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Multiphysics Simulation Study to Microwave Cast Allen Key of Stainless Steel

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Abstract

Microwave casting is a new technique where microwave energy is used for casting materials. Microwave casting promotes sustainability through energy efficient approach, less waste production rate, and enhanced product quality. An Allen key is commonly used for driving fasteners with hexagonal sockets. It features an L-shaped cross-section and is integral to machinery assembly. In this study, a 3D finite element (FE) model of a microwave-assisted casting setup is developed using COMSOL software tool to manufacture a stainless-steel Allen key. The FE model incorporates a household microwave oven and a refractory brick casting setup. The casting process utilizes an applicator with a power output of 900 W and a frequency of 2.45 GHz. Through FE simulations, the exposure time required for effective casting of stainless-steel Allen key within the applicator cavity is optimized. The effects of microwave heating on the material during the casting process are thoroughly analysed.

Keywords:Microwave casting; Allen key; COMSOL; Stainless steel.

1. Introduction

Microwaves are the form of electro-magnetic waves. Microwaves consist of an electric field and a magnetic field. The electric field and magnetic field are perpendicular to each other, and microwaves have frequencies varying from 0.3-300 GHz. The domestic microwave oven has 2.45 GHz frequency with varying output power capacity (700-1400) [1]. In the past there are various methods are developed for manufacturing materials that come in use till date. But for years, research has been going on to find another method for material processing called microwave processing [2]. There are many flaws in conventional methods like excessive energy consumption, longer time of processing, and uneven heating [3]. Microwave heating comes with the solution to these drawbacks by the inverse heating method. In inverse heating, heat is transferred from the core through to the surface by the intermolecular moment [4]. Microwave processing comes with several advantages over conventional processing methods, like less time consumption by fast and efficient heating through intermolecular interaction. The microwave processing technique uses frequency 2.45 GHz in material processing, and it is used in several industries, including chemical and polymer synthesis, metal melting, and processing of food [5]. However, the processing of metallic material is difficult because of the reflective nature of microwaves at room temperature [6]. The absorption of microwave to material depends on several parameters; one of the factors is skin depth of material. According to interaction of microwave with materials, they are classified as absorbing, reflecting, and transmitting materials. Metallic materials tend to reflect microwave. The critical temperature is the temperature at which the metals also start absorbing microwaves [7]. To process metallic materials MHH (Microwave hybrid heating) process has been devised. In this approach, a material called as susceptor is used to heat the metal first through conduction mode. It contributes in raising the temperature of metals. As critical temperature is approached, metal gets heated very fast through hybrid mode of heating [8]. In microwave casting, MHH phenomenon is used to melting and casting metallic materials in the desired form. The various tests are performed by D. Agarwal, and he reported that the bulk metal such as aluminium, copper and stainless steel can be melted [9].

Conventional casting results in significant environmental aspects by producing air pollution through high temperature heating furnaces and waste generation. Microwave casting is the approach towards sustainable development. It reduces air pollution by eliminating the need of traditional furnaces. Microwave casting contributes to sustainable approach of manufacturing from future aspects.

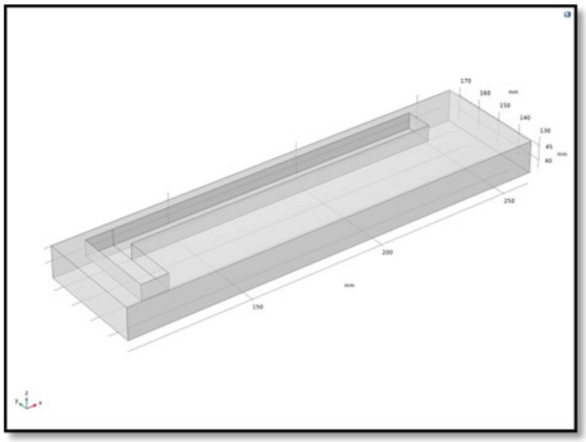
Allen key is an important tool in mechanical industries. It is used to drive screws and bolts with hexagonal sockets. It is also known as hex key and comes with an L-shape. In this study, a 3D simulated model of a microwave-assisted casting is designed using COMSOL software to manufacture a stainless-steel Allen key, and its exposure time is predicted. A model was developed to analyze the electric field dispersion, and temperature profile, during the casting process for the stainless-steel Allen key.

