The Eurasia Proceedings of Science, Technology, Engineering & Mathematics (EPSTEM)
ISSN: 2602-3199

The Eurasia Proceedings of Science, Technology, Engineering & Mathematics (EPSTEM), 2023

Volume 24, Pages 287-300

IConTech 2023: International Conference on Technology

# Numerical Simulation on Microwave Melting of Hastelloy C-276

**Kadapa Vijaya Bhaskar Reddy**
National Institute of Technology Warangal

**K.V. Hari Shankar**
National Institute of Technology Warangal

**Venkatesh Gudipadu**
National Institute of Technology Warangal

**Abstract:** Melting of metals is of utmost importance in the manufacturing industry as it is the primary manufacturing process to obtain the desired shape and size. microwave melting is a novel technique that uses electromagnetic wave radiation to heat materials. In the present work, the melting of Hastelloy C-276 inside a multimode microwave applicator operating at 2.45 GHz and 900 W input power, is explored in numerical and experimental. This results in a significant reduction in processing time and leads to lesser material wastage. The distribution of temperature, electric field, and resistive losses was analysed to understand the microwave melting of the Hastelloy C-276 sample. The study revealed that the melting time taken was ~440 seconds for microwave melting of Hastelloy C-276.

**Keywords:** Microwave melting, Hastelloy C-276, Susceptor, Skin depth.

## Introduction

Microwave processing is a material processing technique that uses electromagnetic waves at a frequency of 2.45 GHz. This technique has emerged in the last decade and is widely used in various industries, including food processing, chemical synthesis, melting of metals, etc(Mishra & Sharma, 2016b). Microwave processing has several advantages over traditional processing methods, fast and efficient method that can reduce processing time and energy consumption(Gupta& Sharma,2014). However, microwave processing also has some limitations, such as the need for specialized equipment and the potential for uneven heating furnaces. Metals do not couple with microwave (MW) radiations, however, they require initial heating to reach critical temperature (until then they act as reflectors to MW). İnitial heating is enabled by using susceptor material which couples with microwaves and heats the bulk metal or alloy. Once the bulk metal reaches its critical temperature direct coupling of microwaves takes place and then gets heated.(Mishra & Sharma, 2016a).

Various studies were carried out on microwave melting of different metals. in-situ microwave casting of AA 7039 was examined using an industrial multimode microwave applicator running at 1400 W power and 2.45 GHz frequency( Mishra & Sharma, 2016c). The results show that 920 seconds of microwave irradiation was sufficient to produce a thick cast. It was seen that the oxide layer was forming; this layer serves as a susceptor and aids further in the casting process. It was determined that by adjusting the microwave irradiation period during its processing, it could be possible to develop a material with the necessary amount of hardness. The results of the study showed that the use of microwave energy resulted in faster melting times and reduced energy consumption compared to conventional melting methods. The authors attributed this to the selective heating of the material due to the interaction of microwaves with the alloy. This method also produced a finer microstructure, which improved the mechanical properties of the aluminum alloy. The study concludes that in-



- Selection and peer-review under responsibility of the Organizing Committee of the Conference

situ microwave casting of aluminum alloys is a promising technique that can provide significant benefits in terms of energy efficiency, cost-effectiveness, and improved material properties. It has the potential to revolutionize the casting industry and reduce the environmental impact of traditional casting methods. Copper casting was analyzed inside the applicator cavity using MHH at 2.45 GHz and 1400 W. There was an improvement in the properties of the microwave cast. A study was carried out to know the microwave interaction with the charge during exposure and how the oxide layer affected on melting of the copper(Mishra & Sharma,2018b). There has been an improvement in the microwave cast's mechanical characteristics. The uniform and dense structure demonstrates the potential of the process. However, the porosity was reported to be 2–5% and the castings were found to have an average micro indentation hardness of 93±20 HV. Similarly, using microwave radiation, the Al-Zn-Mg alloy (Al 7039) was cast(Mishra& Sharma, 2018a). The alloy charge was subjected to microwave hybrid heating using SiC and CC susceptors. It was discovered that the susceptor material's qualities have a substantial impact on how hot the charge becomes. The temperature of the mold has a major impact on the size of the grain in alloy castings. This effect results from the interaction of microwaves with the mold materials throughout various exposure intervals, which leads to a range of temperatures reached by the mold during preheating, exposure, and post-exposure.

The study by Fujiwara et al.investigated the microwave heating behavior of fine stainless steel powders in an H-field at 2.45 GHz (Fujiwara et al.,2020). The authors utilized a resonant cavity to measure the temperature rise of the samples. Results showed that the temperature of the samples increased rapidly within the first few minutes of microwave irradiation. The heating behavior was found to be strongly dependent on the particle size, with smaller particles exhibiting a more rapid temperature increase. Additionally, the heating behavior was found to be influenced by the packing density of the samples and the presence of air gaps. The study suggested that microwave heating can be a promising method for the sintering of fine stainless steel powders, with potential applications in the production of various metallic components.

The energy consumption of melting bulk non-ferrous metallic materials utilizing microwave hybrid heating (MHH) and conventional heating was examined in the study by Lingappa et al. The authors used a specially designed microwave cavity to heat the samples and measured the energy consumption during melting. Results showed that the energy consumption during MHH was significantly lower than that during conventional heating. Additionally, the study found that MHH was able to achieve complete melting of the samples in a shorter time compared to conventional heating. İt is attributed to the lower energy consumption during MHH due to the selective heating of the metallic materials, which reduces heat loss to the surrounding environment. The study suggested that MHH can be an effective and energy-efficient method for the melting of non-ferrous metallic materials, with potential applications in various industries (Lingappa et al., 2018). Microstructural investigation revealed that the samples melted using microwave processing had a finer grain structure and uniform distribution of intermetallics than the conventional processing. The study conducted by Gouthama et al. (2016). compared the melting behavior of tin using a muffle furnace and microwave energy. It was found from the study that microwave energy was more efficient and had a shorter melting time than the conventional method. It was observed that the microwave-melted tin had a finer grain size and higher hardness compared to the conventionally melted tin.

From the literature, it was observed that most of the studies focused on microwave casting or melting of non-ferrous, ferrous materials. Melting of super alloys was seldom found. Hence, this study focused on the melting of Hastelloy C-276 inside a multimode microwave applicator operating at 2.45 GHz, and 900 W input power. From the simulation study, temperature distribution, electric field, and resistive losses were analyzed to understand the microwave melting of the Hastelloy C-276 sample. The model has been validated by experimentally melted Hastelloy C-276 samples.

## Materials and Methodology

### Modelling

The microwave melting model was developed similarly to the experimental setup using the COMSOL Multiphysics 5.5a software package as shown in Figure 1. The parameters used for modeling are listed in Table 1. The time taken for computation was approximately 180 minutes. The material properties used in the simulation are listed in Table 2. The COMSOL Multiphysics software tool to analyze the thermal characteristics of Hastelloy C-276. The oven walls and the waveguide in the model are made of copper. Although it is anticipated that resistive losses would be minimal, the impedance boundary condition on these walls makes sure that they are taken into consideration. Alumina was used for the cascade because it is a good electrical conductor. An ACER workstation with Ryzen 5, 32 GB RAM, and RADEON graphics card-4GB was used for modelling and simulation studies. Hastelloy C-276 bulk metal having 10 × 10 × 5mm. Graphite is a good susceptor and has good irradiating properties at ambient as well as elevated temperatures with electromagnetic radiation. the susceptor and crucible were considered graphite.

