Thermal Analysis of Microwave Melting of Hastelloy C-276

A dissertation report submitted in partial fulfillment
of the requirements in 4th year 2nd semester for the degree in

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in

Mechanical Engineering

by

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ABSTRACT

Melting involves interaction of the source energy with the target metal (or, the alloy/composite) and the process has significant influence on processing economy and environment. The conventional techniques have large processing time and costs and pose environmental hazards. Due to these limitations, there is a need for a novel technique such as Microwave Melting which uses microwaves to melt the materials. Use of microwave energy for melting of metals or alloys is not common owing to insufficient data in the field. field. This paper reports on microwave melting of Hastelloy using microwave radiations at 2.45 GHz and 900 W. A 3-D model of the process was generated using COMSOL multiphysics software tool. Simulations were carried out to study the thermal history of the metal during melting. The simulation results were obtained for varying power and location of the mold assembly.The possible outcomes were evaluated in terms of melting time, average heating rate and energy required to melt the charge.alloy. The simulation results showed that the melting of Hastelloy is more rapid and uniform at higher power levels and at specific locations of the mold assembly. It is observed that the melting of Hastelloy took 470 seconds while simulation results indicate a processing time of 450 seconds.

Keywords: Hastelloy , Melting , Simulation , Microwave Melting

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Chapter 1

INTRODUCTION

Microwaves are a form of "electromagnetic" radiation; that is, they are waves of electrical and magnetic energy moving together through space. Radiation is ability for transmission of energy from one entity to another with the help of force fields of electromagnetic waves, radiation does not require any medium for transmission of energy and it will radiate across a perfect vacuum.When an electric or magnetic charge in a medium shifts in space, the related field shifts as well. The oscillating wave produced by these changes in electric and magnetic fields is known as an electromagnetic wave. Frequency, velocity, and electric field intensity are all characteristics of electromagnetic waves.

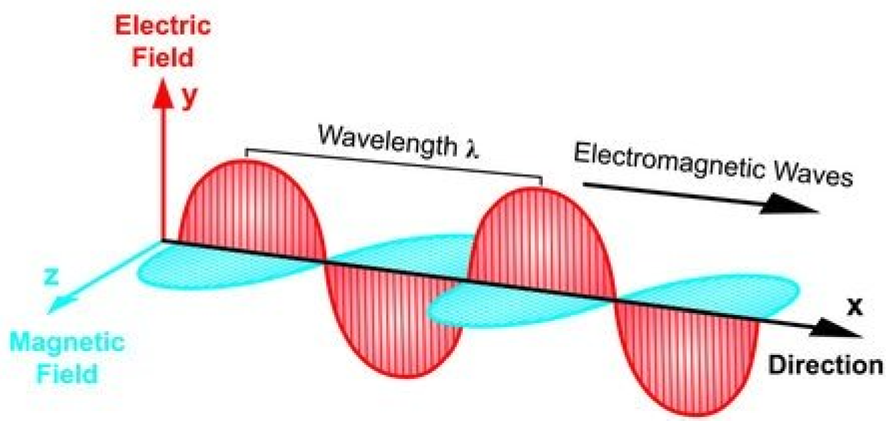


Figure 1.1: The electric field is in the vertical plane and the magnetic field is horizontal which are perpendicular to each other.

1.1 Electromagnetic Spectrum

Microwaves are defined as electromagnetic radiations with a frequency ranging between 300 MHz to 300 GHz. Microwave radiation is commonly referred to as microwaves. They fall between infrared radiation and radio waves in the electromagnetic spectrum. Microwaves are used in heating devices, communication devices, and radar. They are also used in spacecraft communication, and much of the world's data, TV, and telephone communications are transmitted long distances by microwaves between ground stations and communications satellites.

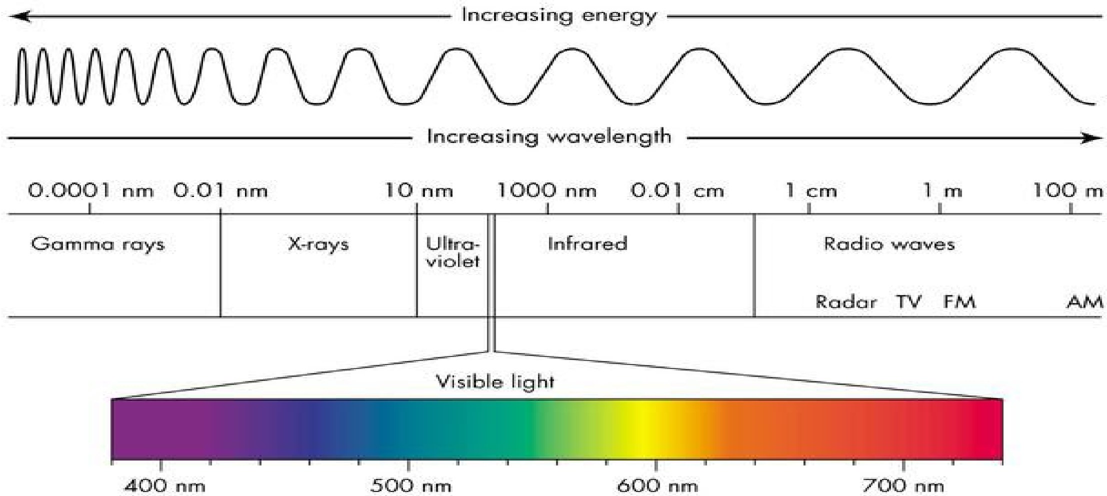


Figure 1.2: Electromagnetic spectrum with respective frequencies and wavelengths.

1.2 Microwave energy

Microwaves are used to detect speeding cars and to send telephone and television communications. Industry uses microwaves to dry and cure plywood, to cure rubber and resins, to raise bread and doughnuts, and to cook potato chips. But the most common consumer use of microwave energy is in microwave ovens. Microwaves have three characteristics that allow them to be used in cooking: they are reflected by metal; they pass through glass, paper, plastic, and similar materials; and they are absorbed by foods.

- Metal surfaces reflect microwaves. Microwaves with a certain wavelength pass through the earth's atmosphere and can be useful in transmitting information to and from satellites in orbit. Hence, the satellite dishes are made of metal as they reflect microwaves well.
- Microwaves of certain frequencies are absorbed by water. This property of microwaves is useful in cooking. Water in the food absorbs microwaves, which causes the water to heat up, therefore cooking the food.
- Microwave transmission is affected by wave effects such as refraction, reflection, interference, and diffraction.