2.FEM (Finite element model) study

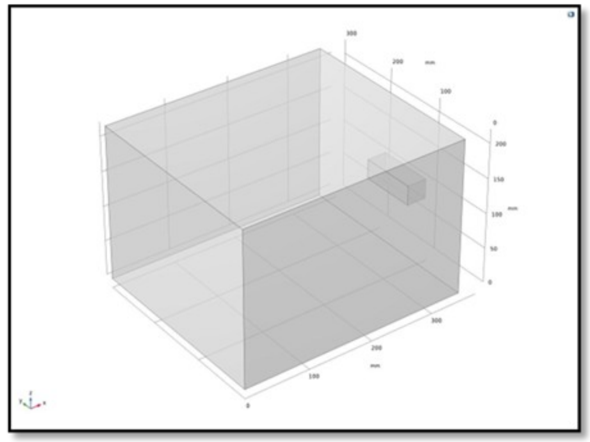
COMSOL software tool is utilized to create an FE model of an in-situ casting setup using microwave energy. In this study, a 3D model is constructed based on the actual dimensions of the microwave oven and other components of the setup. Multi-physics model is used to develop the MHH system for simulation and analysis. Material properties are given for each component near their actual values.

2.1. Geometric model

Figure 1 represents the 3D model of the entire setup which includes a rectangular port waveguide, microwave applicator and material casting setup. To cast the specimen a graphite mold of with an L-shaped cavity is used to get the desired shape. The mold cavity is packed with Stainless steel powder and then covered with a graphene separator sheet. A refractory brick is used to hold the mold and susceptor (Charcoal) in the powdered form. An additional brick piece is used to cover the cavity of refractory brick. Microwaves are permitted through the cylindrical holes of that small brick piece.



(a)



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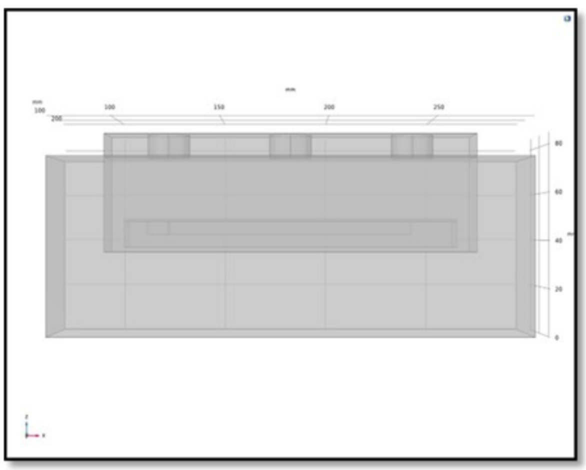

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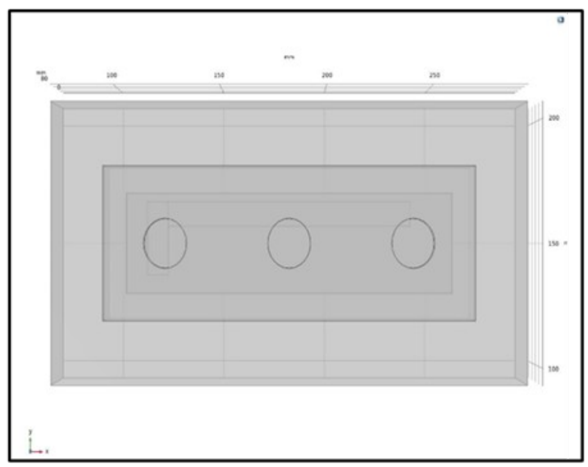