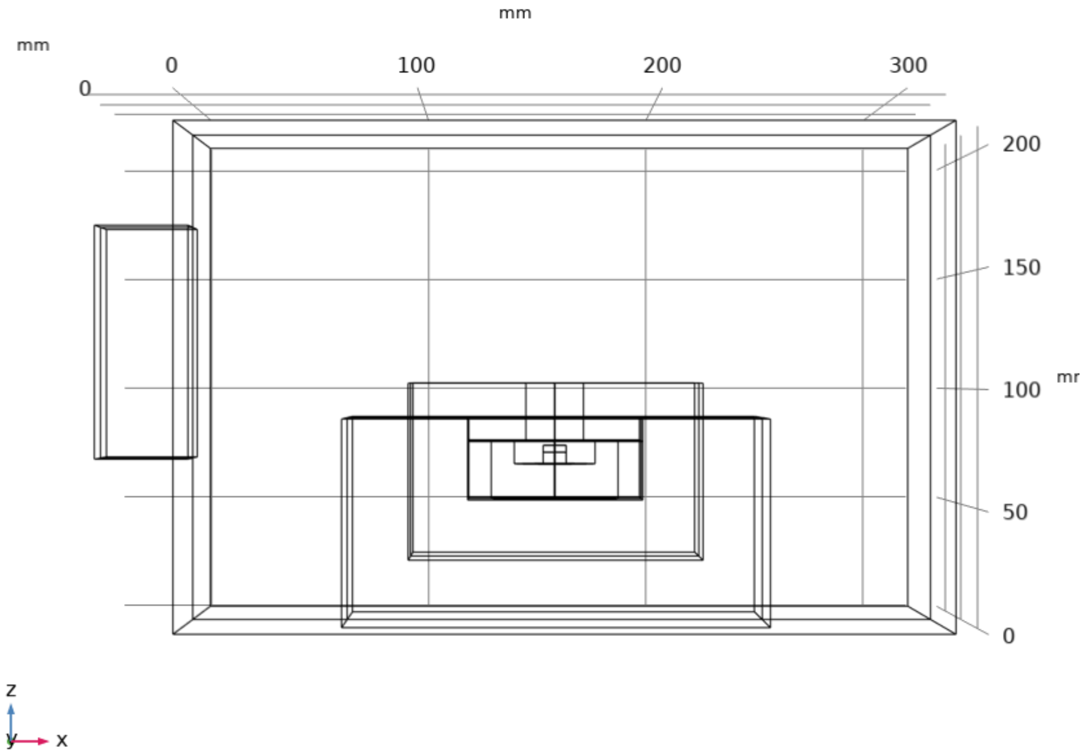



Figure 1. The 3D geometry model in Comsol

Table 1. Model parameters used for simulation

| Serial No | Label | Dimension (mm) |
|---|---|---|
| 1 | Microwave cavity | 320 x 320 x 210 |
| 2 | Waveguide | 40 x 80 x 100 |
| 3 | Bottom cascade | 185 x 185 x 140 |
| 4 | Top cascade | 125 x 125 x 110 |
| 5 | Through-hole diameter | 25 |
| 6 | Graphite susceptor | 10 x 10 x 5 |
| 7 | Graphite Cylinder outer | 55 x 25 |
| 8 | Graphite Cylinder inner | 55x10 |
| 9 | Hastelloy C-276 plates | 10x10x5 |

Table 2. Material properties

| Property | Unit | Air(Tamang & Aravindan, 2022) | Copper(Tamang & Aravindan, 2019) | Alumina (Reddy et al., 2023) | Graphite(Reddy et al., 2023) | Hastelloy C-276 (Haynes Hastelloy® C-276 Alloy & Solution Heat Treated Flat Products, n.d.) |
|---|---|---|---|---|---|---|
| Relative Permeability | 1 | 1 | 1 | 1 | 1 | 1 |
| Relative Permittivity | 1 | 1 | 1 | 4.2 | 23.5 | 1 |
| Electrical Conductivity | S/m | 0 | 5.99e7 | 1e-14 | 1.667 | 1/(1.26e-6) |
| Heat Capacity at constant pressure | J/(kg-K) | - | 385 | 900 | 707.7 | 427 |
| Density | $Kg/m^3$ | - | 8960 | 3900 | 2490 | 8890 |
| Thermal Conductivity | W/(m-K) | - | 400 | 27 | 24 | 18.3 |

**Governing Equations**

Permittivity is the property of a material to get polarized under the influence of an external electric field. It is also called the dielectric constant. The absolute permittivity of a material is given by Eq.1 (Mishra&Sharma, 2017)

$$\varepsilon' = \varepsilon_0 \varepsilon'_r \tag{1}$$

Where $\varepsilon_0$ = 8.854×$10^{-12}$ F/m is the permittivity of free space and $\varepsilon'_r$ is the relative permittivity. The complex permittivity of a material accounts for the absorption and storage of the electrical energy inside the material. It is given by Eq.2 (Gupta & Eugene,2011)

$$\varepsilon^* = \varepsilon' - j\varepsilon'' \tag{2}$$

where ε" is the dielectric loss factor. The extent of penetration and absorption of microwaves inside a material is represented by its permittivity, ε', and the ability to store energy is represented by the dielectric loss factor, ε". The dielectric loss factor accounts for the various losses occurring due to the resistance offered to the translational and rotational motions of electrons, ions, and dipoles, which in turn are induced due to the electric field generation inside the material.

The effect of the magnetic field on the absorption of microwaves and heating is generally ignored since it is dominated by the electric field. However, a magnetic property called permeability (μ') has a significant influence on the skin depth of the material. For better penetration of microwaves, more skin depth is required, and this is possible only when the permeability is low. Permeability (μ'), accounts for the effect of the magnetic field on the material and is given by Eq.3 (Reddy et al.,2023).

$$\mu' = \mu_0 \mu'_r \tag{3}$$

Where $\mu_0$ =8.854×$10^{-12}$ F/m is the permeability of free space and $\mu'_r$ is relative permeability. The complex permeability, μ*, is given by Eq.4(Gupta &Eugene,2011).

$$\mu^* = \mu' - j\mu'' \tag{4}$$

Where $\mu''$ is magnetic loss factor. The magnetic loss factor accounts for relaxation and resonance occurring due to the magnetic field.

