfuel spraying [89], tungsten inert gas (TIG) cladding, laser cladding, and submerged arc welding (SMAW) based cladding, etc [84]. Laser cladding is the most effective process in terms of its superior properties resulting in reduced cracks, porosity and errors in bonding along with the controlled cooling rate. The major issue with laser-based processes is the cost and thermal stresses developed due to the concentration of heat [33].

With a greater understanding of microwave heating phenomenon, several applications of coating and cladding using microwave thermal energy have been reported. Gupta and Sharma [33] demonstrated successful cladding of EWAC (97% nickel) over austenitic stainless-steel substrate. The process was carried out in the domestic microwave oven (1 kW, 2.45 GHz). The clad exhibited metallurgical bonding with the substrate and developed intermetallic compounds, such as iron-nickel and nickel-silicide. The average microhardness achieved was about 304 ± 48 HV, which is twice than that of the substrate material. Additionally, the clads were observed to be of a superior quality which was evident through its pores-free characteristics as can be seen in Fig. 8.

In extension to this work, Gupta and Sharma [29] carried out cladding experiments to gauge the effectiveness of microwave cladding of a composite (EWAC-Ni-based and 20% Cr23C6 powder) over austenitic stainless steel. The results were encouraging as the obtained clads exhibited desired properties. Using similar methodologies, the cladding of anti-wear powders to improve wear resistance have been achieved [37,38,40].

Fig. 7 – (a) Comparison of hardness achieved in the microwave and conventional sintering, (b) Comparison of MOR achieved in the microwave and conventional sintering, (c) Comparison of time required to achieve the desired temperature [41,74].

Fig. 8 – Microstructure of EWAC microwave cladded cross-section (Reprinted from Surface and Coatings Technology, 205 /21-22, Dheeraj Gupta, A.K. Sharma, Development and microstructural characterization of microwave cladding on austenitic stainless steel, 5147-5155, 2011, with permission from Elsevier) [33].
The quality of the coating and cladding is determined by characterizing and measuring response parameters, such as micro-hardness, wear resistance, deformation index, and thickness. In order to understand the conditions under which these parameters have attained the desired levels, the results of various researchers are presented in Table 7.

Microwave-based cladding or coating has the potential to be developed as an alternative to conventional surface modification techniques. Microwaves ability to achieve uniform
heating makes a case for strong thermal stress-free surface modification. Another important observation in the area of surface modification application is the lack of studies on the effect of process and response parameters. This could be a result of the lack of suitable experimental set-ups and the early days of development of such an application. This offers tremendous scope for future research on the reliability of the process control, the advent of clads of novel materials and optimization of processes.

3.3. Microwave joining of materials

A wide variety of materials such as plastics, mild steel, stainless steel, copper have been tested for suitability of joining through microwave energy. The process is based on utilizing the heat developed by microwave energy for melting interfacing powder material at the joint either directly or through hybrid heating and fusion of the melted powder with the rectangular plates or cylindrical specimen to be joined [90–100].

Sioreis and Diego [101] carried out pioneering work in microwave joining. Set-ups for carrying out joining of plastics and metals were developed and bonding agents having low loss factors were used for the joining purpose to enhance microwave absorption. The set-ups were specially devised to utilize microwave energy with minimum losses. Diagnostic tools were incorporated for measuring process parameters, such as the strength of the electric field, the temperature of the specimen, incident and reflected power and joining interface pressure. This provided an opportunity to detect and control joining processes with the help of microcomputer. Investigations showed that microwaves can be successfully used for joining not only high loss materials such as mullite, alumina, but also low loss materials viz. plastic polymers and metals. Rods of the composite of alumina (48%), zirconium (32%), SiO₂ (20%) were butt welded in a single mode applicator using microwaves generated by the variable power source with pulsating input [90]. It was observed that at higher power ratings, 1 and 1.25 kW, and loading pressure of about 1 MPa, the joint strength was found to be reduced. It was due to the formation of blowholes and flash. On the other hand, very low power and loading pressure of magnitude 0.5 MPa resulted in incomplete joints. Ahmed and Sioreis [90] have also reported that joint quality is affected by the rate of temperature rise which can be controlled with the use of incident power pulsing. Therefore, an efficient microwave joining process requires close control over the rate of temperature rise.

