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Review

Microwave hybrid heating (MHH) of Ni-based alloy powder on Ni and steel-based metals –A review on fundamentals and parameters

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A B S T R A C T

Microwave hybrid heating (MHH) is widely used for rapid heating and short-time reaction in the food industry and scientific fields. MHH processes also include the implementation of lightweight metals joints such as Ni-based alloys. The advantages of using the MHH technique are providing sufficient joint between similar or dissimilar lightweight metals, which reduces the time needed to melt and reduces defects on the joint surface. However, for the MHH applications, major parameter settings and design models of heating have not been extensively explored. Ni-based alloy powder (approximately 9–10%) exhibits low ductility because of its poor solidifying property and high melting point at room temperature. This phenomenon has caused some challenges for weldability in various manufacturing processes. In order to attain the melting point in a shorter time, researchers had implemented microwave hybrid heating (MHH) techniques by improving the rapid heating rate, mechanical characteristics (tensile strength and hardness), and microstructures properties by using carbon-based (absorber) and silicon-based materials (insulator). This paper aims to review the joint of Ni-based alloys on steel-based materials by using the MHH approach. In this review, the main structures of application (cavity design), design of heat application (heat materials), and various crucial parameters settings were discussed. It can be noticed that charcoal and graphite powder were frequently used in the MHH system due to its better effectiveness. Most of the literatures used the microwave frequency between 2.00 – 2.45 GHz, whereby the microwave power was set between 800 – 900-Watts with exposure time between 300 to 720 s to observe high penetration depth for the joining of Ni-based alloy powder.

1. Introduction

Microwave is a unique heat source that has been commonly used for lightweight metal manufacturing. It is known for better efficacy to produce heat where the dielectric materials can absorb the microwave heat and transfer the heat on the surface of metals through microwave hybrid heating (MHH) application. The ability of dielectric materials for transferring heat is highly dependent on its dielectric properties [1]. MHH is widely used in food industries, domestic purposes, medical treatments, agriculture and forestry industries [2], and the rubber manufacturing sector due to its good characteristics such as rapid heating. MHH application plays important role in safety production which involves drying and sterling processes. These processes tend to be exposed to irradiation and ionization. For example, gamma rays, high-energy electrons, and X-rays are produced by microwave sources (magnetron) in where the wave sources have been approved for safety methods [3]. Microwaves' electromagnetic spectrum can absorb and transmit wave energy within the 1 mm and 1 m range, which the radioactive applications have been fully implemented in the industries such as TV signals, radar, medical applications, radio astronomy, microwave oven. Microwave radiation has three different ranges of frequencies, i.e., ultra-high-frequency (from 300 MHz to 3 GHz), super high frequency (from 3 GHz to 30 GHz), and extremely high frequency (from 30 GHz to 300 GHz). For domestic usage, the operating frequency of the microwave ranged from 915 MHz to 2450 MHz [4–6]. The microwave energy power distribution converted at 20%, 40%, 60%, 80%, and 100% in the commercial microwave oven for different research or usage purposes

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[7]. The microwave absorption activity is a kind of molecular motion that employed by the dielectric rotation in where the weak bond of intermolecular is transformed to a new bond via the thermal effects. The molecular and atoms of the materials were able to absorb the heat from the microwave and caused the dielectric loss in the materials [8].

In MHH applications, the energy efficiency and heat dissipation in microwaves are determined by the dielectric properties of the specimen such as dielectric loss tangent. This can be calculated through the dielectric constant and loss factor [9], which describes the material's energy absorption and heat loss. The dielectric properties include two main parameters such as dielectric constant ($\bar{r}$) and loss tangent (tan $\acute{o}$), where these parameters can measure the real part permittivity and imaginary part of dielectric materials. These parameters will determine the quality of absorbed electromagnetic waves in the materials [10,11]. The metals' reflection is the main point for the setting or designing of the MHH technique. Thus, the additional absorber materials are mostly contributed to the joint and increase heat temperature during the MHH process [12]. Compared with other joining techniques, the advantages of using the MHH approach are this technique uses low power, low temperature, and is environmentally friendly for metal joining. Meanwhile, the ability of absorbent in absorbing the microwave energy to convert it to thermal energy is highly dependent on its dielectric properties. The energy conversion rate is influenced by reaction time and temperature [13]. The ability of materials to absorb radiation wave and convert it to microwaves are determined by the optimum frequency absorption rate. Temperature is also an essential variable for measuring the heating point or melting point under the thermal dynamic activity [14]. In microwave radiation, the alloy materials can be rapidly heated up under the static thermal activity (static wave) which will be determined by the dielectric loss in the materials. The metal alloy particles from the microwave irradiation reflection are partially affected on the interior surface that can be heated up through the additional particles (absorber). This will eventually increase the temperature of alloy particles [15].

For metal joining via MHH processes, metal powder selection is very crucial. To attain desired metal composition, epoxy resin is being added to the mixture [16]. Characteristics such as fast heating (energy saving), high accuracy for controlling, selective heating, volumetric heating, eco – friendly and short processing time are the advantages of using the MHH approach [17]. In microwave radiation, the energy absorbed from wave radiation was converted evenly and able to change the intermolecular reaction with a lower power range [18–20]. The interaction between the absorber and microwaves is an essential step for generating heat matter which can replace conventional heating processing due to its rapid heating and efficiency [21]. Even though the MHH provides good mechanical and microstructures properties by reducing reaction time, the most important part is the materials' selection for absorbance and insulation [22]. Hybrid carbon microwave joint (HCMJ) is a new technique modified from the MHH system, where this technique showed the metal joining can be performed at 2.45 GHz of microwave frequency. HCMJ can reduce the size of the heat-affected zone (HAZ) and improves mechanical properties such as high hardness and tensile strength [89]. In the microwave reaction time, the rapid heating rate produces small heat loss which is more efficient than the conventional heating process. In comparison with the reaction time, the conventional heating process takes from 1 to 48 h, meanwhile, the MHH processes just require few minutes. Therefore, MHH processes have good prospects as simple, rapid, and low cost for alloy materials, whilst, the MHH method can be suitably used in large scale of production. Although microwave source heating is clean and convenient, higher frequencies (more than 2.45 GHz frequency) are not very safe for microwave research and testing as the numerical models investigating factors MHH [23–26].

High microwave absorption materials such as carbon fiber [27], carbon black [28], and other carbon-contained materials can obviously improve the efficiency of microwave deicing as metal-based materials such as steel fiber and copper. The microwave absorption can transfer heat into materials via thermal radiation. In general, heat conductivity is determined by the dielectric properties such as relative permeability, relative permittivity, and tangent losses [29,30]. For example, carbon-based materials, such as SiC known for transparent materials which often used as microwave absorbers, are highly lossy materials. The adjective phase of wave mode can improve heat consistency, and reduces the hot and cold spots in testing materials [31].

Therefore, interactions between microwave irradiation and dielectric or absorber materials need to be observed and studied to figure out the correlation with a unique heating source. For example, the special phenomena of interactions between the microwave and absorber materials cannot be ignored as the essential parameters of microwave, where it would form important heating substances. Some lack of observation for potential effects between the microwave irradiation and metals, specifically, lightweight metals during the joint cannot be ignored Thus, this paper aims to conduct a critical review for recent progress in MHH joint technology for Ni-based alloy powder and discuss the carbon-based heat absorber materials properties for improving the MHH process. Some comparisons were conducted to analyze the conventional heating method and electromagnetic and thermal properties of alloy materials.

2. Conventional heating processes and Ni-based alloys

2.1. Fundamental of conventional heating

The heating process (reaction) is a thermo-chemical process used to elevates temperature by using conventional apparatus such as conventional oven and brazing [32]. In the conventional heating process, the heat energy is transmitted to the surface of materials through conduction and convention, where the heating process takes a longer time. For a longer reaction time, the heating process will be non-productive as it will incur additional costs through a higher amount of energy consumption as well as time consumption. Besides, longer heating processing will cause difficulty to manage the melting point through this conventional heating [33,34]. In the oil industries, various heat applications were implemented by using conventional heat processing methods. The most common conventional heating process are hot-fluid injection, steam, and thermal stimulation, which helps to boost oil recovery. In these conventional heating methods, the heat energy can inject into the hydrocarbon reservoirs for reducing oil viscosity that can be increased to production rate. However, these conventional methods are not suitable to be conducted for certain processes mainly for very thick or thin pay zone. It brings to massive heat loss and overloading [35]. In the chemical composites, many composite materials were synthesized via the hot-injection (HI) method, which was used to synthesized uniformly size of composite materials to obtain the specific precise size of the composite materials. However, this method is difficult to control due to uneven nucleation for the fasten injection, whilst, the HI technique is difficult to measure a huge number of composite materials. In manufacturing processes, heat waste generated from low-grade heat, such as from oil and gas had been considered by manufacturers [36,37]. Lee et al. [38] had investigated the boiling heat transfer process under the low heat flux condition. As a result, it can be observed that traditional heating produces low heat transfer on the plate materials (alloy) surface which led to the evaporation temperature increment.