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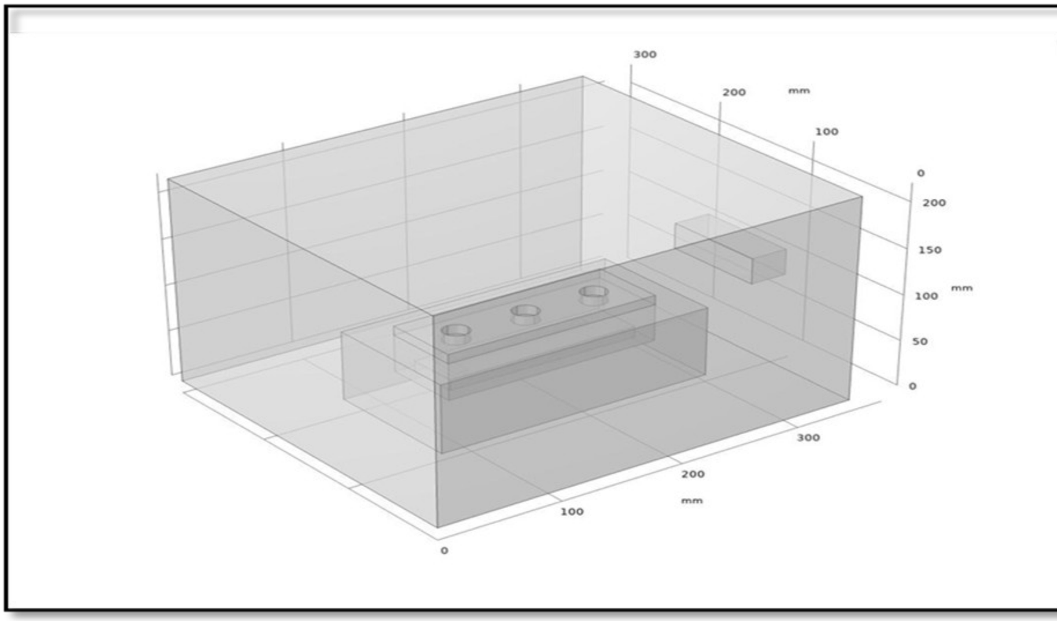

(e)

Figure 1: (a) Mold cavity; (b) Microwave oven with port; (c) Side view of casting setup (d) Top view; (e) Combined 3D model geometry.

2.2. Meshing

Meshing is the representation of complete model geometry into many smaller geometrical segments. Meshing helps to get convergence and accurate simulation [10]. **Figure 2** depicts the meshed geometry.

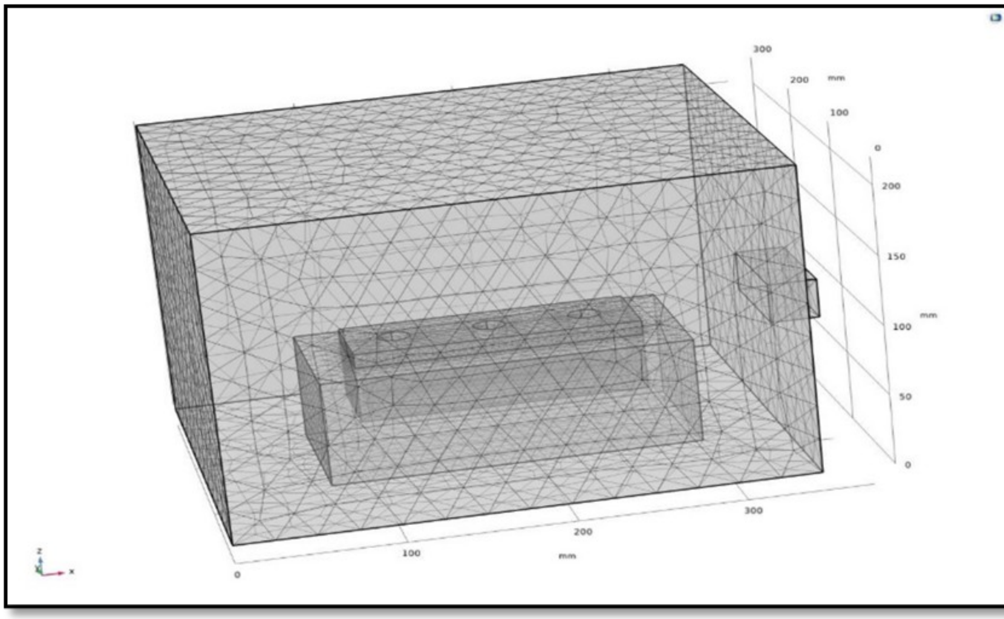

Figure 2: Meshed Geometry Model

3. Results and Discussion

The outcomes obtained from the simulation study discussed in this section.

3.1. Electric Field Intensity

The electric field intensity helps to find optimum place for maximum heating. As the material starts interacting with the microwave, nodal and anti-nodal points are formed. The anti-nodal point represents the hot spot zone with maximum value of electric field, whereas nodal points indicate regions with minimum electric field intensity. The specimen is placed in anti-nodal locations to get the maximum heating effect. **Figure 3** represents the electric field intensity inside the oven cavity during the process of metal casting. Maximum value of electric field intensity is shown in red color, and its value is 4.45×10^{4} (V/m) around the graphite mold. The blue color shows the minimum value of 4.63×10^{-6} (V/m) in the free space of cavity and other regions.