A significant development in microwave joining was the advent of methodologies for joining metals. Experiments were carried out to weld bulk SS316L using microwave hybrid heating [102]. The joint was formed by fusing powdered sandwich layer heated through microwave interaction in 900 W multi-mode applicator at 2.45 GHz frequency. The joints were characterized for morphology and mechanical properties and were found to have good strength and microhardness owing to the formation of carbides in the intermetallic phases due to the use of charcoal as a susceptor. Using a similar methodology, copper plates were joined using microwave hybrid heating with the help of charcoal as a susceptor material [98]. Hybrid heating provided the initial rise in temperature to a critical one of the sandwich layers comprising a powdered slurry of copper. Beyond this temperature, the powder started coupling with microwaves. It was found that the joint had a uniform microstructure, an outcome of uniform heating. This resulted in superior microhardness, denser microstructure, significant tensile strength, and high elongation.

This development is significant due to poor weldability of copper through conventional methods. Another important field in microwave-based joining is the preparation of high-quality dissimilar joints. Upon successful processing of high-quality similar metal joints of copper–copper and SS316L–SS316L, experiments were carried out for joining two different metals SS316L and MS with Ni as an interfacing material [103]. Due to strong intermetallic bonding, high ultimate tensile strength (up to 346.6 MPa) and hardness of 133 HV were obtained. This method was found to be time-efficient. The use of clean energy in the form of microwave radiations made the process eco-friendly too. Bansal et al. [92] examined MS–MS joints formed with nickel as an interfacing material in a multi-mode applicator of 900 W rating at an exposure time of 600 s and a frequency of 2.45 GHz. Complete melting of the interfacing material at the interface led to diffusion bonding which resulted in superior joint quality. The SEM micrograph showed that the joint had a predominant ductile fracture behavior. Badiger et al. [97] showed the joining of bulk Inconel-625 alloy using a novel technique based on microwave heating. The researchers followed a similar procedure with that of earlier experimental studies. Butt joining of the square specimens was carried out using nickel powder as an interfacing material. The joint strength obtained was observed to be greater than 35% of the base metal strength. Most of these experiments were conducted in a multi-mode domestic microwave oven. Hoyt et al. [104] carried out soldering of copper with lead telluride using a customized microwave-based welding system. It was cost and time effective. Numerical simulation of the joining process has also been done on COMSOL, a commercial package, to understand the temperature distribution and the results were compared with experimental values [73].

It can be concluded that main response parameters in the microwave-based joining of materials are: joint hardness, joint strength, porosity, percentage elongation of the joint and time required for processing as shown in Fig. 9.

The magnitude of response parameters of the joint obtained using microwave-based heating for various combinations of metals, interfacing powders and susceptors used is shown in Table 8.

The magnitude of joint hardness, porosity, joint ultimate tensile strength proves the efficacy of microwave-based joining methodology. All these studies focused on investigating the feasibility of joining different materials using microwaves and quantified the magnitudes of response parameters using experiments. The parametric effects of variables, such as powder size, time of materials’ microwave exposure have seldom been reported. Gamit et al. [96] reported the results of time dependency on the strength of the bond formed between the two metal pieces. Although there was not much improvement in the yield strength of the joint with time, it was revealed that the exposure time has a synergistic relationship with the
metallurgical bonding formed between the interface material and the bulk pipes of mild steels.

Investigation on the effect of powder size on joint hardness, ultimate tensile strength (UTS) and percentage elongation in the joining of SS304 specimen was carried out by Bagha et al. [94]. Four joints were prepared with interfacing powder Nickel with a size of 50 μm, 40 μm, 30 μm, and 20 μm. The effect of variation of powder size on the response variables is as shown in Fig. 10. It was found that the size of powders has an inverse relationship with joint homogeneity, strength, and hardness. That is, there is an increase in the joint hardness and ultimate tensile strength with the reduction in powder size; while the ductility tensile strength reduces with decreasing powder size. This is due to increased microwave interaction with reducing powder size. This is attributed to the close proximity of the powder size to the penetration depth of the material.