**Boundary Conditions**

To approach the real experimental conditions, certain selected boundary conditions have been applied by heat transfer in solids and electromagnetic wave frequency domain modules in the developed model. The boundary conditions shall be set out as follows:

***Port boundary condition:*** It was applied on the entrance to the rectangular waveguide as shown in Fig. 2(a) and transverse electric (TE10) mode was considered with 2.45 GHz frequency using Eq.5 (Tamang & Aravindan, 2019).

$$\text{Cut-off frequency } (f_c)_{mn} = \frac{c}{2}\sqrt{\frac{m^2}{a^2} - \frac{n^2}{b^2}} \tag{5}$$

***Impedance boundary condition:*** it is applied on the walls of the microwave cavity and the waveguide as shown in Fig. 2(b) to account for minute losses (skin effect) due to skin depth using Eq.6 (Tamang & Aravindan, 2022)

$$\sqrt{\frac{\mu_r \mu_0}{\varepsilon_r \varepsilon_0 - j\frac{\sigma}{\omega}}}\, n \times H + E - (n.E)n = (n.E_s)n - E_s \tag{6}$$

*Perfect Magnetic Conductor:* It is applied on the central plane of symmetry of the microwave applicator so that the magnetic field and current density along the symmetry plane are zero, which is represented by the following equation: (Mishra & Sharma,2017).

$$\mathbf{n} \times \mathbf{H} = 0$$
(7)

***Heat transfer boundary condition:*** It is applied to the Hastelloy C-276 charge and susceptor using Eq. 8 ( Redy et al., 2023) as shown in Fig. 2(d).

$$\rho C_p \frac{\partial T}{\partial t} = \nabla.(K\Delta T) + Q_{rms}$$
(8)

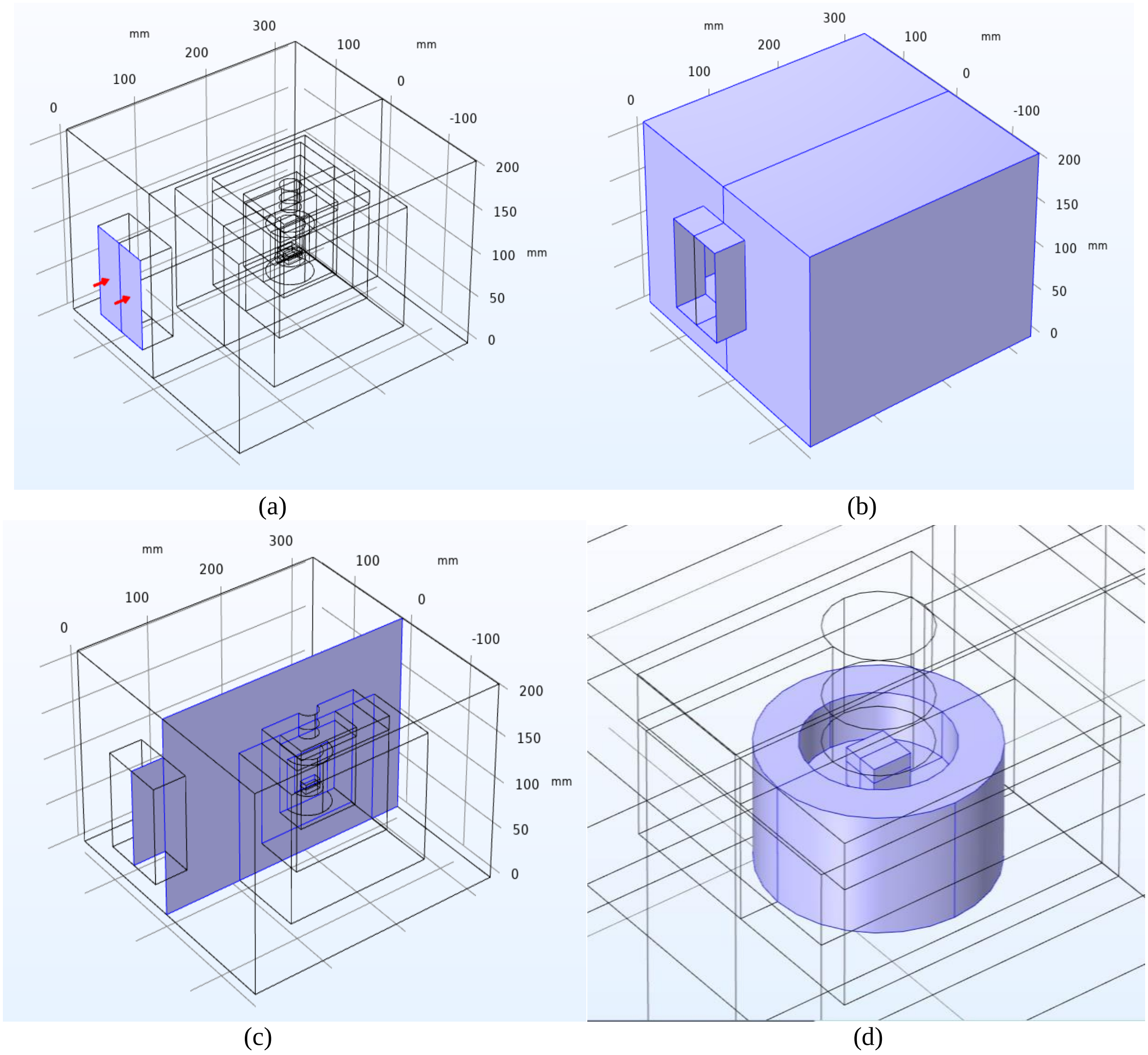


Figure 2. Boundary conditions used (a) Port boundary condition (b) Impedance boundary condition (c) Perfect magnetic conductor (d) Heat transfer in solid

Certain assumptions were considered for simplifying the model. They are as follows:

- Copper has high electrical conductivity, so the walls of the waveguide and the micro-oven are considered to be copper material.
- The surrounding temperature of the system is considered 27 °C.
- Turn table rotation and speed were not considered
- For simulation the phase change is not considered.

## Mesh Quality

Using a model solver tool to facilitate meshing, the 3D model was composed of physics-controlled meshes and tetrahedral elements. The suitable element size was chosen by examining the element quality for 'fine' (Fig. 3(a)), 'finer' (Fig. 3(b)), 'extra fine' (Fig. 3(c)), and 'extremely fine' (Fig. 3(d)) element sizes in terms of average element quality, minimum element quality, and maximum growth rate. 0.0 is a degenerated element while 1.0 is a completely symmetrical element in the element quality. By contrast, the highest element growth rate determines whether or not an element size may increase in a region of smaller elements and grow in a region with greater elements. The mesh generated (Fig. 4(a)) with 'extremely fine' elements (total number: 107724) was found more effective with optimum characteristics (average element quality 0.663, maximum growth rate 1.30) than 'fine', 'finer', and 'extra fine' elements. Fig. 4(b) shows an evaluation of the mesh quality to indicate that it is more than 0.7 for mold assembly and charge.