- Microwaves can pass through glass and plastic. This is the reason why we use a plastic or glass container in a microwave oven and not metal containers, as metal reflects microwaves.

Microwave interactions with materials can be divided into the following categories:

- Opaque materials are usually conducting materials with free electrons, such as metals, that reflect electromagnetic waves and do not enable them to pass through them.
- Transparent materials are materials having low dielectric loss or insulating properties, such as glass, ceramics, and air, that reflect and absorb electromagnetic waves in a minimal way, allowing microwaves to flow through with little attenuation.
- Absorbing materials are those that have a wide variety of characteristics, from conductors to insulators. They absorb electromagnetic energy and convert it to heat, and are commonly referred to as lossy dielectrics or high dielectric loss materials .
- Magnetic materials: materials such as ferrites that heat up when they interact with the electromagnetic wave's magnetic component.

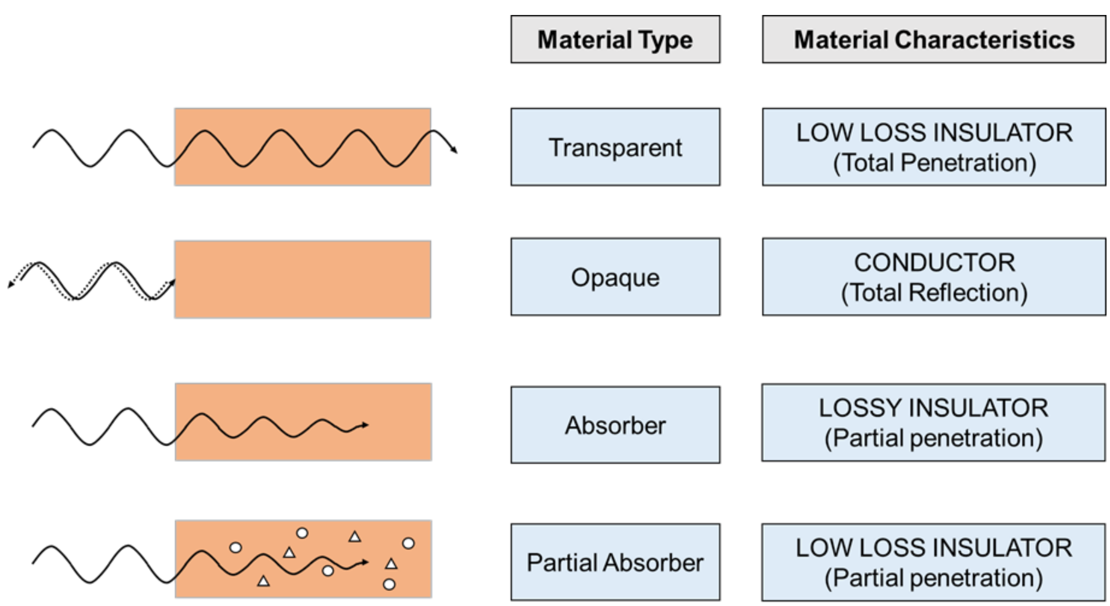


Figure 1.3: Material Absorption Characteristics

1.3 Microwave Processing

Microwave processing is a technique that uses electromagnetic waves in the microwave frequency range to process materials. This technology is widely used in various industries, including food processing, chemical synthesis, and materials science. In materials science, microwave processing can be used to sinter or melt materials, which can lead to improved properties such as increased density or reduced porosity. This technique can also be used for the rapid synthesis of new materials.

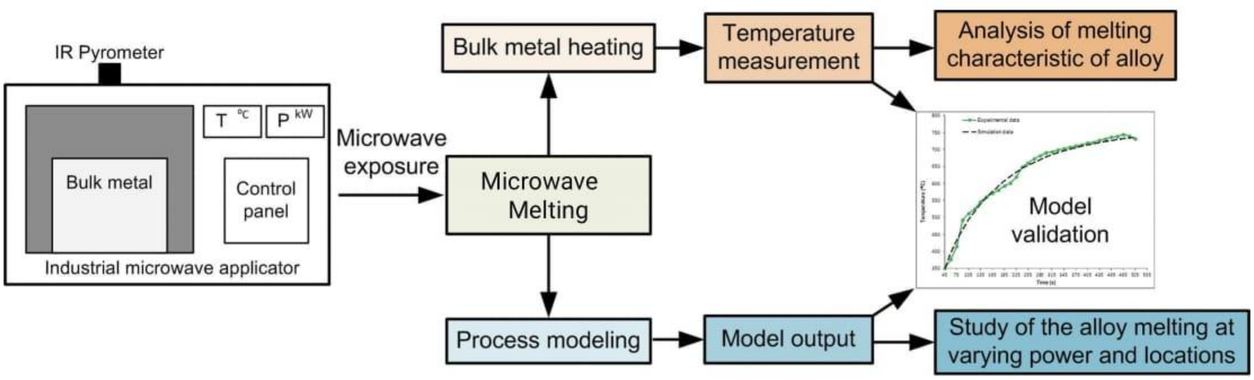


Figure 1.4: Graphical representation of Microwave Melting

Microwave processing has several advantages over traditional processing methods. It is a fast and efficient method that can reduce processing time and energy consumption. However, microwave processing also has some limitations, such as the need for specialized equipment and the potential for uneven heating furnaces.Initially, the susceptor couples with microwave radiations and heats up the bulk alloy which reflects microwaves at room temperature. The bulk alloy absorbs microwave energy and then gets heated.

1.4 Hastelloy

- Hastelloy C-276 is a nickel molybdenum chromium superalloy with additions of iron and tungsten (composition Ni-57% Mo-16% Cr-15.5% Fe-5% W-4%) with extreme resistance to corrosion at high temperatures.

- Hastelloy C-276 has excellent corrosion resistance in both oxidizing and reducing environments.Hastelloy also offers good fabrication characteristics and thermal stability.Hastelloy is used to manufacture high-temperature gas path components such as turbine combustors , liners and pressure vessels in chemical industries.