2.2. Ni-based alloys in conventional joint

Brazing is one of the metal joining (welding) techniques in which similar and similar or similar and dissimilar metals are joined by the melting metal filler into the joint. The brazing technique was investigated by various researchers. Weibo et al. and Ye-Jun et al. [39,40] observed thermal distribution as the ultrahigh-frequency induction brazing process on Ni-based composite, where the $NiAl_3$ was formed onto interface layers with the highest compressive and bonding strength were produced at 965 °C, heating temperature. Li et al. [41] had conducted brazing of super-alloys (Ni and Ti-based) where the interface layer produced by the Ti-Ni-N compound had good bonding strength. High thermal conductivity metals such as copper were observed by using the boiling heat transfer method, while, high flux (coating) also was investigated in industrial fields which uses natural gas, re-boiler, and vaporizer heat treatment methods. However, these methods lead to time-consuming and environmental pollution [42–44]. Meanwhile, it will be difficult to calculate the heating rate under the reaction parameter by using conventional heat treatment methods. The efficiency of heat exchange depends on heat transferred onto the surface of the material. Researchers found Ni-based alloy to create a compound with expected properties using various heat treatment techniques. This includes both hydrothermal [45] and solvothermal [46]. These researchers confirmed both methods were difficult to scale large amounts for production for complex procedures, excessive reaction temperature, and reaction time [47]. Conventional welding processes (SMAW, MIG [48], brazing, and TIG) produced a large amount of heat input where the heat can be transferred from the heat origin (an arc) to the similar and dissimilar solid-state metal surface. It can form a metal joint through the metallic surface reaction. The material deformation, grain refining, and residual stress are determined by high-temperature processing such as fusion welding and casting. However, fusion welding processing can increase the cost of energy consumption and lead to air pollution [49–51]. In fusion welding, the heat treatment method reduces the heat-affected zone, but it is hard to control from various parameters. The fusion welding process which caused welding defects such as cracks and porosity will increase coarse grains in the weld [52,53]. Chai et al. [54] reported some metal alloys (Ni and Mg-based) can lead to liquation cracking during the fusion welding, due to high thermal conductivity and large thermal expansion of materials. It provides peak temperature more than the eutectic temperature of the alloy particles. Leo et al. [55] recorded the lowest microhardness value at the boundary of the weld region because of the thermal cycle in the weld pool which produces coarse grains and porosity on the Ni and Al-alloys. These defects are mostly produced by the fusion welding process due to uneven heat distribution.

3. Technical aspects for MHH

3.1. Basic of MHH

Microwave joining is a unique method for bulk joining by using the wave heating process to join materials. The heat was generated by the oscillation of molecules. In the electromagnetic heating process, the electromagnetic wave was converted to heat energy which acted as absorbers (susceptor powders), and it helps to transfer wave energy onto the material's surface through reflection. The electromagnetic wave energy conversion depends on wave frequency, material's dielectric, and thermal properties. The metallic materials need to be in ambient conditions for the reflected wave irradiation. Thus, an insulation method was required to avoid heat loss [56]. Researchers had provided the schematic diagram for MHH processing which has been shown in Fig. 1. They used a 2.45 GHz frequency of domestic microwave oven [57–59] for this processing. The structures of the MHH process were inclusive of insulation brick, susceptor powder, graphite separator, and rotary fixture. The activated charcoal powder is used as a susceptor for transferring heat energy from the microwave to the surface of the material [60].

3.2. Carbon-based materials for heat absorber and fillers under microwave irradiation

The microwave irradiation was produced by the electric field (E-field) and magnetic field (H-field) as perpendicular where the material heating can be achieved. This depends on the materials' dielectric and magnetic properties because it is difficult to obtain the desired temperature during the joint due to the dielectric and heat loss are on the materials during the MV process [119]. The susceptor and separator, which are known as absorbers are essential elements for heat transferring from microwave irradiation and increasing heat matters using the carbon-based materials on selected metal such as charcoal powder, SiC, and graphite. For the MHH joint, many types of research had been conducted with different materials. For example, SiC and graphite were used as susceptors and separators on the Ni-based alloys during the MHH process [121]. Charcoal powder and graphite were applied in separator and susceptor for Ni power melting efficiently [125,126], meanwhile the epoxy can be an influencing factor for the heat to transfer on the base materials when mixing with metal powders [128]. The SiC used with susceptor during MHH can be interacted with microwave irradiation and produce desired heat for metal powder's joint [129]. Meanwhile, the SiC and alumina crucible (23 mm × 25 mm) were implemented to susceptor and insulator as the making block for rapid heating melting of Ni-powder during the MHH processing [132], and the quartz glass was utilized as susceptor and insulator as it was transferring microwave irradiation on the metal surface, which was sufficient to heat power-based metals such as pure Ni powder [133]. Saxena et al. [61] used three different materials for susceptors such as stone charcoal, wooden charcoal, and graphite powder. The optimum susceptor was observed in the graphite powder is suitable as the heating source from the microwave. Chen et al. [62] investigated electromagnetic waves from the two-way coupled Maxwell's equation and heat transfer equation for frozen thawing condition using the domestic microwave oven cavity and they found the load size determined to change the size of energy absorption as the dielectric and thermal properties. Srinath et al. [63]. used in stainless steel (SS) 316 plates (25 mm × 12 mm × 6 mm) for joint. The nickel and charcoal powder was selected to interface metals and susceptor, respectively. Direct heating via microwaves is prohibited as the insulator mask was arranged in metal pieces. Bansal et al. [64]. conducted research with mild steel using nickel-based powder as filler metal and charcoal as the susceptor for joining. The charcoals can absorb microwave excellently and transfer to heat on the Ni-based powder through uniform heating. Badiger et al. [65] successfully joined Inconel-625 plates (51 mm × 12 mm × 6 mm) with Ni-based powder via the MHH, where the charcoal was used as a susceptor to increase the temperature of Ni powder. 1 mm of graphite sheet was used to separate the Ni powder and charcoal to avoid the intermixing between the interface layers. Singh et al. [66] investigated

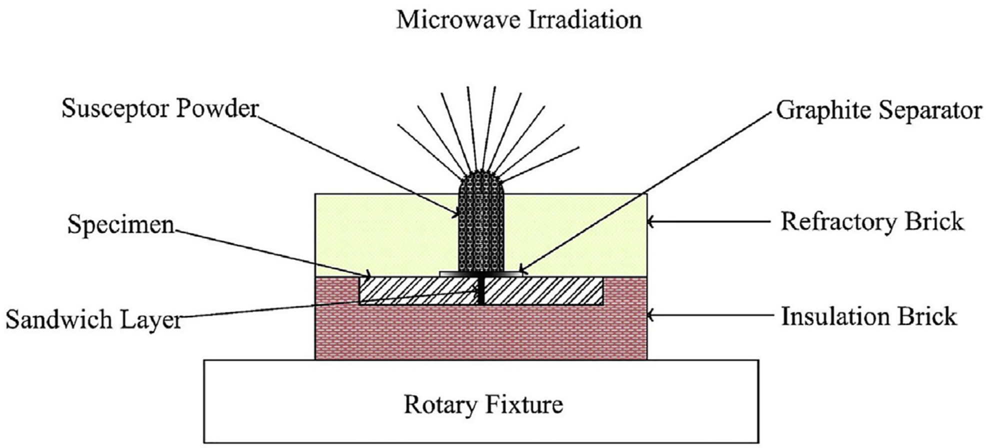

Fig. 1. MHH processing for the metal joint [57], copyright 2020, with permission from Elsevier.

aluminum plates to join using silicon carbide as the susceptor in which it creates a boundary for melted interlayer.