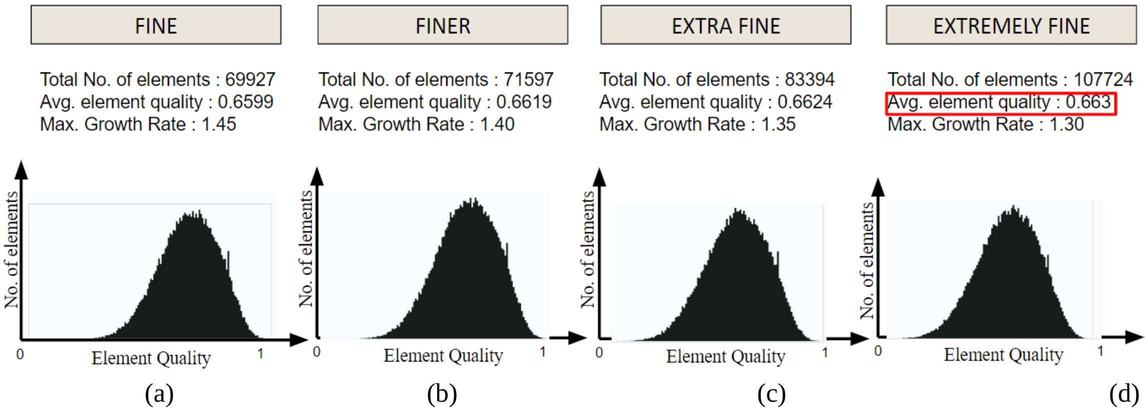



Figure 3. Comparison of element quality in (a) fine, (b) finer, (c) extra fine, and (c) extremely fine element size.

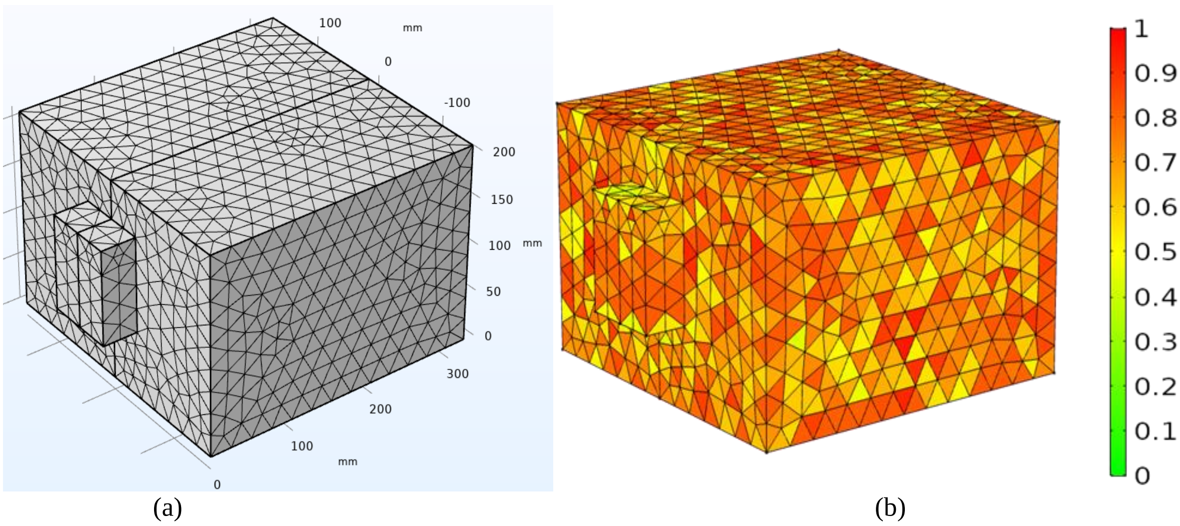



Figure 4. (a) Meshed model (b) Mesh quality

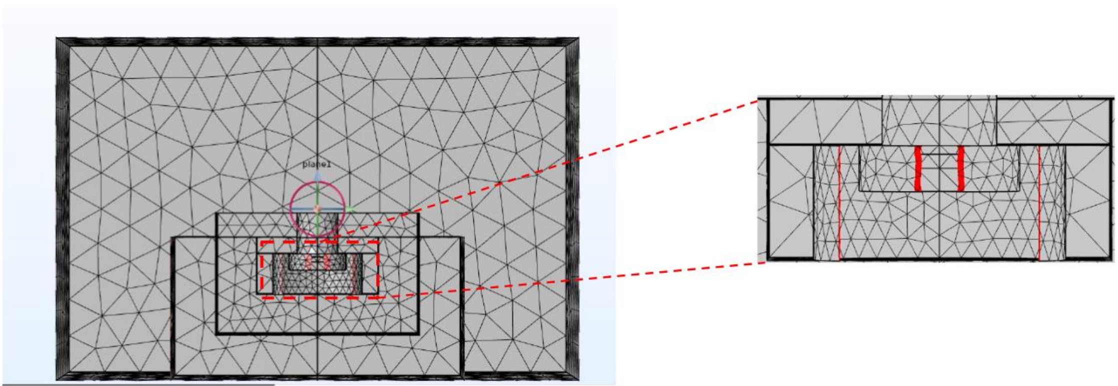


Figure 5. Mesh distribution of microwave setup with an enlarged view of the interlayer.

Physics-controlled mesh of size “extremely fine” containing 107724 elements was used for the simulation as depicted in Fig. 5, the enlarged view of the figure shows that the interlayer has very fine elements compared to the substrate, which is necessary for accurate results.

## Results and Discussion

The results in the form of resistive losses due to electric field distribution, magnetic field distribution, variation of electric field distribution, magnetic field distribution, and temperature distribution of Hastelloy were studied.

### Effect of Power

With the following stages of unit power: 1500 W, 2000 W, 2500 W, 3000 W, and 3500 W, the impact of power fluctuation on the melting of the charge was examined. Figure 6(a) illustrates how power affects the distribution of the electric field inside the microwave cavity and the related temperature distribution in the charge at the moment of melting. The distribution patterns of the electric fields in all of the situations are clearly shown in the figure. The intensity of the electric field, however, rises as the power increases. The pattern of temperature distribution shows the impact of increasing electric field intensity. The temperature distribution reveals that as power increases, both the distribution pattern and temperature change. Although heating is caused by dielectric losses in the Hastelloy, the conduction loss and eddy current loss dominate heating in the metallic charge. An increase in power increases the heat generation inside the charge and materials. An increase in power increases the field intensity inside the cavity, making more energy available for heat generation and heat dissipation inside the metallic charge.