1.5 Conventional and Microwave Heating

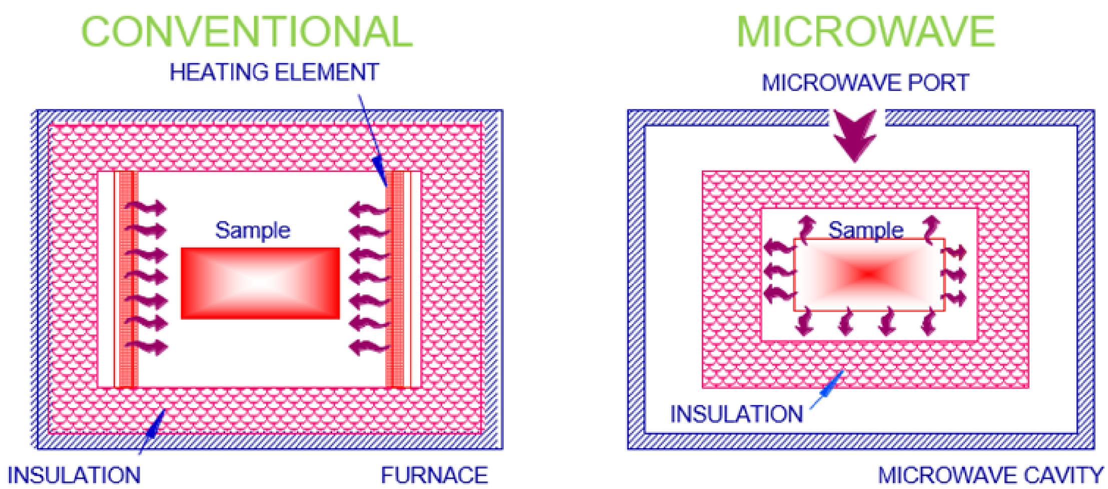


Figure 1.5: Conventional and Microwave Heating

1.5.1 Conventional Heating:

Conventional heating is a process of transferring heat from an external heat source, such as a flame or an electric heating element, to a material through conduction or convection. This is the most common method of heating and is used in many industrial processes and household appliances such as ovens and stovetops. The heating rate in conventional heating is typically slower than other methods, and there can be a temperature gradient within the material which may lead to thermal residual stresses and inconsistencies in the properties of the material.

1.5.2 Microwave Heating:

Microwave direct heating is a process of generating heat within a material by converting microwave energy into heat. In this process, microwaves are directed towards the material, and as the material absorbs the microwaves, the energy is converted into heat.

This type of heating allows for faster and more efficient heating compared to conventional heating methods because the heat is generated directly within the material.Microwave direct heating is used in various industrial applications, such as food processing, chemical synthesis, and material processing. One of the advantages of microwave direct heating is that it can be used to selectively heat certain materials or parts of a material, which can lead to better control over the heating process and higher quality end products. However, the use of microwave direct heating requires careful consideration of factors such as the material's dielectric properties and the design of the microwave heating equipment to ensure optimal efficiency and safety.

1.6 Governing Laws and Equations:

Depending upon the microwave interaction with the material, the microwave energy may get converted to heat energy. This interaction depends on the material properties such as dielectric and magnetic properties because these properties determine the ability of the material to effectively couple with the microwaves.

1.6.1 Permittivity and Permeability:

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. 8.1.

$$\varepsilon^{'} = \varepsilon_{0}\varepsilon'_{r} \tag{8.1}$$

Where, $\varepsilon_0 = 8.854\times10^{-12}$ F/m is the permittivity of free space and ε'_r is the relative permittivity.

Complex permittivity of a material accounts for the absorption and storage of the electrical energy inside the material. It is given by Eq. 8.2.

$$\varepsilon^{*} = \varepsilon^{'} - j\varepsilon'' \tag{8.2}$$

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.

1.6.2 Loss Tangent:

Loss tangent tan δ is the property of the material which represents the extent of conversion of microwave energy into heat energy. It is given by the ratio of dielectric loss factor and permittivity as shown in Eq. 8.3.

$$tan\,\delta = \frac{\varepsilon''}{\varepsilon'} = \frac{Energy\ lost\ per\ cycle}{Energy\ stored\ per\ cycle} \quad (8.3)$$

Where δ is the angle between the resultant permittivity and its real part in the vector diagram as shown in Fig. 1.6.

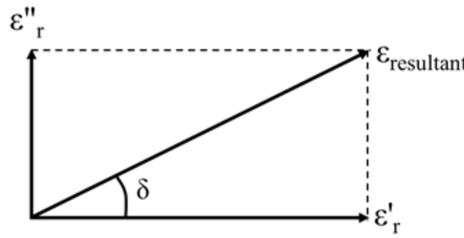


Figure 1.6: Loss Tangent

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. 8.4.

$$\mu' = \mu_0 \mu'_r \quad (8.4)$$

Where μ_0 =8.854×10^{-12} F/m is the permeability of free space and μ'_r = relative permeability.

The complex permeability, μ*, is given by Eq. 8.5.

$$\mu^* = \mu' - j\mu'' \quad (8.5)$$

where μ" = magnetic loss factor. The magnetic loss factor accounts for relaxation and resonance occurring due to the magnetic field.

1.6.3 Maxwell's Equations:

The electric field causes polarization of charges within the material. But when the electric field alternates rapidly, the charges are not able to change their polarization as fast as the electric field. This causes agitation and then heating occurs within the material. The heating is influenced by the power input and duration of the microwave radiation.

After Faraday discovered electromagnetic induction, Maxwell predicted the existence of electromagnetic waves and gave his electromagnetic theory which consisted of 20 equations. These equations were later reduced to only 4 equations by Heaviside and they are famously known as Maxwell's equations, as given in Eq. 8.6. (a)-(d)

Faraday's Law: $$\nabla \times E = -\frac{\partial B}{\partial t} \qquad 8.6(a)$$

Ampere's Law: $$\nabla \times H = J + \frac{\partial D}{\partial t} \qquad 8.6(b)$$

Gauss's Electric Law: $$\nabla . D = q \qquad 8.6(c)$$

Gauss's Magnetic Law: $$\nabla . B = 0 \qquad 8.6(d)$$

where E = electric field intensity (V/m), H = magnetic field intensity (A/m), D = ε(ω)E(t) is the electric displacement (N/V.m), B = μ(ω)H(t) is the magnetic induction (T), J = σ(ω)E(t) is the flux of the electric current (A/m^2), q is the electric charge density (C/m^3), ω is the circular frequency (radians /s), σ is the electrical conductivity (S/m), ε is the permittivity (F/m), and μ is the permeability (H/m). Faraday's law of electromagnetic induction describes the phenomenon of electromagnetic induction that involves interaction of a magnetic field with an electric circuit to generate an electromotive force (EMF). Ampere's law states that the intensity of the magnetic field is proportional to the electric current which produces that magnetic field. Gauss's electric law predicts that the net electric flux emanating from a closed region is equal to the total charge trapped within the region. Gauss's magnetic law indicates that the net magnetic flux coming out of a closed region is zero.