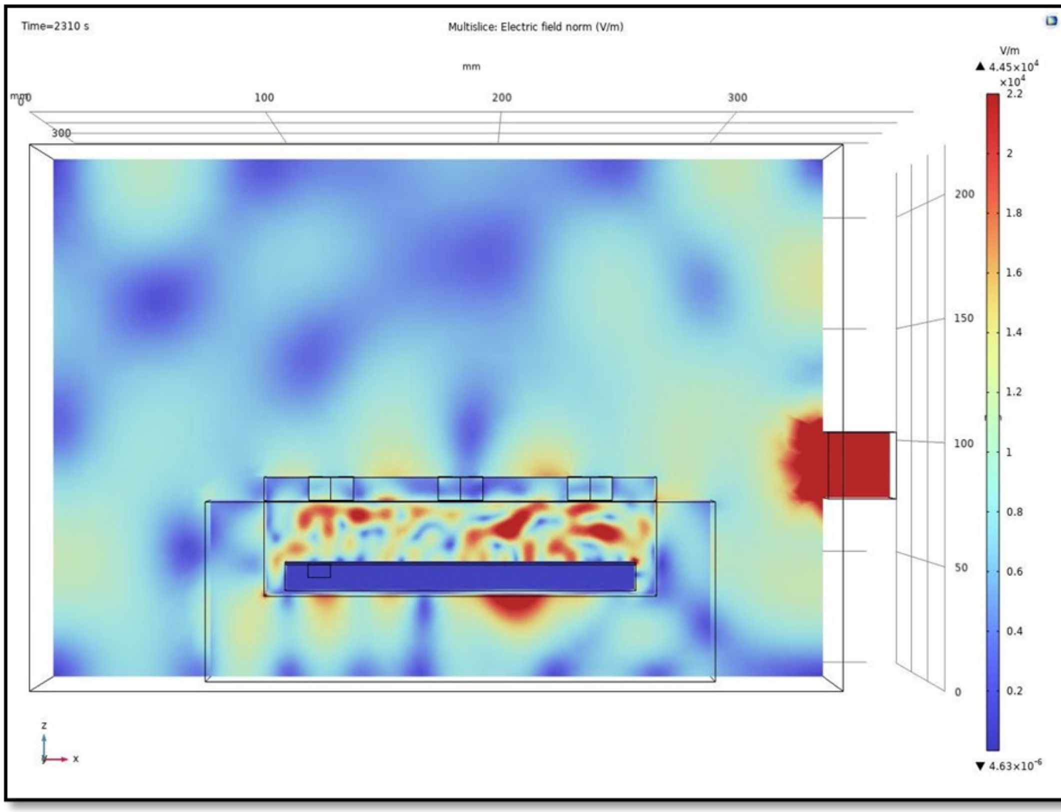

Figure 3: Electric field distribution inside oven at 2310 s.

3.2. Resistive Heating

As microwaves are absorbed within the material, atoms start interacting with radiation. Which results in the conversion of radiation energy into thermal energy. **Figure 4** represents the resistive heating inside the microwave. Simulation results define the red colour for maximum heat dissipation. Blue and green color designates the negligible resistive heating.