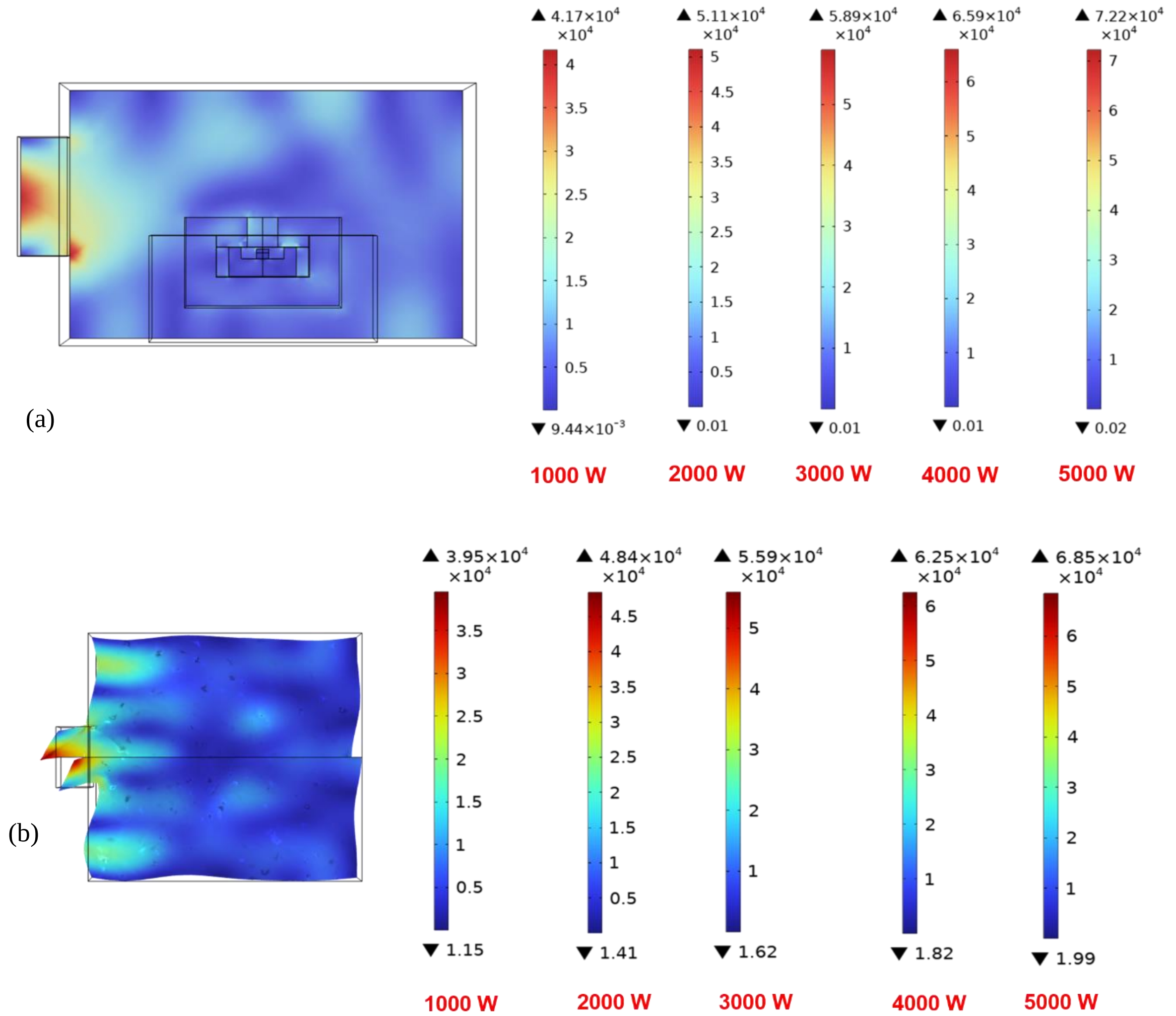



Figure 6. Electric field distribution (a) in Enorm direction with different powers. (b) in Ez with different Powers

The distribution of temperature inside the charge is substantially impacted by power change. Heat dissipation inside the assembly and the susceptor rises as power levels rise. The charge is quickly carried into the microwave absorption domain by heat transfer from these components (assembly and susceptor) into it. More heat is released inside it at a higher strength as the charge interacts with the microwaves. Due to the conduction of heat dissipated within the charge, temperature distribution will be less uniform at lower power steps. Due to a decreased mean free path of free electrons, a metallic charge's thermal conductivity and energy conduction reduce as temperature rises. At increased power, heat transmission will be slower because of improved heat dissipation across the charge volume, which will outweigh heat conduction. As seen by the predicted temperature distribution at the moment of charge melting, increased power thus delivers a more uniform temperature distribution inside the charge. The temperature will drop as we approach the charge's outer surfaces. Convective and radiative heat losses from the charge into the cavity environment are responsible for this. This is yet another distinctive feature of microwave heating, commonly known as inside-out heating

It is important to determine the electric field distribution inside the microwave applicator as it assists in the appropriate location of the sample to ensure less processing time. The positions having higher field intensity enable better microwave coupling of materials. Electric field distribution in the XY plane ($E_Z$) is shown in Fig. 6(b). The distortion in the electric field represents the conversion of microwave energy to heat energy. The locations of maximum and minimum electric field intensity represent the nodes and anti-nodes in the propagation of microwaves. It is observed that the electric field distribution ranges from $4.17 \times 10^4$ (V/m) to $7.22\times10^4$ (V/m).

Figure 7. depicts the impact of power on the charge's melting time. The amount of time needed for the charge to melt is reduced when input power is increased. The data are mathematically correlated, and the relation between melting time and input power is as follows:

$$t= -187.4\ln(P)+ 441.44 \qquad (9)$$

The model displays a hyperbolic trend and a correlation of almost 99% (R2 = 0.994). Additionally, it is clear from the equation that melting time (t) decreases as power provided (P) increases and follows a hyperbolic trend. As a result, the mathematical model depicted in the aforementioned equation is comparable to the model based on simulation data.

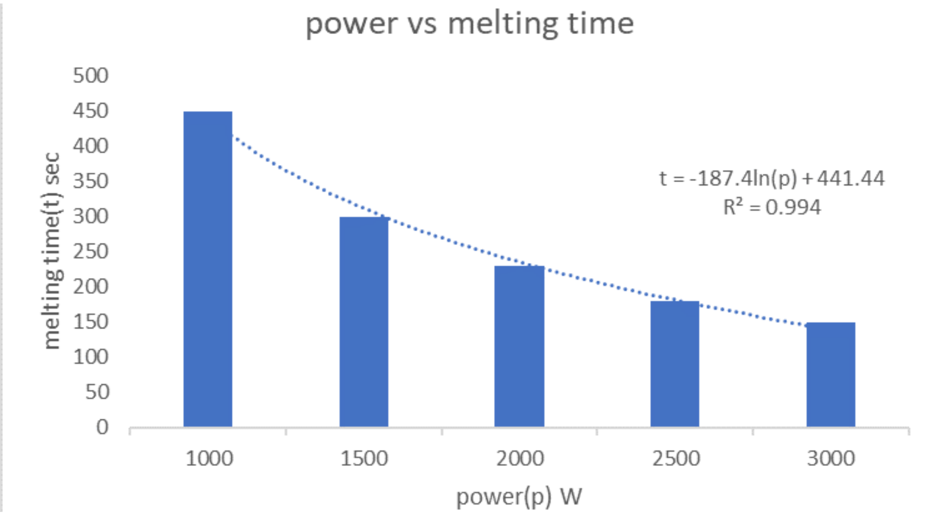



Figure 7. Influence of input power (P) on melting time (t).

Figure 8 depicts the impact of power on the charge's average heating rate. In compared to 1500 W, the charge heats up more quickly on average at 3500 W (200.285%). By accelerating the rate at which heat escapes from the charge, the rate of heat generation is improved and the time needed to heat the charge to its melting point is shortened, due to increase in input power. When power inside the microwave applicator increases, so does the average heating rate of the charge. Figure 4 depicts how power affects the amount of energy needed to melt the charge.2. Immense generation of energy and the resulting increased dissipation of microwave energy inside the metallic charge due to improved electric and magnetic fields at higher powers are responsible for the greatest energy reduction.