Maxwell's equations can be used to determine the distributions of the electric and magnetic field inside the microwave cavity, which could assist in finding the most suitable location of the experimental setup so that the processing time is reduced. Generally, if the setup is placed at locations where the field intensity is maximum, the material experiences enhanced coupling with the microwaves, and this results in faster processing.

Due to material-field interactions, the microwave energy gets absorbed by the material and the power gets dissipated as heat. Assuming that the power absorption is uniform throughout the volume, the power absorbed in a unit volume of the sample due to the electric field is given by Eq. 8.7.

$$P = 2\pi f \varepsilon_0 \varepsilon'' |E|^2 = 2\pi f \varepsilon_0 \varepsilon' \tan tan\, \delta\, |E|^2 \tag{8.7}$$

Where, |**E**| is the absolute value of the electric field intensity. The absorbed power has a linear variation with the loss tangent, permittivity, and frequency, and it varies with the square of the electric field.

Similarly, the power absorbed in a unit volume of the sample due to the magnetic field is given by Eq. 8.8.

$$P = 2\pi f \mu_0 \mu'' |H|^2 = 2\pi f \mu_0 \mu' \tan tan\, \delta_\mu\, |H|^2 \tag{8.8}$$

Where, |**H**| is the absolute value of the magnetic field intensity. The absorbed power has a linear variation with the loss tangent, permeability, and frequency, and it varies with the square of the magnetic field.

Therefore, the total power absorbed per unit volume ($W.m^{-1}$) of the sample is given by Eq. 8.9.

$$P = 2\pi f \varepsilon_0 \varepsilon'' E_{rms}^2 + 2\pi f \mu_0 \mu'' H_{rms}^2 \tag{8.9}$$

where E_{rms} is the root-mean-squared value of the electric field ($V.m^{-1}$) and H_{rms} is the root-mean-squared value of the magnetic field ($A.m^{-1}$). For diamagnetic materials, the value of permeability is very less, and thus the effect of the magnetic field on power absorption can be ignored. Therefore, Eq. 8.9 gets reduced to Eq. 8.10.

$$P = 2\pi f \varepsilon_0 \varepsilon'' E_{rms}^2 \tag{8.10}$$

As the material gets heated and its temperature rises, the material properties get altered and therefore influence the power absorbed.

The extent of penetration of microwaves inside the material from its surface has a significant effect on the power absorbed by the material. This depth of penetration from the surface is called Penetration Depth or Skin Depth depending on the type of the material. The penetration of microwaves is different for different materials. While non-metals allow significant penetration of microwaves, for bulk metals this penetration is negligible at room temperature. Hence, the term 'Penetration Depth' is used for non-metals, and 'Skin Depth' is used for metals. Penetration depth for non-metals is given in Eq. 8.11.

$$D_P = \frac{1}{\omega\sqrt{\left[0.5\mu_0\mu'\varepsilon_0\varepsilon'\left\{\sqrt{\left(1+\left(\frac{\varepsilon_{eff}''}{\varepsilon'}\right)^2\right)}-1\right\}\right]}} \tag{8.11}$$

Skin depth for metals is given by Eq. 8.12.

$$D_S = \frac{1}{\sqrt{\pi f \mu \sigma}} = 0.029\left(\rho\lambda_0\right)^{0.5} \tag{8.12}$$

where σ is the specific electrical conductance ($S.m^{-1}$), ρ is the specific electrical resistance ($\Omega.m$), and λ_0 (m) is the wavelength of the incident microwave. Therefore, it is clear that the absorption of power depends on electromagnetic variables and sample thickness.

1.6.4 Lambert's law:

It is difficult to determine the microwave power dissipation using Maxwell's equations unless the distribution of the electric field inside the microwave cavity is known. An alternate method to determine the power dissipation in the material during microwave processing, without using the electric field distribution, is given by Lambert's law. So, it could be useful in quickly obtaining the temperature distribution since the cumbersome procedure of electric field calculation is avoided. Lambert's law states that the power incident on the material is perpendicular to the surface of the sample and the power is dissipated exponentially as it progresses through the material. The power dissipated at a depth x from the surface of the sample is given by Eq. 8.13.

$$P(x) = P_0 e^{-2\beta x} \tag{8.13}$$

where, P_0 = power incident on the surface of the sample (W), β = propagation constant (m^{-1}). The propagation constant depends on the loss tangent , radiation speed, and the frequency of the radiation.

For simplified power calculations, certain assumptions are associated with Lambert's law. These are-

1) The sample extends to infinity in one direction i.e., it is semi-infinite.
2) The penetration of microwaves occurs from one direction only.
3) The standing wave effect is negligible.

Hence, the power calculation using Lambert's law, although faster, is not as accurate as the power calculation using Maxwell's equation. Still, Lambert's law is quite relevant because it provides a means for faster and more accurate prediction of temperature distribution. The obtained results are quite consistent with the experimental results. Whereas using Maxwell's equations, the first electric field needs to be determined which involves dielectric properties that are very sensitive. So, even a slight error in the values of the dielectric properties causes a huge variation in the predicted temperature distribution. Hence, Maxwell's equation fails to maintain consistency with the experimental results.

Chapter 2

REVIEW OF LITERATURE

2.1 Literature Review

Radha Raman Mishra and Apurbba Kumar Sharma(2016): Development of in-situ microwave cast of AA 7039 aluminum alloy using microwave irradiation at 2.45 GHz and 1400 W.The results reveal a dense cast. The oxide layer formed during microwave heating acts as a microwave susceptor and assists further in the heating process. It was concluded that it may be then possible to develop a material with desired level of hardness by controlling the microwave irradiation time during its processing.

Radha Raman Mishra and Apurbba Kumar Sharma(2016):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-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.

Radha Raman Mishra and Apurbba Kumar Sharma(2017): Casting of copper developed inside applicator cavity at 2.45 GHz using 1400 W using MHH.Improvement in mechanical properties of the microwave cast was observed.The interaction of microwave with the charge during exposure and the role of oxide layer during melting the copper was studied. Improvement in mechanical properties of the microwave cast was observed.The homogeneous and dense structure of the in-situ cast reveals potential of the process. However, The observed porosity of the in-situ casts (2-5%) could be a concern.

The average micro indentation hardness of the casts was observed to be 93±20 HV.