Various materials can be used to absorb microwave radiation and convert it to heat energy as the susceptor on the surface of the sample, such as carbon-based materials (etc. charcoal and graphite). It can be formed as an activation process from the MHH (rapid heating and short time) [67,68]. Even though the porous carbon materials are poor susceptor, but it has been successfully activated using the MHH process (carbonization process) as the higher yields. In heat supercapacitor fields, carbon-based pure or synthetic materials are widely used due to its characteristics as good electrical conductivity and chemical stability in electrochemical heat capacitors [69–71]. Activated carbon with graphite is one of the best options to be used in supercapacitor equipment with its good electrode material. The graphite samples can be irradiated from the microwave in the high-temperature resistance, low thermal expansion, and good insulation materials such as quartz glass and silicon carbide as shown in Fig. 2. It can obtain activated carbon products as the high-performance electrode in a short period of microwave radiation [72]. The synthesis of carbon nanotube is one of the attractive products from the biochar that is formed by the microwave radiation at 600 °C of temperature in 5 min. In general, the activation of carbon requires high microwave power and a longer exposure time. Under the optimum activation, the porous carbon structure needs a certain radiation time for the MHH application [73–75]. Li et al. [76] reported that the activation time is only a few minutes. For example, the porous carbon can be fabricated with the power ranged between 600 − 800 W of microwave power which requires above 3 min and the high specific area reaches 2055 m^2g^{-1}. It can be observed that porous carbon synthesized under microwave radiation contributed as electrode materials for superheating capacitors. The specific surface area in the activated carbon is related to the volume and size of micropores and mesopores, which can be restricted small size of molecules and provides higher capacities [77]. Carbon fiber is also one of the important composites from carbon-based materials that are activated by the microwave hydrothermal technique. The carbon fiber was being used to improve the recycling rate for TiO_2 particles due to high surface area and photocatalytic property [78].

With a fast-heating rate, graphite boats were used as good absorber structures for MHH processing. This is because the graphite boats can melt easily and join metals with this property. Neeraj et al. [79] used a graphite boat for susceptor with 900 W of outpower and 2.45 GHz of frequency during the MHH process, as shown in Fig. 3(a and b). Fig.ure 3(a) indicates the direct relationship between the temperature and exposure time that the chamber temperature rises when the exposure time increases. Alumina is a good insulator to avoid heat loss by creating an efficient heat chamber with a graphite boat for the MHH process. The carbon-based fabricated materials have been investigated by several authors. Geng et al. [80] conducted research with carbon wood using the MHH procedure for activation and they found that the maximum temperature of carbon wood would reach 2200 K as the rapid heating. The porous carbon structure can be converted to a fine carbon structure from the carbonizing process using MHH. It contributes to the increase of heat absorbance properties.

In addition, Jingjing et al. [81] investigated the interaction between the carbon fiber and polymer using microwave radiation (2.45 GHz) as the Floquent unit cell technique. They found the improvement of the fiber-polymer interface layer when the fiber surface roughness was increased, the viscosity of polymer intermolecular interaction decreased. Furthermore, the interfacial shear strength between the carbon-polymer also increased above 30% at 180 s exposure time.

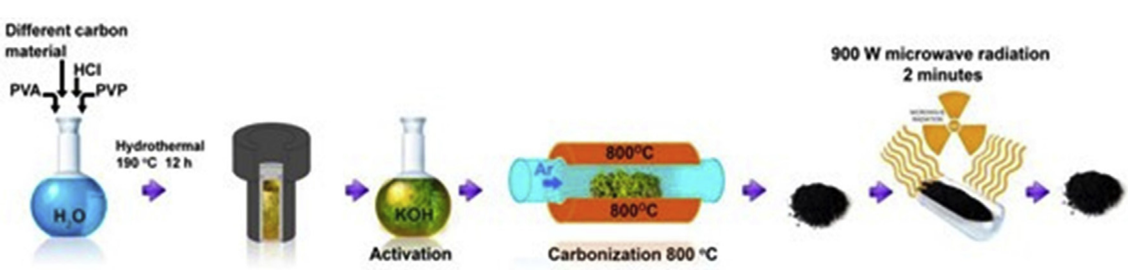

Fig. 2. Schematic diagram of processing of activated carbon [72], copyright 2019, with permission from Elsevier.

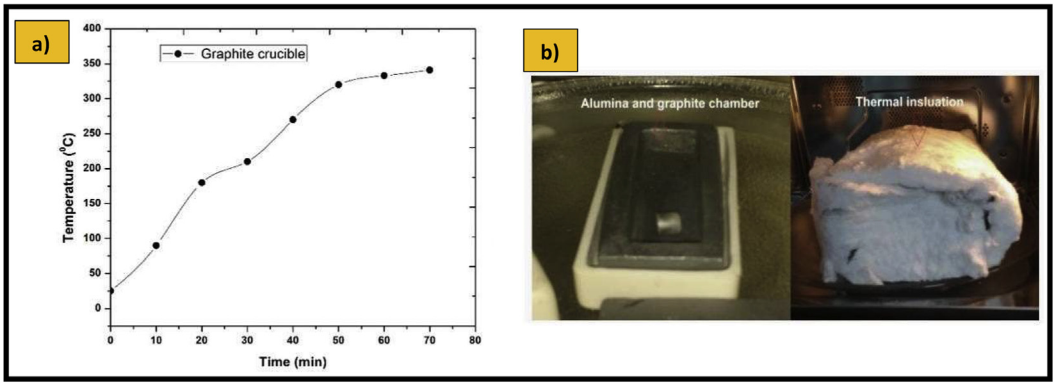

Fig. 3. (a) Heating diagram for graphite crucible, (b) experimental setup for the MHH process [79], copyright 2019, with permission from ProQuest.

3.3. Microwave cavity design

MHH is a rapid heating process that reduces the reaction time for energy saving. The electric and magnetic distribution is successfully implemented by the designed microwave cavity which helps to extract expected temperature profiles [82,83]. The study of cavity design in MHH processes has been addressed by several researchers. Nigar et al. [84] used a solid-state microwave generator (2.35–2.47 GHz, 150 W) as the TE10 mode of microwave cavity which included fixed-bed quartz ($D = 7–9$ mm), circular sampling port, fiber optic sensor, and quartz wool as shown in Fig. 4. The quartz glass tube (7–9 mm) was adjusted inside the cavity as a round shape of sampling ports and the internal temperature was calculated by the quartz optics for its accuracy. Quartz glass has more advantages compared with other materials which portray good ultra-violet and infrared wave transmission, the resistance of high temperature and thermal shock, excellent insulation, good electrical conductivity. The heating behavior in the quartz tube was measured through the infrared thermographic camera. The magnetron is a microwave generator that can expose waves as heat energy into the cavity. Meanwhile, the hollow waveguides the wave transfer via the fixing mode from the magnetron. Dinani et al. [85] investigated food system heating by using a solid-state microwave generator system (2.45 GHz, 500 W). Guided coaxial cabled wave is a general waveguide (TE10) which replaced from the circular shape of turntable rotation waveguide by avoiding some errors of calibration, heat loss, and evaporation on the material surface to compare general TE mode. Meanwhile, Krouzek et al. [86] used 6 kW of power and 2.45 GHz of frequency of microwave generator with stainless steel waveguide (activated carbon used for absorber) as a good heat transferring material. Wei et al. [87] explained industrial multi-mode MHH application. The MHH system includes microwave magnetron as the tunable power system (0–6000 W), programmable logic controller (PLC) with the dimension of 110 mm × 110 mm × 110 mm cavity was covered by the insulator. As shown in Fig. 5, the PLC controller provides high accuracy of input power and exposure time from the waveguide during the MHH process, this cavity structure was unique compared with other semi-controlled applications. Besides, Liu et al. [88] observed concrete surface using the self-designed microwave oven (2.45 GHz, 0.5–1.5 kW), whereby, the silicon-carbon and graphite act as an absorber. The waveguide of 1000 mm from the heat source and the thermal behavior was measured by the infrared thermal camera (−25 to 400 °C) which is located on top of the cavity and the digital recorder to collect the temperature inside the cavity. Compared with the PLC controller, the cavity applicator is more advance through its smart and digital features. A microwave reaction system with dimension 635 mm × 508 mm × 584.2 mm was observed at the frequency of 2.45 GHz [89]. Apart from this, Ye et al. [90] studied a fast-rotating mode stirrer system with model

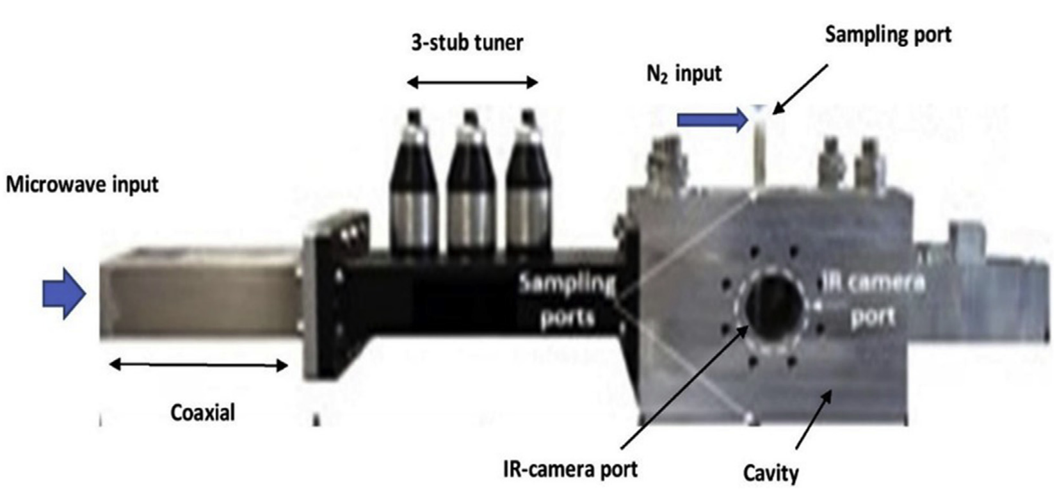

Fig. 4. Microwave heating cavity.