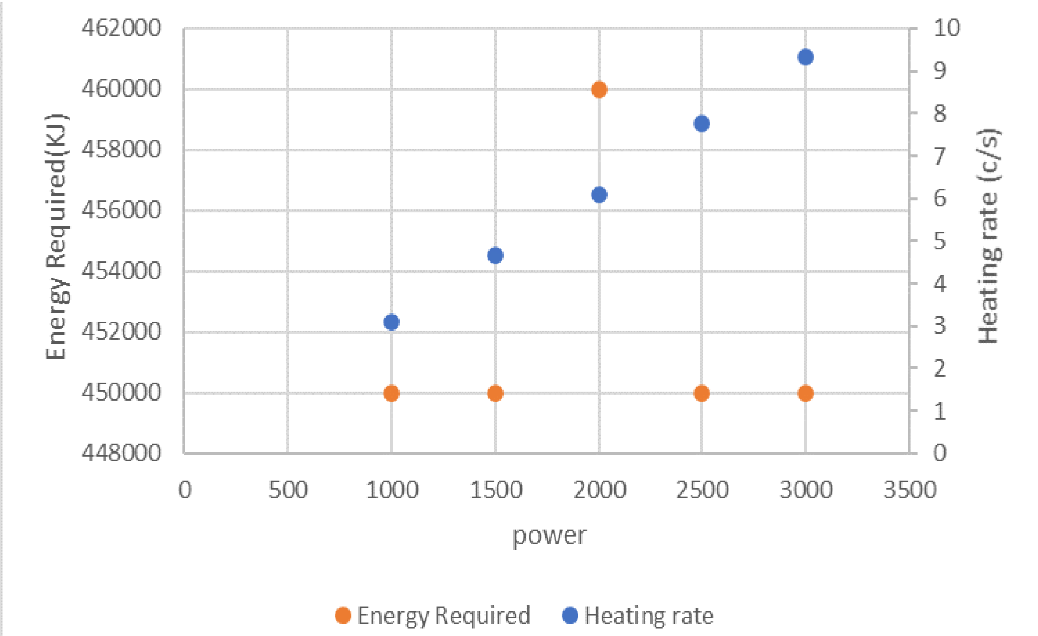
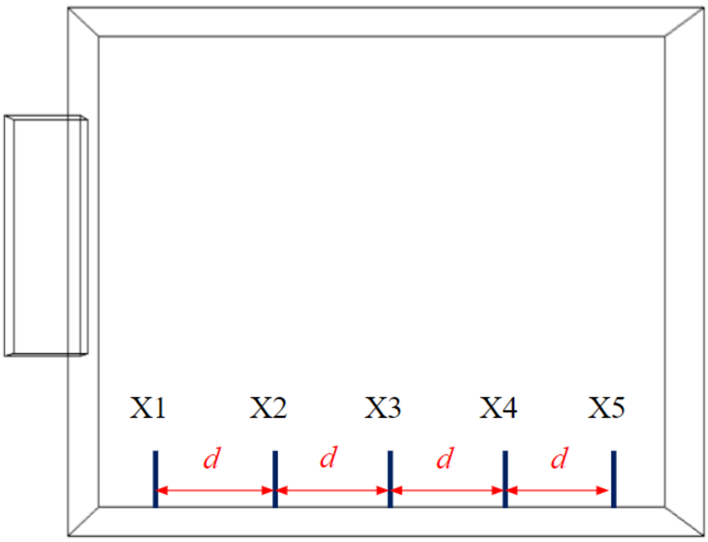



Figure 8. Influence of input power on heating rate and energy requirement for melting of the charge.

**Effect of Assembly Location**

According to a report, the electric and magnetic field strengths are distributed in a high-low pattern inside the microwave applicator cavity. When a material is present in the cavity during processing, this pattern reorients itself. A method for locating the setup at ideal coordinates within the cavity can be found by simulating the operation.

Figure 9. depicts the equivalent impact of mold assembly position (at X1, X2, X3, X4, and X5) on the cavity's electric field distribution and the charge's temperature distribution. According to location, the distribution shows the pattern and value of field intensity. In addition, due to potential disruption in the absorbed and reflected microwaves, the distance (L) between the source and the location of the load influences the interference pattern and placements of nodes (L=n k, where n is a positive integer). The decline in field strength near the charge when it is transported in the x-direction is another finding in the simulated electric field distribution (Fig. 9). On the other hand, the temperature gradually drops away from the charge's outer surface in a more consistent manner. This is explained by the heat that is lost by convection and radiation from the charged surface into the hollow environment.



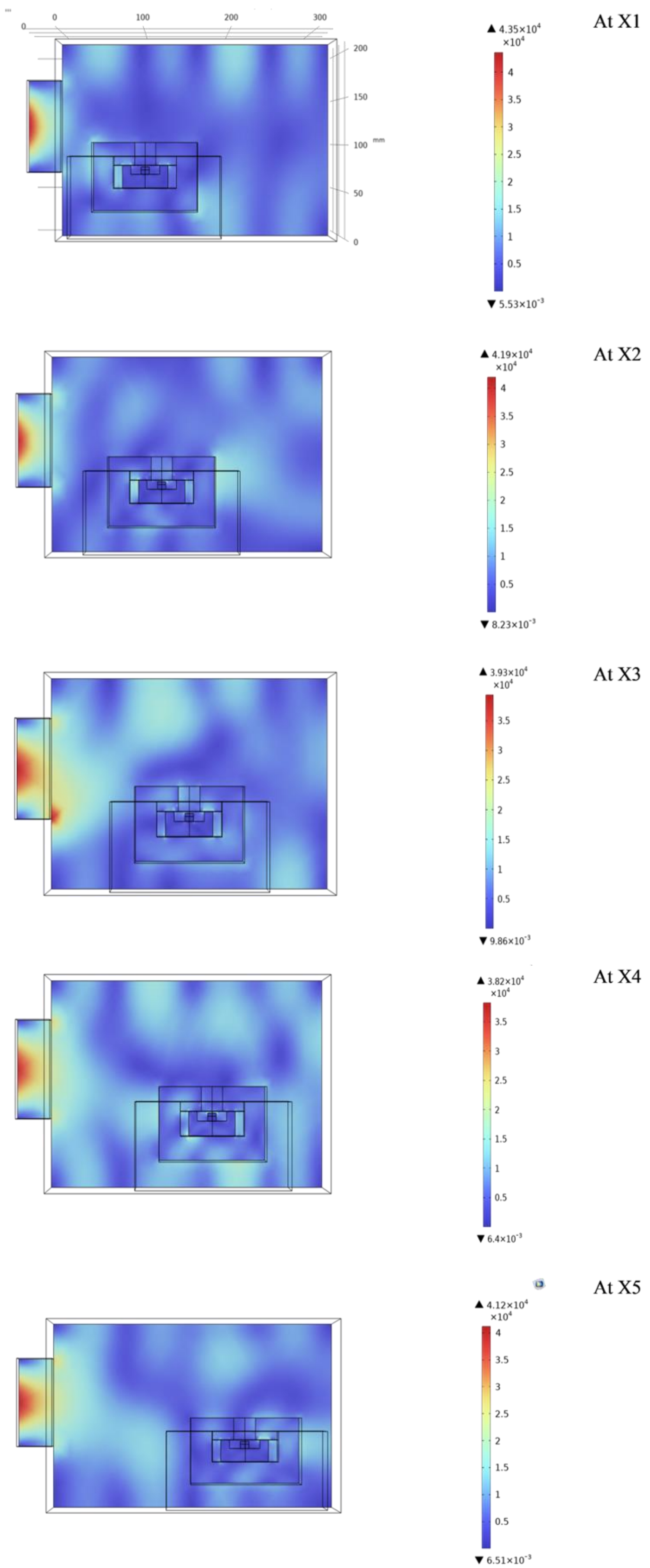



Figure 9. Effect of location on electric field distribution ınside microwave applicator