Radha Raman Mishra and Apurbba Kumar Sharma(2017): The Al-Zn-Mg alloy (Al 7039) was cast in situ using microwave energy. Microwave hybrid heating of the alloy charge was carried out in presence of the SiC and CC susceptors. It was revealed that properties of the susceptor material significantly influence the heating of the charge. Effect of the mold temperatures on the grain size of alloy casts is significant.This effect is because of the interaction of microwaves with the mold materials during different exposure times and subsequently, different temperatures attained by the mold to get preheated, its capacity to retain heat during exposure and post-exposure.

H. Fujiwara1, *S. Toyota2, L. Anggraini(2019): The study by Fujiwara et al.investigated the microwave heating behavior of fine stainless steel powders in an H-field at 2.45 GHz. 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.

Shashank M. Lingappa, M. S. Srinath, H. J. Amarendra(2017): The study compared the energy consumption of melting bulk non-ferrous metallic materials using microwave hybrid heating (MHH) and conventional heating. 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. The authors attributed the lower energy consumption during MHH 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.

Shashank M. Lingappa, M. S. Srinath, H. J. Amarendra(2017): The authors investigated and compared the microstructure of bulk brass samples that were melted using both conventional and microwave processing methods. The authors used optical microscopy and scanning electron microscopy to analyze the microstructure and found that the samples melted using microwave processing had a finer grain structure and more uniform distribution of intermetallics than the samples melted using conventional processing. The authors concluded that microwave processing could be a promising method for producing brass with improved microstructural characteristics.

T R Gouthama1, G Harisha2, Y R Manjunatha 3(2016): The study conducted by T.R. Gouthama et al. compared the melting behavior of tin using a muffle furnace and microwave energy. The researchers analyzed the melting time, energy consumption, and temperature distribution of the two methods. They found that microwave energy was more efficient and had a shorter melting time than the muffle furnace method. The researchers also characterized the microstructure and mechanical properties of the melted tin samples. They observed that the microwave-melted tin had a finer grain size and higher hardness compared to the conventionally melted tin. Overall, the study suggested that microwave energy can be a promising method for melting tin and potentially other metals with improved energy efficiency and material properties.

Shashank M. Lingappa, M. S. Srinath, H. J. Amarendra(2016): In this study, the melting of a 60Sn40Pb alloy was investigated using microwave energy, and its characterization was performed. The experiment was conducted by exposing the alloy sample to microwave energy, and the temperature variation was monitored using an optical pyrometer. The results were compared with conventional heating methods. It was found that the melting point of the alloy was decreased under microwave energy, and the time required for melting was also reduced significantly. The microstructural analysis of the melted sample showed that the grain size was reduced, and the sample had better mechanical properties compared to the conventionally melted sample. The study concluded that microwave energy could be a promising alternative to conventional melting techniques for alloys, resulting in a reduction of energy consumption and processing time, along with improved material properties.

2.2 Literature Gap

- Very little work has been done on the analysis of thermal properties of alloys using Microwave processing.
- Hastelloy is used in different applications and very little work has been done on analysis of melting characteristics of this alloy.
- Till now, no work has been reported involving the simulation analysis of Microwave melting of Hastelloy C-276.

2.3 Objectives

- To perform the modeling and simulation of Microwave melting of Hastelloy C-276.
    - To study the effect of power and setup locations on Electric field distribution.
    - To study the effect of power on Melting time , Heating rate and Energy required.
    - To obtain the Temperature Distribution.
    - To determine the best setup location for minimum Melting time.
- To find out the melting time of Hastelloy C-276 and compare the experimental results with the simulation results.

Chapter 3
METHODOLOGY

3.1 Geometry

The microwave joining model was developed similarly to the experimental setup using the COMSOL Multiphysics 5.5a software package as shown in Fig. 3.1. The parameters used for modeling the geometry are listed in Table 3-A. The time taken for computation was approximately 180 minutes. The material properties used in the simulation are listed in Table 3-B.The COMSOL Multiphysics software tool to analyze the thermal characteristics of hastelloy.The model uses copper for the walls of the oven and the waveguide. Although resistive metals losses are expected to be small, the impedance boundary condition on these walls ensures that they get accounted for. The cascade is made of aluminum as it is a good electrical conductor.

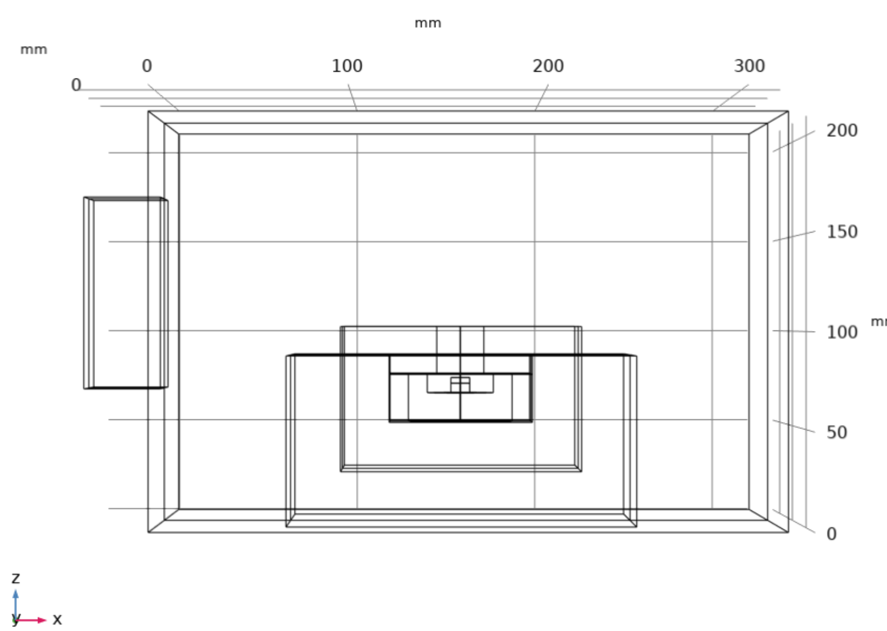


Figure 3.1: The 3D geometry model in comsol

Table 3.A :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 3-B: Material properties

Property	Unit	Air	Copper	Alumina	Graphite	Hastelloy C276
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

3.2 Boundary Conditions

Some selected boundary conditions were implemented through heat transfer in solids and electromagnetic wave (frequency domain) modules on the developed model in order to approach the real experimental conditions. The details of the boundary conditions are as follows:

Port boundary condition: It was applied on the entrance to the rectangular waveguide as shown in Fig. 3.2(a) and transverse electric (TE10) mode was considered with 2.45 GHz frequency using eq. 8.14.