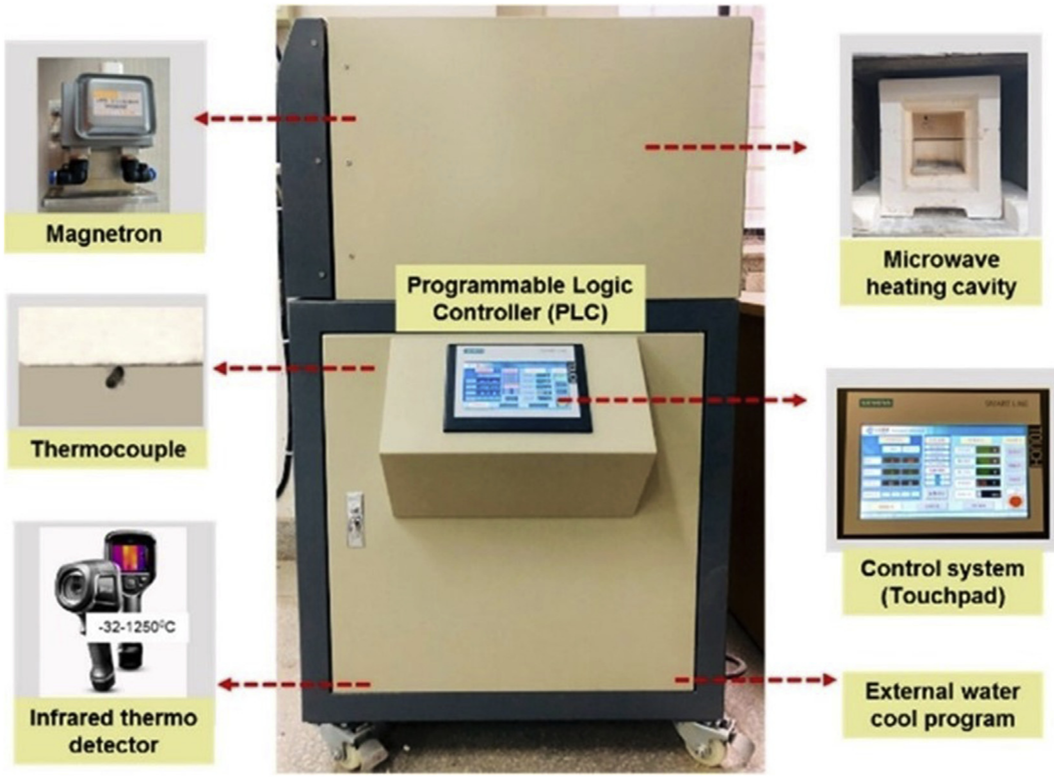

Fig. 5. Multi-mode MHH system [87], copyright 2021, with permission from Elsevier.

components were included in the domestic microwave cavity, standard waveguide (WR340), rotary shaft, and aluminum mode stirrer as shown in Fig. 6. The microwave irradiation was exposed by the coaxial connector in the waveguide (300 W of output power and 2.45 GHz) and the two motors were used to rotate the panel in the cavity. To observe the temperature accuracy through the thermal distribution, the fiber optics thermo-sensor (each response is approximately 0.2 s) was located on the top side of the cavity and the infrared thermal camera was added on the top side of the cavity. On the other hand, the direct heating, selective heating, and hybrid heating (HH) techniques were implemented to heat the materials in which can transfer heat from the microwave, by using material such as metallic powder [91].

Figure 7 (a)-(c) show three types of application methods used in MHH processing. The methods include rod, powder, and plate or tubular susceptor. Fig. 7 (a) indicates the sample was surrounded by using a rod-shaped susceptor. This susceptor tends to absorb heat and transform it to heat in the sample. Zirconia and Alumina were used as heat insulators to reduce heat losses. Fig. 7 (b) showed the MHH can be implemented via susceptor powder in the sample. This

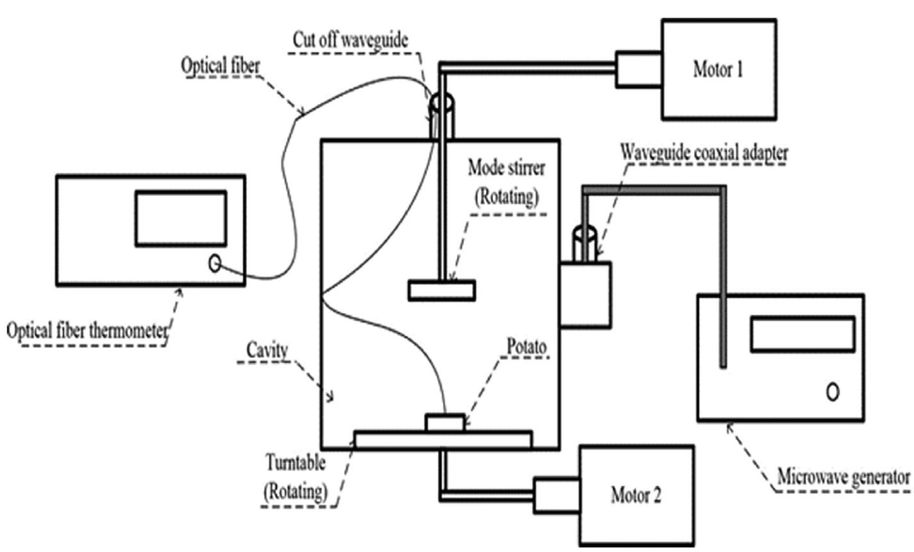

Fig. 6. Experimental setup for MHH system [90], copyright 2019, with permission from Elsevier.

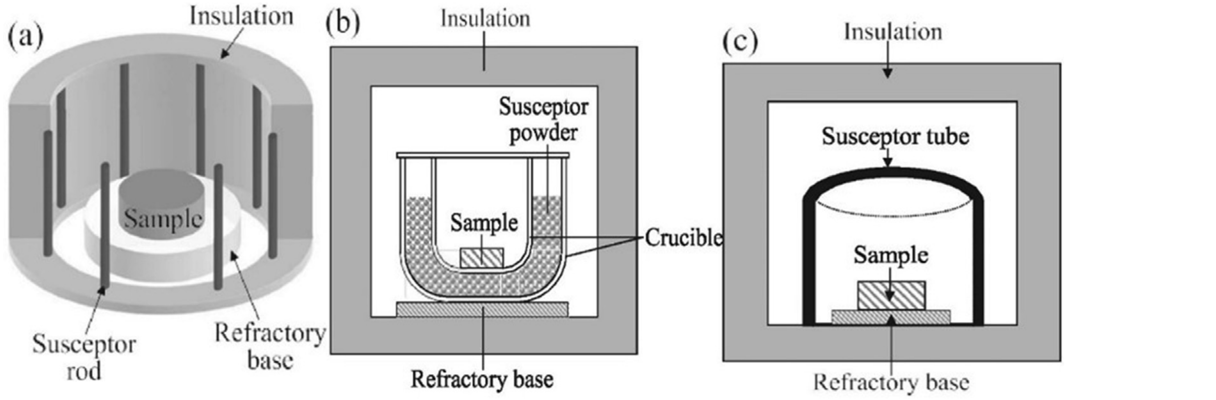

Fig. 7. Schematic diagram for three different MHH with (a) rod-like (the picket-fence arrangement), (b) powdered (in the two-crucible set-up) and (c) tubular susceptor [92], copyright 2016, with permission from Elsevier.