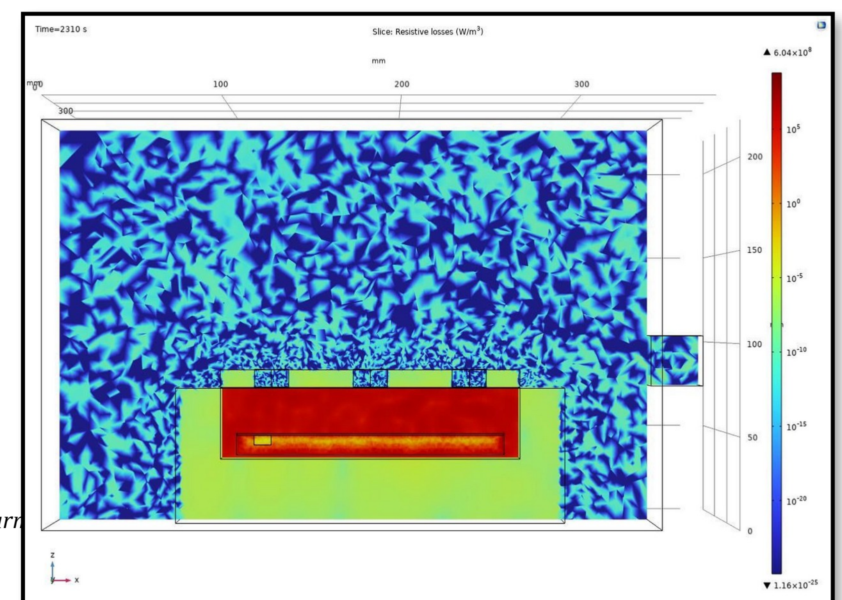

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Figure 4: Resistive heating.

Maximum resistive heating is observed near the susceptor with a value of $6.04\times10^{8}W/m^{3}$. This heat is also responsible for the further rise in temperature of the cast specimen.

3.3. Temperature profile

When the temperature of metal powder reaches to critical temperature value, properties of metal powder are changed, and it also starts absorbing the microwaves. Now, cast specimens reach its melting point at faster rate. The volumetric temperature profile of the cast specimen subjected to MHH at 2310 s is represented in **Figure 5**. Uniform and entire volume heating of specimen is observed. The temperature of the cast specimen is reached near its melting point (around 1490 ˚C) in approximately 38.5 minutes.