$$\text{Cut-off frequency} \quad (f_c)_{mn} = \frac{C}{2}\sqrt{\frac{m^2}{a^2} - \frac{n^2}{b^2}} \qquad (8.14)$$

Impedance boundary condition: it is applied on the walls of the microwave cavity and the waveguide as shown in Fig.8.13b to account for minute losses (skin effect) due to skin depth using Eq.8.15

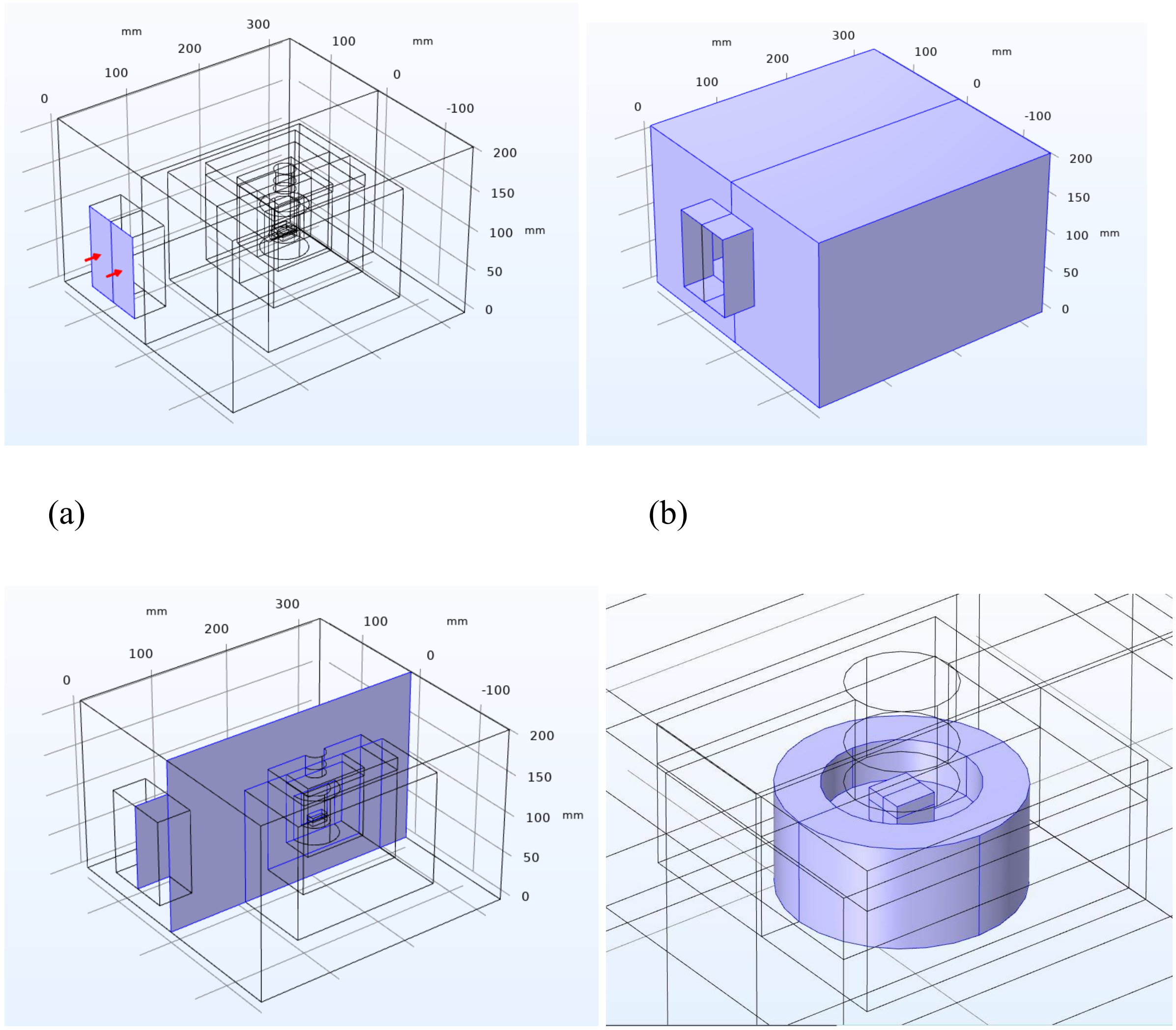
$$\sqrt{\frac{\mu_r\mu_0}{\varepsilon_r\varepsilon_0 - j\frac{\sigma}{\omega}}}\, n\times H + E - (n.E)n = \left(n.E_s\right)n - E_s \qquad (8.15)$$

Heat transfer boundary condition: It is applied to the Hastelloy, cylinder and the susceptor using Eq. 8.16. as shown in Fig. 8.13 (c).

$$\rho C_p \frac{\partial T}{\partial t} = \nabla.(K\Delta T) + Q_{rms} \qquad (8.16)$$

Perfect Magnetic Conductor: It sets the tangential magnetic field to zero as shown in Eq.8.17

$$n \times H = 0 \qquad (8.17)$$



(a) (b)

(c) (d)

Figure 3.2: Boundary conditions used (a) Port boundary condition (b) Impedance boundary condition (c) Perfect magnetic conductor (d) Heat Transfer in Solid

The following assumptions were made to simplify the model:

- Copper has high electrical conductivity, so walls of waveguide and the micro-oven are considered to be copper material.
- The ambient temperature of the system is considered 27 C.
- The walls of the waveguide and the cavity are copper.
- For simulation the phase change is not considered.

3.3 Mesh Quality

The 3-D model was meshed using physics controlled mesh and tetrahedral elements as facilitated by the modeling solver tool. The suitable element size was chosen by examining the element quality for 'fine' (Fig. 3.3(a)), 'finer' (Fig. 3.3(b)), 'extra fine' (Fig. 3.3(c)) and 'extremely fine' (Fig. 3.3(d)) element sizes in terms of average element quality, minimum element quality and maximum growth rate. In element quality 0.0 represents a degenerated element while 1.0 represents a completely symmetric element. The maximum element growth rate, on the other hand, determines the maximum rate at which the element size can grow from a region with small elements to a region with larger elements. The mesh generated (Fig. 3.4(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. The quality evaluation of the mesh is shown in Fig. 3.4(b) which indicates that the mesh quality is generally more than 0.7 in the mold assembly and the charge.