technique needs to synthesize materials such as SiC powder, carbon powder, and CuO powder. Meanwhile, Fig. 7(c) described that the sample was fully blocked by the susceptor tube for reducing heat loss [92]. The sample thickness is also an important parameter that has the potential to influence the microwave reflection [93]. Maniere et al. [94] conducted microwave stirring by using a microwave furnace. They used magnetron (WITOL 2M343K E625) which is connected to a rectangular waveguide in the microwave cavity as the two susceptors for heat transferring such SiC and zirconia as shown in Fig. 8. In the microwave cavity, the 135 mm of cylinder cavity were covered by the composites of alumina-silica (80% of Al_2O_3 +20% of SiO_2) insulator, where the high heat temperature was observed. Shelef et al. [95] used the selected MHH method to melt the powder batch. This microwave system includes a coaxial waveguide and inner electrode as shown in Fig. 9, it can be seen that the power batch was generally added and built by the building blocks with lower MHH processing, where the blocks were melted and cooled down for solidification. Samyal et al. [96] and Kumar et al. [97] had investigated microwave joining for similar and dissimilar metals using the selective heating technique. In addition, Crane et al. [98] conducted research on metal and metal oxide powder using an electromagnetic exposure chamber as shown in Fig. 10. Signal generator, microwave amplifier, power sensor, coaxial waveguide adapter, waveguide, infrared camera, and sample holder are the chamber components used to observe the electric and magnetic field. In this chamber (cavity), the microwave amplifier is a unique heat source that produces microwaves and transmits it to the sample surface through the waveguide. The samples can absorb and reflect electromagnetic waves from the waveguide. The solid brass (WR229) was used to generate the waveguide because it has a good electrical and thermal conductivity characteristic, where the signal generator and inferred thermal camera were located on the top side of the chamber for detecting the thermal behavior.

3.4. Advantages of MHH process

The application of MHH processes is highly preferred by manufacturers and industrialists in the heating and melting process,

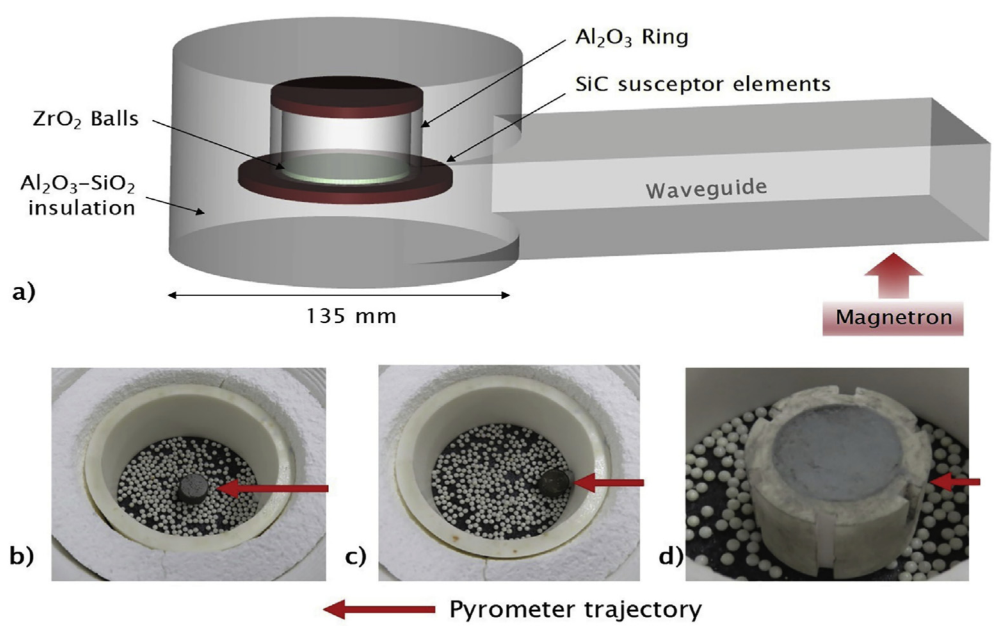

Fig. 8. Schematic diagram for Microwave furnace (a) cavity, different sample heating modes (b) free surface in the center (c) free surface on the edge (d) nano-SiC powder surrounded sample [94], copyright 2018, with permission from Elsevier.

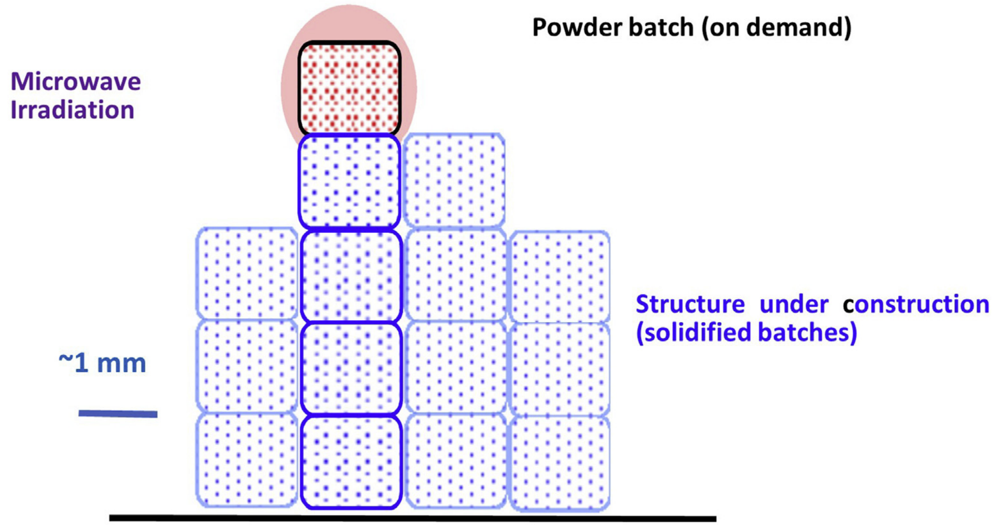

Fig. 9. A conceptual schematic diagram of MHH [95], copyright 2020, with permission from Elsevier.

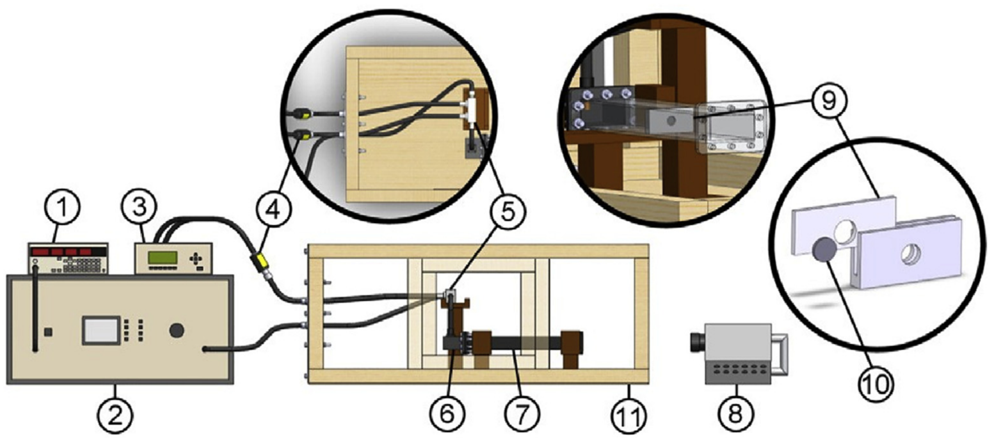

Fig. 10. Structure of Electromagnetic chamber for microwave radiation: (1) a signal generator, (2) microwave amplifier, (3) power meter, (4) power sensors, (5) directional coupler, (6) coaxial to waveguide adapter, (7) waveguide, (8) infrared camera, (9) sample holder, (10) the sample, and (11) the Faraday cage (shown without the aluminum meshing) [98], copyright 2014, with permission from Elsevier.