The materials joined by microwave heating have shown good characteristics and shorter processing times in different investigations. Apart from conventional materials such as steel and copper, this technique of joining can be used in different applications involving difficult-to-join materials, such as aluminum and its alloys, magnesium and its alloys and various dissimilar joints.

The major challenges posed by the microwave-based joining process is selection of suitable interfacing powder or filler material compatible to the materials to be joined, preparation of set-up that includes selection and positioning of susceptor and masking materials to avoid bulk specimen from getting exposed to microwaves while ensuring maximum heat.
transfer from the susceptor to the joint area. In addition, the most significant challenge is to estimate the processing time, which is still based on trial and error [96].

3.4 Microwave casting/melting applications

Researchers have also explored possibilities in utilizing microwave-based heating technology in melting or casting processes. One of the earlier usages of microwave energy for casting process is the de-waxing operation in the investment casting process. Brum et al. [105] evaluated the feasibility of using microwave technology in dewaxing while Yahaya et al. [106] implemented the concept of microwave hybrid heating for in microwave dewaxing. It offered advantages, such as non-degradation of wax quality and faster processing time.

Although microwave-based melting of copper, aluminum and steel specimen have been reported earlier by Agrawal [7], however, not many details are available on the experimental parameters. Chandrasekaran et al. [107] carried out a similar investigation to understand the heating characteristics of metals, such as lead, tin, copper, and aluminum in a multimode oven under hybrid heating environment. The process parameters selected were microwave power and the quantity of material being processed (load). The results of the experiment were compared with conventional melting. Microwave heating resulted in rapid temperature rise attributed to the increased interaction of microwaves with the material. Three different power levels 100% (1300 W), 70% (910 W) and 40% (520 W) and at various sample loads (25–150 g) were used for investigation. An important outcome was the fact that melting through microwave power was found to be twice faster than conventional heating-based melting and it is also a cleaner process with reasonable control.

The success achieved in the melting of metals using microwave energy led to the research on casting. An in situ casting set-up was developed in an industrial multi-mode microwave oven (1.4 kW at 2.45 GHz) by Mishra and Sharma [108]. This was used to melt a cylindrical piece of 100 g aluminum 7079 alloy. Major parts of the set-up were made up of materials that exhibit good interaction with microwaves. This included a pouring basin with SiC susceptor; alumina sprue and a graphite mold in two pieces (cope and drag). The casting process got completed with microwave exposure for only 8 min and 45 s. COMSOL Multiphysics, a commercial package was also used to indicate the thermal history of the load under the influence of microwave irradiation. The simulation results demonstrated that the location of charge to be melted had a significant effect on heating characteristics.

An important parameter in microwave processing is the rate of temperature rise. Xu et al. [44] performed the melting of copper powder of three different sizes of 25 μm, 38 μm, and 74 μm. An additional experimental factor was quantity. These were used in three different quantities, viz. 50 g, 100 g, and 150 g. The samples were exposed to 1.3–1.8 kW power at 2.45 GHz in a multi-mode industrial applicator. The applicator had a provision for temperature measurement and setting up of a controlled atmosphere of Ar gas. The research resulted in the development of a model for the rate of temperature rise in copper of powder size 74 μm. The rise in temperature has been expressed as a function of ‘t’ using Eq. (5).

\[
T = \begin{cases} 
8.8t + 443.7, & R^2 = 0.9993 \quad (0 \leq t \leq 26) \\
-294.5 + 49.9t - 0.46t^2, & R^2 = 0.9793 \quad (26 \leq t \leq 55)
\end{cases}
\]  

(5)

Xu et al. [44] also showed that an increase in temperature leads to densification from 2.13 g/cm³ at room temperature to 3.31 g/cm³, 4.29 g/cm³, 4.85 g/cm³ and 8.07 g/cm³ at 900°C, 1060°C, 1083°C and 1090°C respectively for the powder size of
74 \mu m. Thus, the desired level of cast quality can be obtained by controlling the temperature rise.