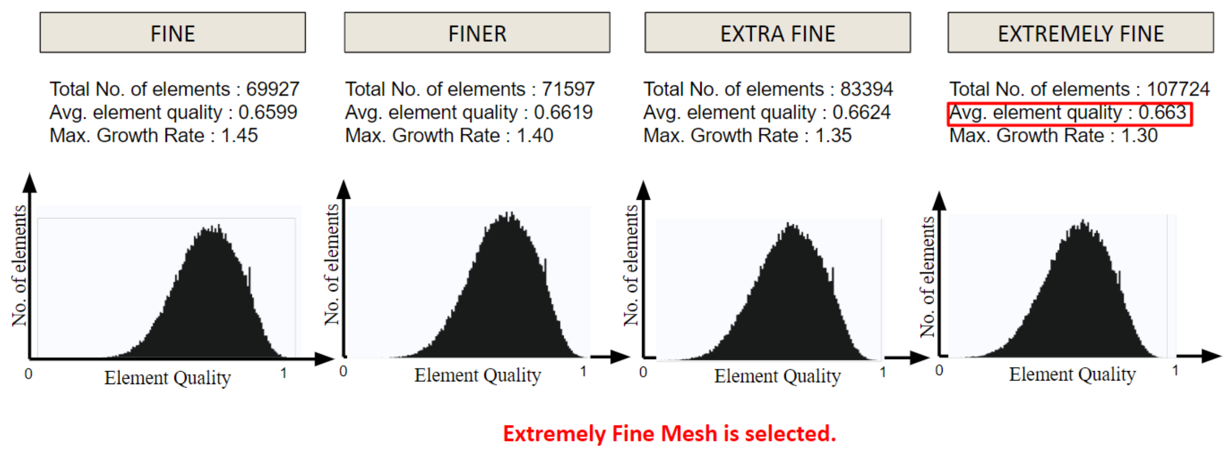


Figure 3.3: Comparison of element quality in (a) fine, (b) finer, (c) extra fine and (c) extremely fine element size.

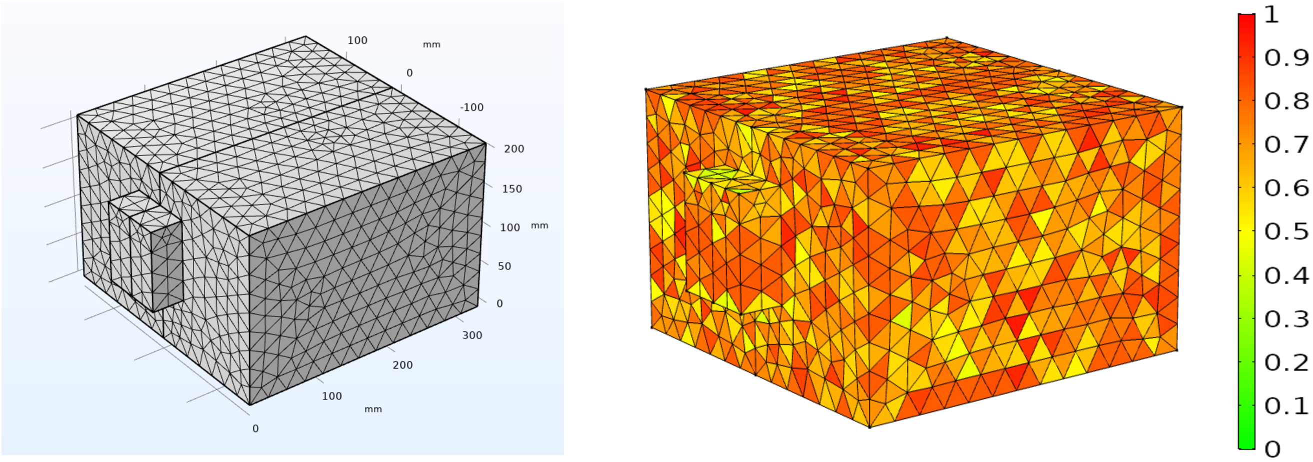


Figure 3.4:(a) Meshed Model (b) Mesh quality statics

Physics-controlled mesh of size "extremely fine" containing 107724 elements was used for the simulation as depicted in Fig. 3.5, the enlarged view of the figure shows that the interlayer has very fine elements compared to the substrate, which is necessary for accurate results.

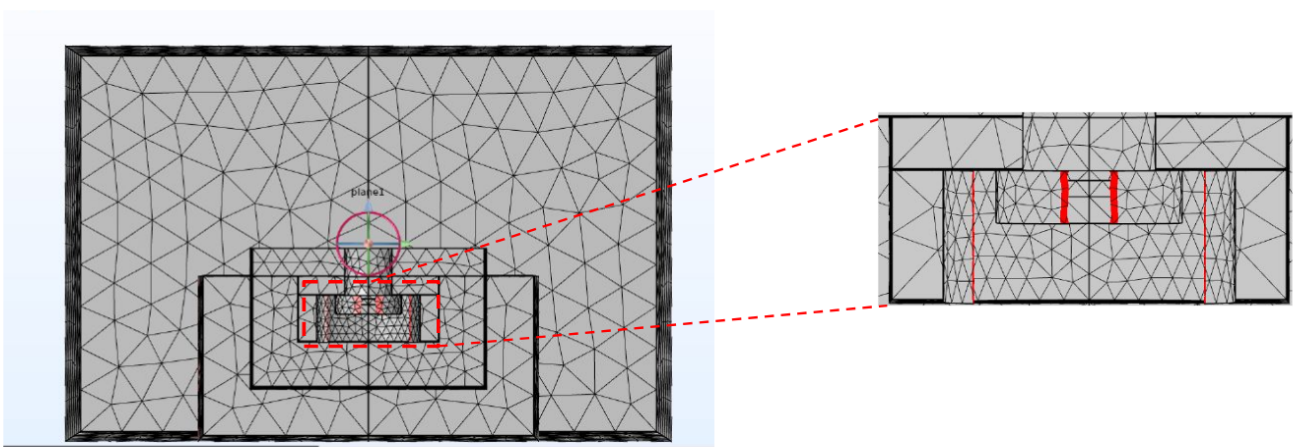


Figure 3.5: Mesh distribution of microwave setup with an enlarged view of the interlayer.