compared with the conventional heating methods. This is due to the better characteristics portraited such as rapid heating, short reaction time, energy-saving, inter-layer fast heating, avoid repeat reaction with high quality of energy carrier. The MHH is consists of three main interactions between the materials and microwave, namely reflection of conductor, transparent (insulator), and dielectric (absorber) [99,100]. MHH has been replaced with the conventional heating method in which can be forced to absorb heat through convection and radiation [101]. In contrast to MHH, the electromagnetic irradiation wave can be simultaneously converted to thermal energy [102]. Microwave application is also applied in biochar production, where it can protect unwanted processes such as condensation pyrolysis volatiles and combustions, while, it increases the reaction time. The biochar creates a new porous formation and increases the material's yield with better quality of char [103]. MHH processing is variable under different conditions, that means the heat components can be controlled from the heterogeneous system at the different rate. Thus, the MHH provides a unique heat source as the radiation lead rapture of cells in material for higher yields [104]. Several researchers had investigated the vaporization in the cellular as part of the MHH advantages. Chan et al. [105] studied cell pressure using the microwave for cellular steam generation, which the researchers found the quantitative model such as couples of microwaves and mechanical cell wall properties can be predicted via internal pressure of cell and time periods for cell. Lee et al. [106] reported MHH basically to change the mass transfer process and increase to modify the structure of the cell. On the other hand, compared to the conventional heating process, MHH can be directly heated inside of material as its characteristic of rapid heating. Furthermore, the modern MHH process is mostly attracted by industrialists for the applications in microwave generator (magnetron), waveguide, resonant cavity, temperature measuring system, control system heat chamber, and cooling system. From the modern MHH technique, the multi-mode microwave reactor can be used widely in the materials and metallurgy fields as a capability of their immense processing capacity [107]. Furthermore, Zhi et al. [108] found the waste catalysts of Mo and V were recovered through microwave have high yields up to 94.35%–96.23% respectively. Moravvej et al. [109] reported that microwave radiation can influence by increasing the leaching rate for copper more than 2.5 times compared to the traditional heating process. Meanwhile, Choi et al. [110] confirmed that the leaching rate significantly improved on the surface of pyrite as the cracks appears using microwave radiation. Hence, the MHH process can be used in recovery processes under the minimum energy and time consumption. Furthermore, microwave radiation may upgrade the efficiency in the leaching process of material under the reduction of passivation layers [111].

Advantages of the MHH process are as follows [112–115]:

1) MHH is able to provide high heating efficiency for rapid heating (approximately 80%).
2) MHH generates high penetration depth.
3) MHH can reduce energy consumption in a short reaction time.
4) MHH can reduce temperature drastically as the high heating rate.
5) MHH processing is suitable for applications in high viscosity and multiphase fluid.
6) Microwave provides safety operating environment during the heating process.
7) MHH can reduce noise level and materials cost due to its low energy consumption.
8) MHH processing is the green manufacturing process that is able to prevent environmental pollution.

4. Ni-based powder on the Ni and steel-based metals under the MHH process

4.1. With Ni-based powder interface

Ni-based powders have been widely used in manufacturing and engineering fields in recent years due to its good mechanical and weldability properties. MHH is one of the best options for metal joining as its rapid heating and prevents environmental-related pollution [116]. Nowadays, many researchers have conducted studies on microwave joints using steel-based materials as base metals like stainless steel to increase mechanical properties for industrial applications. Phanendra et al. [117] used austenitic stainless steel (SS-321) for the joining by using nickel-based powder (50 μm) for interface metal which is implemented by the MHH process (2.45 GHz) with the setting time around 10–35 min of exposure time and the microwave power set at 900–1300 W. They reported that nickel powder has joined at 10 min of exposure time and 1300 W of output power, in where the substrate produced 458 HV of microhardness in the joint region of the stainless steel. Kumar et al. [118] also conducted the joining of stainless steel using nickel-based powder as the interface filler. They found the stainless-steel joint at 700 s, whilst, they reported that the highest tensile strength in stainless steel indicated at 323.16 MPa with 11.3% of elongation when the exposure time increased. However, the hardness had decreased. The SS316L stainless steel was used to join with pure Ni-powder using different sizes of particles (5–40 μm) during the MHH process, in where the experimental found that the 338 HV (high microhardness) was produced at 900 W (output power) and 40 μm of particle size [119]. The wear rate frequency was observed at 2.45 GHz and 1–25 min of exposure time using the stainless steel (SS-304, 65 mm × 25mm × 6 mm) welded joint with the Ni-based clad powder under the MHH process [120]. Bagha et al. [121] found pure Ni powder (99.9%) was successfully joined at 360 s of exposure time, where the pure Ni powder produced 42.67 HRC of hardness on the joint with stainless steel, SS304. Akshay et al. [122] found the 980 HV of microhardness produced in the joint zone using the 900 W of power and 2.45 GHz of frequency as the Ni-based alloys (EWAC + 20% WC10Co2Ni) on the mild steel, and Ni-Carbon (Ni-C) composites mostly activated at 200 °C around 5 min during the MHH process [123]. Some reactive particles such as Ni, Al, and C powder strongly interacted between steel-based materials and particles using the epoxy resin in MHH processing. Thus, high tensile strength was observed [124] and Ni-based nanoparticles (NiCuZn) were successfully melted on the steel-based materials with low power and low temperature. The effects of the dielectric constant on nanoparticles were observed [125]. Furthermore, the Ni-based composites (Ni-Al) were formed by using 1100 W of microwave power, and the phases of Al_3Ni_2 and Ni_3Al were found to have good strength [126]. Nickel(III) oxide and manganese dioxide were interacted at up to 560 °C as 800 W of output power that the element content of Ni account for 68.7% of total content [127]. Gunawan et al. [128] found that Ni_2P was melted by the carbonization materials (high carbon content materials) through the MHH process, where low nickel ions were observed. Ni-based diamond composites (NiCuSnFe) were formed at 2 kW output power with 30 min of exposure time in the MHH process, which produced 271 MPa of bonding strength and 99 HRB of hardness with good thermal conductivity [129]. Singh et al. [130] used MHH processing to join cast-iron plates with the dimensions of (20 mm × 10 mm × 10 mm) and the power of 900 W, the frequency at 2.45 GHz together with nickel-based powder with a particle size of 35 μm. They claimed the specimen was successfully joined at 440 s of exposure time and the result revealed some porosity was found in the joint region, and higher microhardness and tensile strength were observed. On the other hand, the superalloys were investigated by several researchers for MHH approaches. Bansal et al. [131] used MHH to join Inconel 718 as the nickel-based powder and epoxy as the interface layer purpose. They found the Inconel 718 was fully melted at 580 s of exposure time with the tensile strength of 400 MPa, and 6% of elongation was observed in the joint zone. Badiger et al. [65] found that the Inconel 625 was successfully joint at 21st min while using 900 W of power and the frequency was at 2.45 GHz in the nickel-based powder. The researchers reported deposition of chromium carbide was produced in the interface layer, where it increases the hardness and produced 326 MPa of tensile strength with 9.04% of elongation. SS-430 stainless steel with dimensions of (45 mm × 12 mm × 3 mm) was investigated by Nalin et al. [132]. These researchers had used Ni powder (99.5%, 40 μm) for interface filling (sandwich layer materials), and they noticed the high tensile strength was achieved at 471 MPa and the elongation was at 9.02%. The phases of Ni_3Si and Ni_3C were formed in the interface layers at 900 W output power and 720 s of exposure time. Ajit et al. [133] had investigated microwave joints using stainless steel (SS-304) with Ni-based powder for the interface layer. The result showed the Ni powder melted at 900 W of output power and 2.45 GHz of the frequency with a microhardness of 364HV. Researchers had found the results of the experiment exhibits greater metallographic bonding between nickel powder and stainless steel (substrate). The phases of NiSi and $FeNi_3$ were formed in the interface layer, and the nickel steel (FC-0208) was formed at 1140 °C with the microwave power of 2 kW and exposure time of 20 min using multi-cavity mode in MHH processing [134].