In general, the response parameters in any casting process are the strength of the cast, porosity, microhardness of the cast, the rate of temperature rise, different phases obtained after the process, microstructure, and elemental analysis as shown in Fig. 11.

For developing the understanding of the structure and property of the cast, Mishra and Sharma [109] determined the characteristics of the in situ Al-Zn-Mg alloy cast. Characterization was done to obtain cast microstructure, elemental analysis, phase analysis, porosity, micro-indentation hardness and tensile strength. The porosity of the cast was found to be less than 2%. Fig. 12 shows the comparison between properties of received aluminum alloy material and cast alloy. The cast alloy exhibited superior characteristics with increased yield strength, 86 MPa against 70 MPa; ultimate tensile strength, 149 MPa against 112 MPa and larger percentage elongation, 1.92% versus 1.59%.

Melting application or casting through microwave energy is a recent development in the context of microwave-based heating applications and therefore, further research is anticipated to establish its reliability at the commercial level for different castable materials. The characteristics that make it a lucrative research domain is the amount of energy savings that can be achieved through this process and superior cast product quality in terms of mechanical properties that can be obtained with better control over the process.

4. Conclusion and potential areas for research

Efficient microwave-based processing techniques save cost, time and energy. There is wide scope for introduction of novel materials in microwave-based coating and cladding such as the use of conducting polymers for anti-corrosion and stealth applications, microwave-based joining and microwave-based casting. Development of experimental set-ups is required for dedicated application areas. It can enhance the predictability of newly developed processes. Further research and analysis are required to describe the relationships between the input and response parameters for accurately achieving reliable process control. Summary of the present research in the field of microwave processing is described as follows:

- Four significant input parameters have been identified that control the microwave-based heating process. These input parameters are dielectric and magnetic properties, heating mechanisms, load and applicators.
Each of these parameters is influenced by several factors such as morphology and size of the material being processed, frequency, positioning inside the applicator, the type of applicator and the set-ups used, the dominant heating mechanisms, etc.

The type of applicator i.e. single mode or multi-mode, size of the material, heating mechanism and the temperature of the process need finer attention and control.

The material, especially metals when used in the powder form with a size of the order of penetration depth (around 10 mm) increases interaction, which results in uniform heating and superior properties along with a reduction in processing time. This reduction is quite drastic that is, from hours required in conventional processes to minutes in microwave-based applications.

Microwave-based processing scope can be widened using a microwave hybrid heating approach at a large scale to process the materials with poor microwave interaction.

Selection of susceptors such as silicon carbide, charcoal, graphite, alumina, mullite, zirconia, etc. requires a thorough understanding of the applications. In addition, the selective heating capability of the microwave can be utilized in composite materials synthesis as these have distinct phases with variable microwave interaction capability.

Future studies can focus on overcoming the challenge of an uncontrolled rise of loss tangent at elevated temperatures, which leads to excessive undesired heating.

The common response parameter of all the microwave-based heating applications is the rate of temperature rise that indirectly affects product characteristics. Control over the heating rate offers advantages in the form of improved morphology and properties of the processed material.

In the case of sintering, the response parameters are sinter density, modulus of rupture, hardness, the rate of temperature rise. Sintering has been the most widely practiced microwave-based materials processing application and has shown to be effective in microwave-based processing.

Cladding and coating applications have exhibited enhanced wear properties, improved micro-hardness and sufficient thickness. Still, these are in their infancy stage and demand further development for large scale processing.

Microwave-based joining is characterized by joint strength, joint hardness, porosity, percentage elongation. Joint quality is a function of the rate of temperature rise. Hence, hybrid heating and careful selection of applicator with precise control is an area that needs to be intensively investigated. Loss of weld strength (up to 50%) during microwave joining. Therefore, the development of higher strength welds and microwave joining of novel materials are impending challenges.

Melting or casting processes have exhibited advantages and desired output parameters such as mechanical and physical properties have been obtained in the cast product. However, quantitative analysis of energy conserved using this clean production methodology needs further extensive research.

**Conflicts of interest**

The authors declare no conflicts of interest.

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