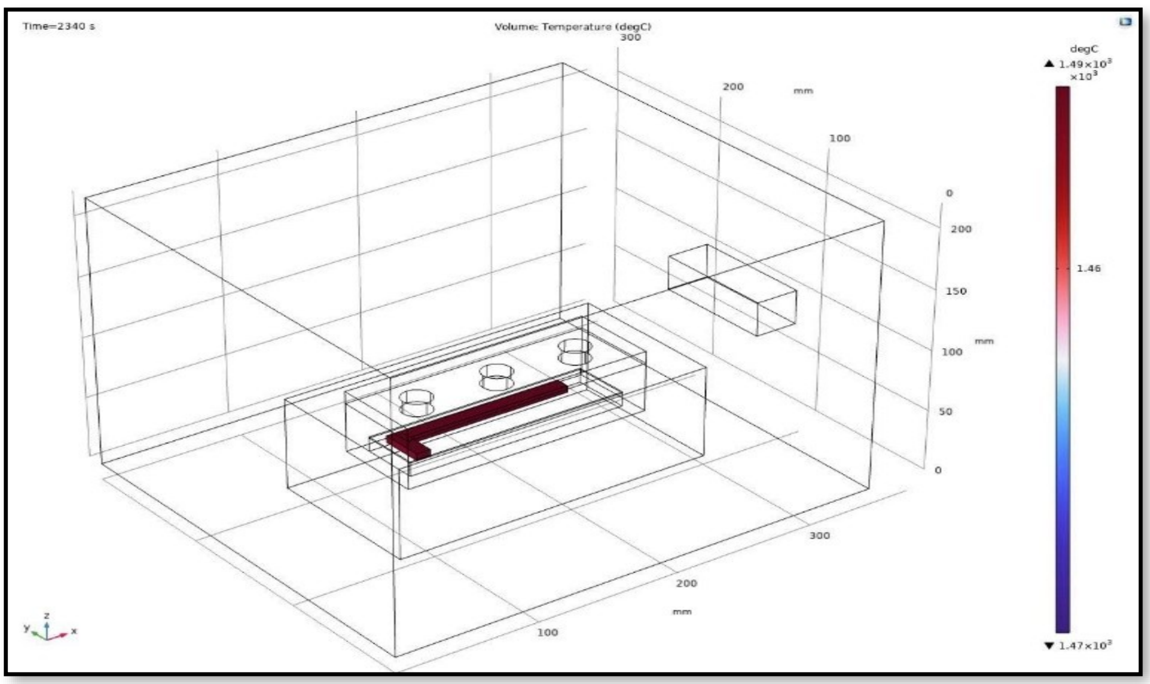

Figure 5: Volumetric temperature of cast specimen

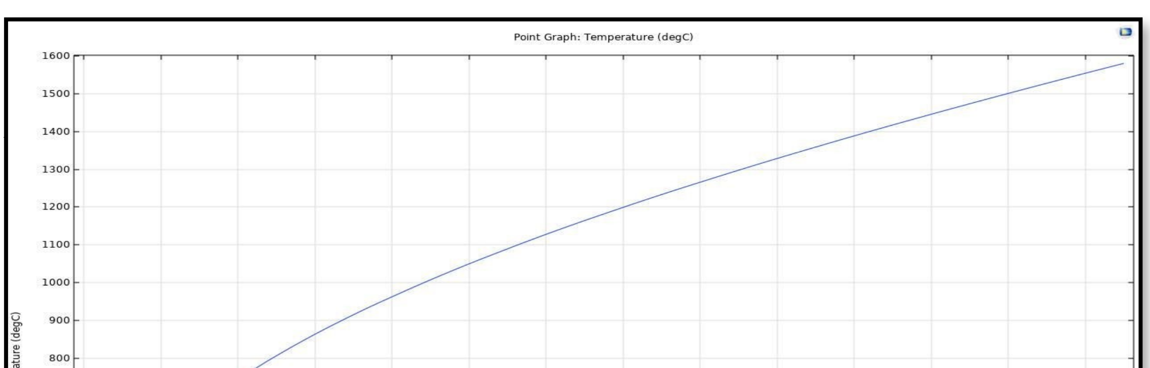

Figure 6: Time-temperature profile of cast specimen.

4. Conclusions

In this study, the microwave casting setup of the hexagonal Allen key of stainless-steel specimen is developed through COMSOL simulation software. From this study, the following conclusions are obtained.

- From the simulation study, the maximum electric field of 4.45×10^4 (V/m) is observed around the mold.
- The susceptor region is observed with maximum resistive heating of $6.04 \times 10^8\, W/m^3$.
- As per the simulation results, it takes 38.5 min for the cast material to reach its melting point.
- Volumetric and even heating is observed of cast specimens due to intermolecular heating.

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References

[1] Nesterov DA, Derevyanko VA, Suntsov SB. Experimental investigations of flat T-shaped copper and titanium heat pipes. Appl Therm Eng 2021;198:117454. https://doi.org/10.1016/j.applthermaleng.2021.117454.

[2] Li R, Zhao Y, Li R, Liu H, Ge Y, Xu Z. Plasmonic optical trapping of nanoparticles using T-shaped copper nanoantennas. Opt Express 2021;29:9826–35. https://doi.org/10.1364/OE.420651.

[3] Salonitis K, Zeng B, Mehrabi HA, Jolly M. The Challenges for Energy Efficient Casting Processes. Procedia CIRP 2016;40:24–9. https://doi.org/10.1016/j.procir.2016.01.043.

[4] Mishra RR, Sharma AK. A Review of Research Trends in Microwave Processing of Metal-Based Materials and Opportunities in Microwave Metal Casting. Crit Rev Solid State Mater Sci 2016;41:217–55. https://doi.org/10.1080/10408436.2016.1142421.

[5] Samyal R, Bagha AK, Bedi R. The casting of materials using microwave energy: A review. Mater Today Proc 2020;26:1279–83. https://doi.org/10.1016/j.matpr.2020.02.255.

[6] Bhoi NK, Singh H, Pratap S, Jain PK. Microwave material processing: a clean, green, and sustainable approach. In: Kumar K, Zindani D, Davim PBT-SEP and MT, editors. Sustain. Eng. Prod. Manuf. Technol., Academic Press; 2019, p. 3–23. https://doi.org/10.1016/B978-0-

12-816564-5.00001-3.

[7] Mishra RR, Sharma AK. Microwave–material interaction phenomena: Heating mechanisms, challenges and opportunities in material processing. Compos Part A Appl Sci Manuf 2016;81:78–97. https://doi.org/10.1016/j.compositesa.2015.10.035.

[8] Mishra RR, Sharma AK. On mechanism of in-situ microwave casting of aluminium alloy 7039 and cast microstructure. Mater Des 2016;112:97–106. https://doi.org/10.1016/j.matdes.2016.09.041.

[9] Singh S, Gupta D, Jain V. Novel microwave composite casting process: Theory, feasibility and characterization. Mater Des 2016;111:51–9. https://doi.org/10.1016/j.matdes.2016.08.071.

[10] Marahadige SL, Sridharmurthy SM, Jayraj AH, Mahabaleshwar US, Lorenzini G, Lorenzini E. Development of copper alloy by microwave hybrid heating technique and its characterization. Int J Heat Technol 2018;36:1343–9. https://doi.org/10.18280/ijht.360425.