Dissimilar metal joining was studied by several authors. Pal et al. [135] had investigated SS304 and SS3016 stainless steels using nickel-based powder with various particle sizes of 20 μm, 50 μm, and 70 μm, and the frequency was constantly set at the constant 2.45 GHz with the power at 800 W as shown in Fig. 11. They found the 20 μm size of nickel-based powder was successfully joint with higher quality. Anoop et al. [136] and Ravindra et al. [137] reported that the microhardness of 289.9 HV and tensile strength at 377 MPa were produced through the joining of SS304 stainless steel and Inconel 625 (super alloys) using MHH. The researchers also identified the formation of laves phase in the grain boundary and the microhardness was at 245HV, with 7% of porosity. Bulk materials such as copper plate, stainless steel, mild steel, and Inconel with

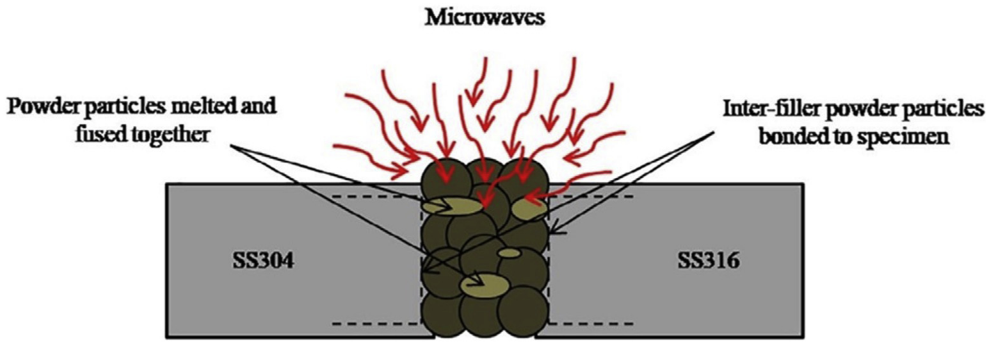

Fig. 11. MHH configuration in Stainless steel as the filler metal [135], copyright 2020, with permission from Elsevier.

nickel powder were used in the microwave for joining as observed by Srinath et al. [138]. They reported that the microhardness and tensile strength increased when these bulk materials were joined under the microwave. Bhupinder et al. [139] found the nickel-based clad powder deformed with 45 min of exposure time and 1.5 kW of microwave power. The Inconel 601 and titanium subtract were performed for the joining by Rosa et al. [140], using the nickel and aluminum powder at 300 W of power and 2.45 GHz under the single-mode (TE10) applicator. and they found NiFe in the interface layers at 422HV of microhardness. Sarbjeet et al. [141] investigated the Ni+20% SiC powder to join with stainless steel (SS304) using the MHH process. As result, it can be seen that the Ni-based powder was formed at 360 s of exposure time and 900 W of microwave power, and the microhardness was observed as 763HV, as shown in the schematic setup in Fig. 12. They also found free cracks and porosity in the interface layers and the phases of Ni_2Si_3, NiSi, and $Cr_{23}C_6$ were observed at joint region. The joint of stainless steel using Ni-based powder was investigated by Srinath et al. [142]. These researchers found the phases of NiC and Fe_3C were observed in the intermetallic field under the power of 900 W and frequency at 2.45 GHz with 450 s of exposure time. They reported the tensile strength of 346.6 MPa with 13.58% elongation was produced, where the intermetallic compound completely melted and formed a bulk interface.

By using stainless steel SS316, Rahul et al. [143]. attained expected microstructure correlation and microhardness through MHH processing. They used stainless steel SS202 with the specific dimension of (160 mm × 31 mm × 1 mm) in joining bulk with nickel powder particle size at 40 μm under the output power of 700 W, the frequency at 2.45 GHz, and exposure timing between 15 and 25 min. The results indicated that the exposure time mostly influenced the damping characteristic of interface layers and achieved good quality of joining at 19 min of exposure time; Gurbhej et al. [144] reported the Ni-based alloys melted at 1.2 kW of output power and frequency of 2.45 GHz on the mild steel, where the columnar dendrites were observed in the joint region. Tamang and Aravindan [145] conducted at WC-Co (6 wt% Co, 12 mm × 12 mm × 5 mm) as the APA7 alloys (metal filler, 59 wt% Ag, 27.25 wt% Cu, 12.5 wt% Ni and 1.25 wt% Ti) for microwave joint at 2.45 GHz of frequency and 700 W power. The schematic diagram is shown in Fig. 13. The results showed the WC-Co was successfully joint via MHH application, where a reaction layer was produced by Ni and Ti as a sign of diffusion from the WC-Co

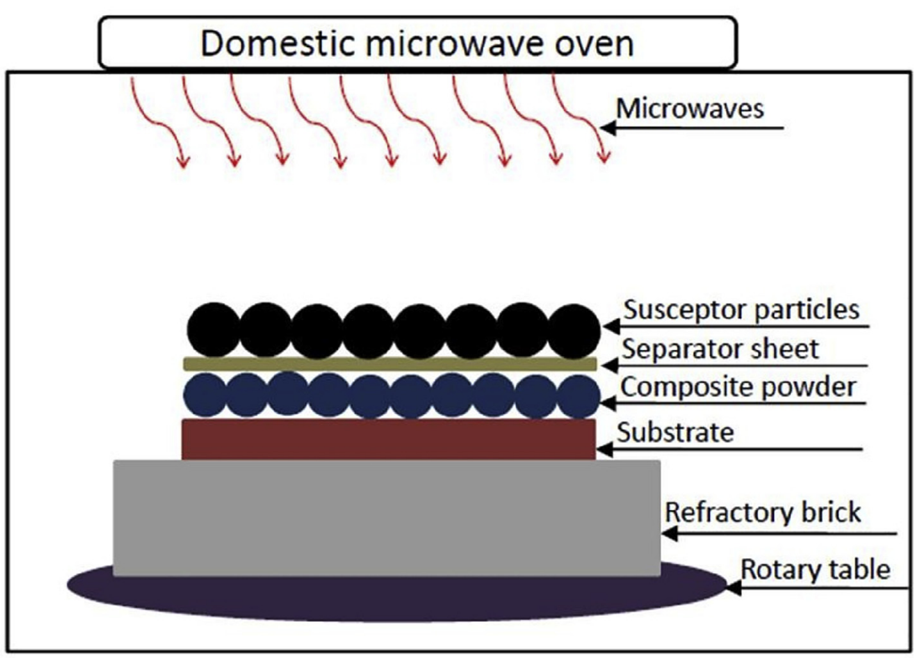

Fig. 12. Experimental setup for microwave joint as the nanoparticles [141], copyright 2020, with permission from ProQuest.

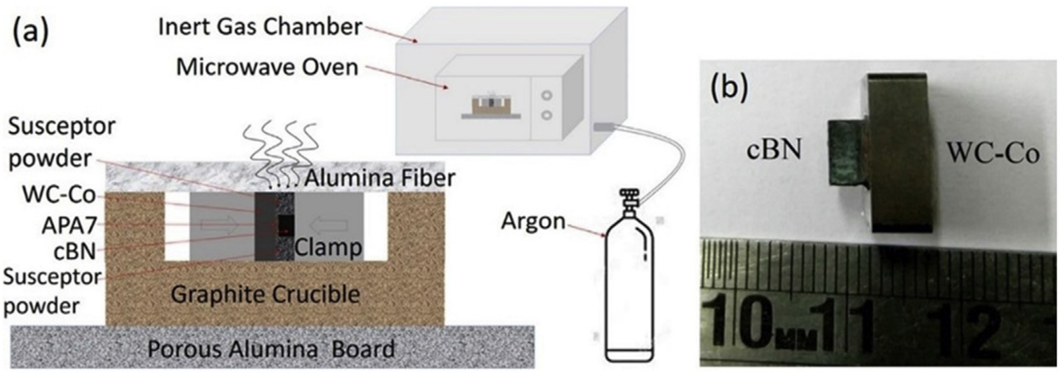

Fig. 13. (a) Configuration of the experimental setup (b) typical macrograph of brazed joint [145], copyright 2019, with permission from Elsevier.

surface. The mild steel also joined using nickel powder at 600 s of exposure time and 900 W power that the ductile fracture behavior was found in the intermetallic field [146]. Additionally, Rahul et al. [147] investigated joint of SS304-SS304, SS316-SS316, and SS202-SS202 of stainless with various exposure times (200–900 s) using the MHH process. As a result, the SS304-SS304 were joined at 370 s of exposure time and output power of 900 W for better heat transferring. SS202-SS202 were deformed due to weak joint at 250 s of exposure time and 900 W of microwave power because it is portraited as lower mechanical properties than SS304. Meanwhile, the SS316-SS316 were formed at 270 s of exposure time as the 900 W microwave power.

4.2. Without filler powder interface

Researchers had tried to join metals without any filler for the dissimilar and similar metal joining via MHH processing. With the homogeneous and rapid heating rate properties of MHH, the penetration and the density of fine grains onto the joint surface were significantly improve. Since no powders and fillers were used,

Table 1
Summary of essential parameters for the MHH process.