Figure 10 illustrates the impact of mold assembly position on melting time during charge heating. The charge's heating properties are impacted by the fluctuation in electric field strength as the mold assembly and charge are placed in various places. When compared to places with low electric fields, higher electric fields improve the polarization of molecules in the Hastelloy and the susceptor, which also improves the mobility of the free electrons in the charge. The typical heating period of the charge to reach the critical temperature is shortened by the rapid heating of the Hastelloy and the susceptor. The charge is heated over the critical temperature by coupling with microwaves. The charge heats up quickly, which shortens the whole melting time.

The melting time is influenced by the node distribution and the strength of their fields. The charge has the quickest melting time and the least amount of non-uniformity when it is heated quickly at site X4. As a result of the charge heating more uniformly at site X4, there is less heat transfer through conduction mode within the charge. As a result, the charge melts faster when the degree of non-uniformity is lower (Figure 10). When compared to site X2, the melting time of the charge decreased by 51.61% and 40.3%, respectively, at locations X4 and X5. To guarantee that the charge is melted in less time with a lower amount of microwave energy, the mold assembly and the charge should be placed in an appropriate area.

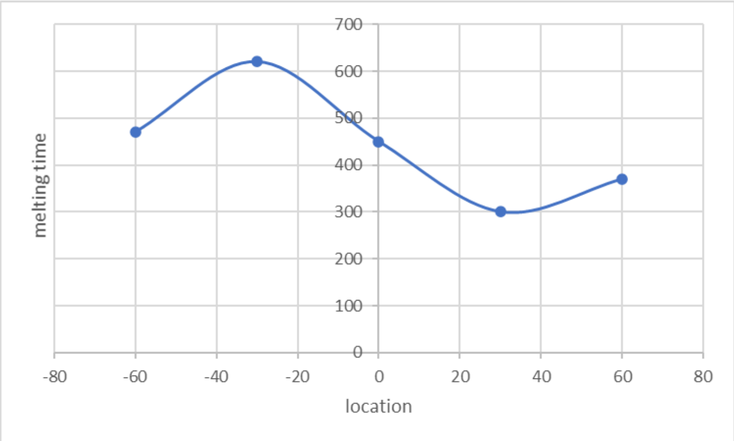
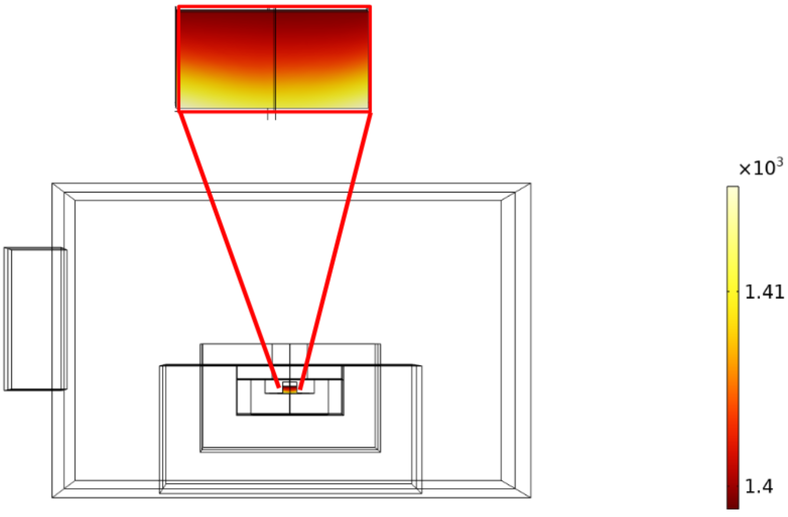



Figure 10. Influence of setup location on melting time.

**Temperature Distribution**

The temperature distribution in Hastelloy is shown in Figure 11. It is consistent with the fact that the heat is transferred from the graphite susceptor to the joining region. The temperature change across the Hastelloy is achieved by measuring the temperature along a line from the bottom of the assembly to the top of the assembly (Figure 11). The temperature of the bottom layer, i.e. Graphite is higher at each time interval, whereas the temperature of the top layer is lower compared to graphite plate and almost uniform. Temperature value depends on the permeability, permittivity, and electrical conductivity for simulation, and various thermal properties are also required for the study.



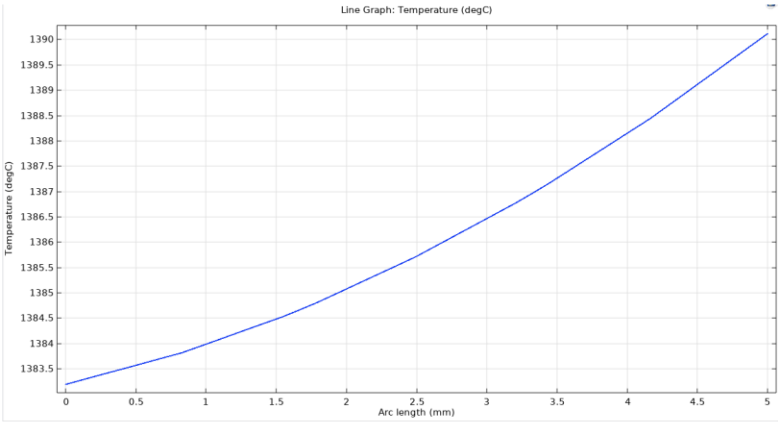



Figure 11. Temperature distribution and Temperature v/s distance plot

**Resistive Losses**

It is observed from Fig. 12 The resistive losses are not uniform throughout the assembly. Mostly it is concentrated at the corners of the graphite cylinder and graphite plate, this may be due to the effect of conduction of heat by the interface layer or it might be microwave energy absorption.