Base material	Filler material	Microwave power (W)	Exposure time (s)	Frequency (GHz)	Joint status	Refs.
Austenitic stainless steel (SS-321)	Nickel-based powder	1300	600–2100	2.45	Joined (458HV of microhardness)	[117]
Stainless steel	Nickel-based powder	/	700	2.45	Joined (323.16 MPa with 11.3% of elongation)	[118]
SS316L stainless steel	Ni-powder (5–40 μm)	900	/	2.45	Joined (338HV of microhardness)	[119]
Stainless steel (SS-304, 65 mm × 25 mm × 6 mm)	Ni-based clad powder	/	60–1500	2.45	Joined	[120]
Stainless steel, SS304	Ni powder (99.9%)	/	360	2.45	Joined (42.67 HRC of hardness)	[121]
Mild steel	Ni-based alloys (EWAC + 20% WC10Co2Ni)	900	300	2.45	Joined (980 HV of microhardness)	[122]
Stainless steel	Ni-based composites (Ni-Al)	1100	/	2.45	Joined (Al_3Ni_2 and Ni_3Al were found to have good strength)	[126]
steel-based material	Nickel(III) oxide	800	/	2.45	Joined (68.7% of Ni)	[127]
Ni-based diamond composites (NiCuSnFe)	Ni powder (99.9%)	2000	1800	2.45	Joined (271 MPa of bonding strength)	[129]
Cast-iron plates (20 mm × 10 mm × 10 mm)	Nickel-based powder (35 μm)	900	/	2.45	Joined (porosity)	[130]
Inconel 718	Nickel-based powder	/	580	2.45	Joined (400 MPa as the 6% of elongation)	[131]
Inconel 625	Nickel-based powder	900	1260	2.45	Joined (326 MPa with 9.04% of elongation)	[65]
SS-430 stainless steel (45 mm × 12 mm × 3 mm)	Ni powder (99.5%, 40 μm)	900	720	2.45	Joined (471 MPa and the elongation was at 9.02%)	[132]
Stainless steel (SS-304)	Ni-based powder	900	/	2.45	Joined (microhardness of 364HV)	[133]
Stainless steel	Nickel powder	2000	1200	2.45	Joined (phases of NiSi and $FeNi_3$)	[134]
SS304, SS3016 stainless steels	Nickel-based powder (20 μm, 50 μm, 70 μm)	800	/	2.45	Joined	[135]
SS304 stainless steel	Nickel-based powder	/	/	2.45	Joined (7% of porosity)	[136]
Inconel 601	Nickel-based powder	300	2700	2.45	Joined (422HV of microhardness, NiFe in the interface layers)	[140]
Stainless steel (SS304)	Ni+20% SiC powder	900	360	2.45	Joined (phases of Ni_2Si_3, NiSi, and $Cr_{23}C_6$)	[141]
Stainless steel SS202 (160 mm × 31 mm × 1 mm)	Nickel powder	700	900–1500	2.45	Joined	[143]
Mild steel	Nickel powder	1200	/	2.45	Joined (columnar dendrites)	[144]
SS202-SS202 of stainless	Nickel powder	900	200–900	2.45	Joined	[147]
Mild steel pipes	/	900	300–500	2.45	Joined (572HV of microhardness)	[148]
Stainless steel (SS304)	/	900	510	2.45	Joined	[101]
SS316L stainless steel	/	900	840–900	2.45	Joined	[152]
SS304 stainless	/	900	900	2.45	Joined	[153]

the energy and time consumption was reduced tremendously. The mild steel pipes are carried out to join without fillers at 900 W for 300–500 s of exposure time. The results indicate the microhardness was at 572HV with an exposure time of 480 s [148]. Meanwhile, Anoop et al. [101] studied on stainless steel (SS304) and stainless steel (SS316) to join without filler metal powders with the experiment settings at 900 W of outpower and 2.45 GHz of frequency. These researchers found the SS304 and SS316 stainless steels were completely melted at 510 s of exposure time with greater microhardness properties. Inconel 625 was butt joined by the microwave radiation without filler and the joint zone was analyzed. The results explained the Inconel specimen was formed at 570 s of exposure time [149]. Ritsuko et al. [150] found Ni and Si-based composite material and C-based material were melted without interface powder using MHH for 10 min, where the heating temperature at 1580 °C and they confirmed that the ratio of formation of C/Si/Ni was 1:1.5:1.5. The Ni and Si-based alloy materials were used to melt using a single-mode microwave cavity and the results revealed that high power input produced a hot spot in the cavity and it led to melting high nickel and silica content at a high heating temperature [151]. Gamit et al. [152] also found experiment settings at 900 W output power suitable for the joining, as SS316L stainless steel completely melted at 840–900 s of exposure time using the MHH process, while SS304 stainless also joined at 15 min of exposure time and 900 W of microwave power [153]. C-based and Fe-based nanofibers were also being observed for its diffusion behavior using the MHH process [154], whilst, Sun et al. [155]. found that Ni-based synthesis material formed with the carbon N doped nanotube at 700 °C of temperature and produced Ni-C and N-Ni interface layer under the 2.4 GHz and the cobalt and iron were investigated by Pełech et al. [156]. Researchers reported the Co-Fe wall is created under the MHH at 30 min of exposure time and the Fe-Co phase was formed under the thermal stability in which depends on materials physical properties.

In summary, pure Ni powder and Ni-based alloys, or pure Ni powder and steel-based materials have been successfully joined with the suitable parameters as shown in Table 1. This contributed towards desired mechanical and microstructures properties from numerous researchers in the related fields. In steel-based materials, pure Ni powder was used commonly due to its compatibility to join with other steel-based materials. Through this joining, the joined materials have better tensile strength and portraits corrosion resistance at a certain temperature. Moreover, Ni-based alloys and steel-based materials can join without any fillers at suitable parameters. However, the mechanical and microstructure properties of the joint part still need to be studied in-depth.

5. Conclusions

A critical review of MHH in metal-based materials and processes has been conducted in this study. The methods and the quality of MHH processing and its applications were discussed and summarized as follows:

In technical problems for the conventional heating process, authors had concluded that the conventional heating process produced heat energy from external natural sources, and it is transmitted to the surface of materials through conduction and convection. However, it can take a longer time for the healing process, while traditional heating produces low heat transfer on the surface of the material which led to increasing the evaporation temperature. The conventional heat treatment methods are difficult to calculate the heating rate under the reaction parameters. The conventional joint process, as known fusion welding processing, can increase the energy usage costs and contribution towards air pollution. Furthermore, many defects are mostly produced by the fusion welding process by various heat distributions.

In technical aspects for MHH, the three different materials such as stone charcoal, wooden charcoal, and graphite powder were used for susceptor. Among these materials, graphite powder is able to use as a potential susceptor for the heating process from the microwave. Electromagnetic waves from the two-way coupled Maxwell's equation and heat transfer equation were used for an electromagnetic wave in the domestic microwave oven cavity, and it is found that the load size is determined to change the size of energy absorption as the dielectric and thermal properties. The electric and magnetic distribution is efficiently implemented by the designed microwave cavity, which can help to extract expected temperature profiles. Although there is heat loss without fully blocked, it can be used for insulating materials to pack the space such as zirconia and alumina for avoiding heat loss.

In Ni-based powder and without powder under the MHH process, some researchers concluded that nickel powder joined at 900 W and can increase the mechanical strength with the stainless steel joint at 700 s or even longer exposure time. The microhardness and tensile strength increased when these bulk materials were joined under the microwave. The laminar structure is joined at 230 ms and 170 W of power, while the small size of reactive particles improves the joining when the power is increased. On the other hand, the SS304 and SS316 were carried out to join without fillers at 900 W of power and 460 s of exposure time. The result showed the joint surface obtaining no crack and both specimens had perfect diffusion to each other.

In microwave irradiation for carbon-based materials (absorber), the previous studies concluded the synthesis of carbon nanotube is one of the attractive products from the biochar that is formed by the microwave radiation at 600 °C in 5 min and the porous carbon can be fabricated under the microwave power of 600–800 W for above 3 min and the high specific area reaches to 2055 m^2g^{-1}. Carbon wood using microwave radiation heating for activation and they found that the maximum temperature of carbon wood reached 2200 K as the rapid heating. The improvement of the fiber-polymer interface layer when the fiber surface roughness was increased and the viscosity of polymer intermolecular interaction decreased. Furthermore, the interfacial shear strength between the carbon-polymer also increased by 30% above at 180 s of exposure time.

In advantages of MHH process, the authors summarized qualities of MHH that they described that the MHH is suitable to improve high heating efficiency through its rapid heating (approximately 80%), generates high penetration depth, reducing the energy and consumption with the shorter reaction time, creating the desired temperature quickly as the high heating rate and suitable usage for high viscosity and multiphase fluid.

Conflict of interest

The authors declare that there is no conflicts of interest

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