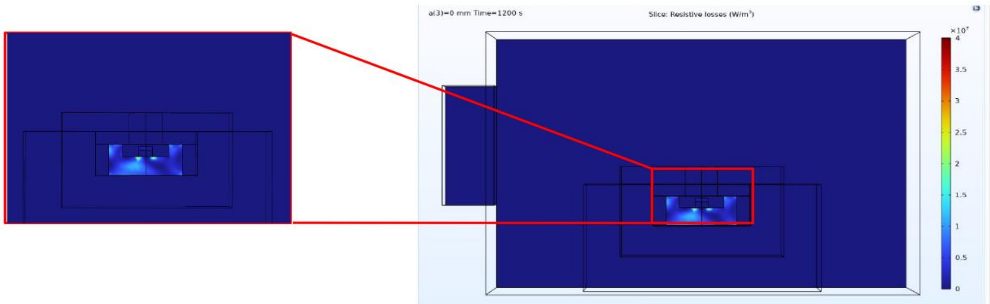


Figure 12. Resistive losses

**Experimental Validation**

The experiment was done using a LG microwave with a frequency of 2.45GHz and 900W power. The assembly was made similar to the geometry used for simulation. An aluminum cascade was placed inside a microwave oven and glasswool was coated around that material. Inside the cascade, a graphite cylinder was placed in the middle and a Hastelloy was placed inside the cylinder, susceptor was also placed on the Hastelloy and then the Hastelloy and susceptor were covered with charcoal powder. This whole setup was placed inside the microwave oven and the experiment was done for 470 seconds. The melting characteristic for different melting times is depicted in Fig. 13.

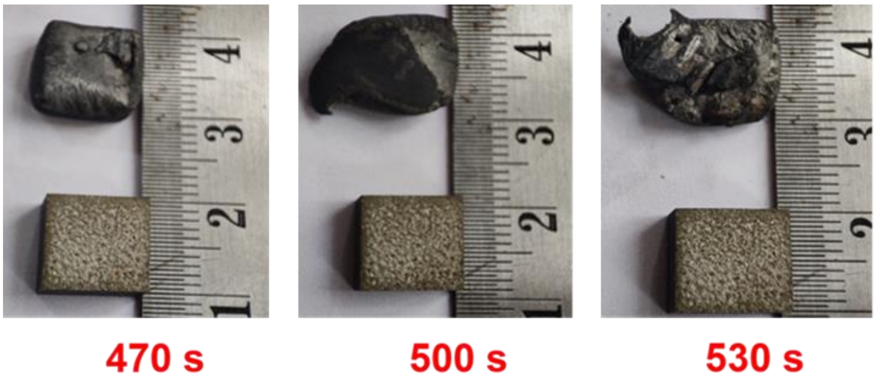



Figure 13. Microwave melting of Hastelloy C-276 with time.

## Conclusions

The simulation of Microwave processing in a domestic oven was successfully performed and the following conclusions were drawn:

Melting of Hastelloy C-276 using microwave casting in a multimode microwave applicator was investigated experimentally and its numerical simulation was also performed using COMSOL Multiphysics. It was found that the temperature profile obtained from the experiment was in good agreement with the results obtained from the simulation as the error was within 5%.

The power input and setup location has significant effects on melting time, heating rate, energy requirement, etc. during the microwave casting process. Electric field distribution influences the temperature distribution inside the charge. At higher power input and favorable setup locations, heating rates are higher which results in uniform heating of the charge and also leads to reduction in melting time and energy.

Melting of the Hastelloy C-276 workpiece took place in 450 seconds in simulation whereas melting took place at 470 seconds while experimenting.

When power input increases, melting time decreases. To get the lowest melting time, x4 is the suitable location and x2 is the least suitable. Maximum Enorm is concentrated for x1 setup location and is least for x4 location. It is observed that the electric field distribution ranges from $4.17 \times 10^4$ (V/m) to $7.22\times10^4$ (V/m) when power varies from 1000W to 3000W.

## Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

## Acknowledgements or Notes

* This article was presented as an oral presentation at the International Conference on Technology ( www.icontechno.net ) held in Antalya/Turkey on November 16-19, 2023.

## References

Fujiwara, H., Toyota, S., Anggraini, L., Ameyama, K., & Agrawal, D. (2010). Microwave heating behavior of fine stainless steel powders in. *International Microwave Power Institute's 44th Annual Symposium*, *44,* 79–82.

Gouthama, T. R., Harisha, G., Manjunatha, Y. R., Kumara, S. M. M., Srinath, S., & Lingappa, M. S.(2016). Melting of tin using muffle furnace and microwave energy and its characterization. *IOP Conf Ser Mater Sci Eng*, *149*(1).

Gupta, D., & Sharma, A. K. (2014). Microwave cladding: A new approach in surface engineering. *Journal of Manuf Process*, *16*(2), 176–182.

Gupta, M., & Eugene, W. W. L. (2011). *Microwaves—theory. Microwaves and Metals.* John Wiley & Sons (Asia) Pte Ltd.: Singapore, 25-41.

Lingappa, S. M., Srinath, M. S., & Amarendra, H. J. (2018). Melting of bulk non-ferrous metallic materials by microwave hybrid heating (MHH) and conventional heating: A comparative study on energy consumption. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, *40*(1), 1–11.

Matweb. (2022). Haynes Hastelloy® C-276 alloy, solution heat treated flat products," matweb material property data. Retrieved from https://www.matweb.com

Mishra, R. R., & Sharma, A. K. (2016). A review of research trends in microwave processing of metal-based materials and opportunities in microwave metal casting. *Critical Reviews in Solid State and Materials Sciences*, *41*(3), 217–255.

Mishra, R. R., & Sharma, A. K. (2016). Experimental investigation on in-situ microwave casting of copper. *IOP Conf Ser Mater Sci Eng*, *346*(1).

Mishra, R. R., & Sharma, A. K. (2016). Microwave-material interaction phenomena: Heating mechanisms, challenges and opportunities in material processing. *Compos Part A Appl Sci Manuf*, *81*, 78–97.

Mishra, R. R., & Sharma, A. K. (2016). On mechanism of in-situ microwave casting of aluminium alloy 7039 and cast microstructure. *Materials & Design, 112*, 97–106.

Mishra, R. R., & Sharma, A. K. (2017). On melting characteristics of bulk Al-7039 alloy during in-situ microwave casting *Appl Therm Eng*, *111,* 660–675.

Mishra, R. R., & Sharma, A. K. (2018). Effect of solidification environment on microstructure and indentation hardness of Al–Zn–Mg alloy casts developed using microwave heating. *International Journal of Metalcasting*, *12*(2), 370–382.

Reddy, K. V. B., Venkatesh, G., & Mishra, R. R. (2023).Microwave joining of SS-316 plates: A multi-physics simulation study. *Journal of Manuf Process*, *98,* 29–41.

Tamang, S., & Aravindan, S. (2022). Joining of dissimilar metals by microwave hybrid heating: 3D numerical simulation and experiment. *International Journal of Thermal Sciences*, *172.*

Tamang, S., & Aravindan, S.(2019). 3D numerical modelling of microwave heating of SiC susceptor," *Appl Therm Eng*, *162*, 114250

## Author Information

**Kadapa Vijaya Bhaskar Reddy**
National Institute of Technology
Warangal, Telangana, 506004
India.
Contact e- mail:*bhaskarsave.61@gmail.com*

**K.V. Hari Shankar**
National Institute of Technology
Warangal, Telangana, 506004
India.

**Venkatesh Gudipadu**
National Institute of Technology
Warangal, Telangana, 506004
India.

**To cite this article:**

Reddy, K. V. B., Shankar, K.V. H. & Gudipadu, V (2023). Numerical simulation on microwave melting of Hastelloy C-276. *The Eurasia Proceedings of Science, Technology, Engineering & Mathematics (EPSTEM), 24,* 287-300