Chapter 4

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

4.1 Effect of Power

The effect of power variation on melting of the charge was studied using the steps of unit power as: 1500 W, 2000 W, 2500 W, 3000 W and 3500 W. The effect of power on electric field distribution inside the microwave cavity and the corresponding temperature distribution in the charge at the time of melting are shown in Fig. 4.1. It is clear from the figure that the patterns of electric field distribution in all the cases are nearly similar; however, the intensity of electric field increases with increasing power. The effect of increasing electric field intensity is reflected in the temperature distribution pattern. It can be seen in the temperature distribution that the distribution pattern and temperature both are changing with increasing power. The increase in power increases the heat generation inside the charge and materials. Increase in power increases the field intensity inside the cavity which makes more energy available for heat generation and heat dissipation inside the metallic charge . While the heating is due to dielectric losses in the Hastelloy, the conduction loss and eddy current loss dominate heating in the metallic charge. However, enhancing the skin depth for coupling the microwave with the bulk alloy needs a material specific elevated temperature. Thus, the irradiation of the assembly ensures first conventional heating of the charge which pushes the bulk metallic charge above the critical temperature more quickly. Further, microwave absorption by the charge increases its temperature rapidly; consequently, the total melting time gets reduced.

The variation in power affects temperature distribution inside the charge significantly. The increase in power increases heat dissipation inside the assembly and the susceptor. Heat transfer from these materials (assembly and susceptor) into the charge quickly pushes it into the microwave absorbing domain. As the charge couples with microwaves, more heat is dissipated inside it at higher power. There will be more non-uniform distribution of temperature at lower power steps owing to transfer of dissipated heat within the charge through conduction. The increase in temperature decreases the thermal conductivity of the metallic charge and conduction of energy inside it due to reduced mean free path of free electrons. However, at higher power, enhanced heat dissipation throughout the charge volume will dominate heat conduction and reduce the rate of heat transfer. Thus, higher power offers a more uniform temperature distribution inside the charge as indicated by the simulated temperature distribution at the time of melting of the charge.There will be decrease in temperature towards the outer surfaces of the charge. This is attributed to the convective and radiative heat losses from the charge into the cavity environment. This is also one of the unique characteristics of microwave heating- also called inside-out heating.

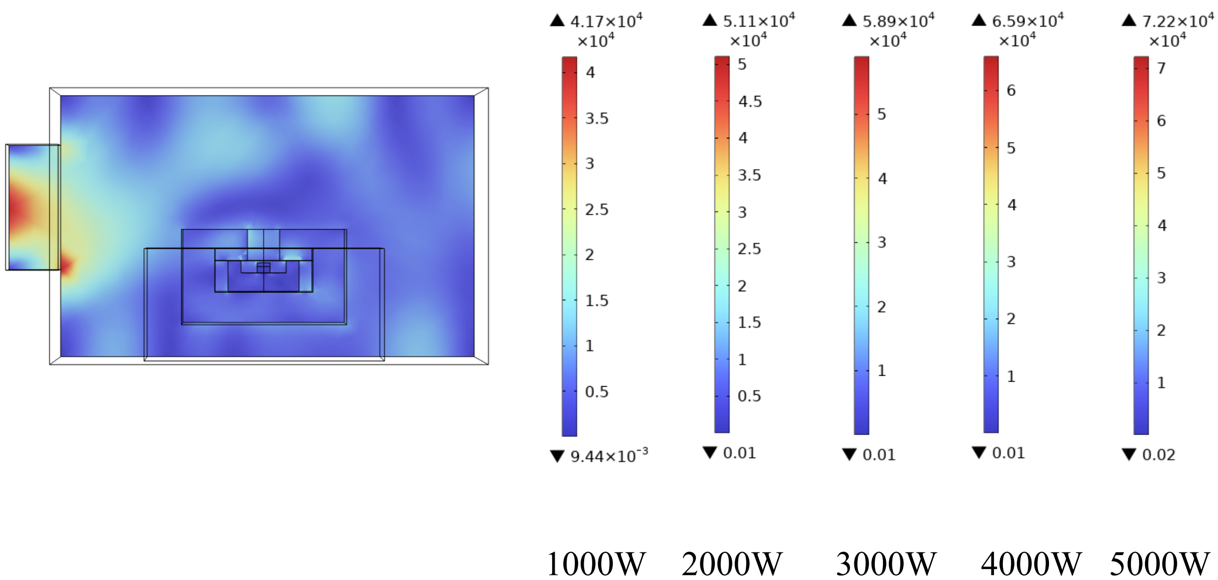


Figure 4.1: Electric field distribution (a) in Enorm direction with different powers.

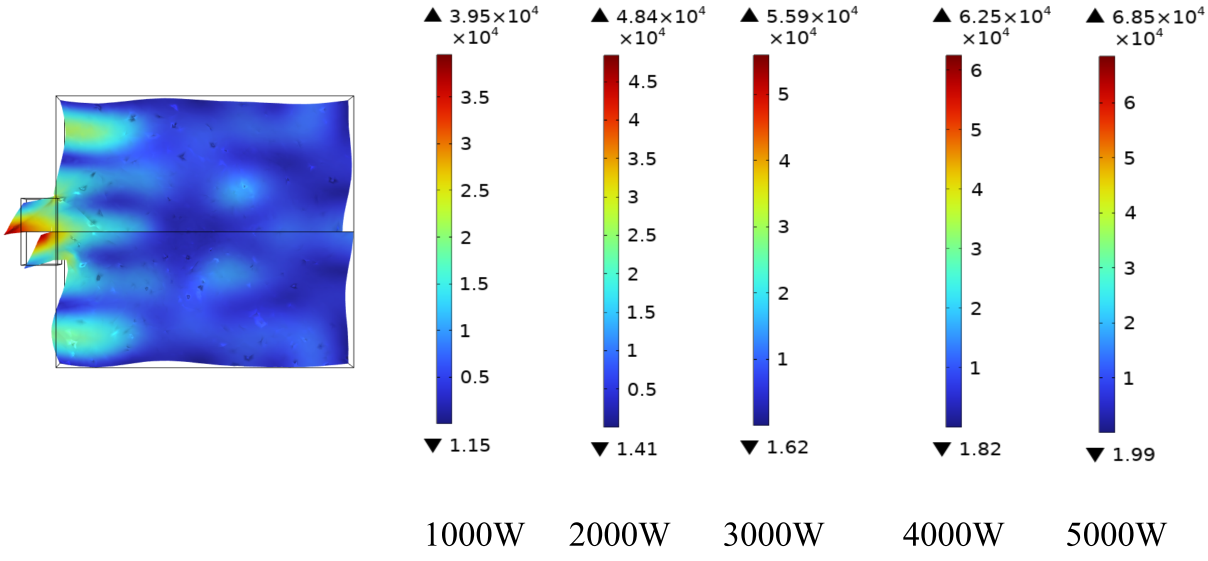


Figure 4.1: (b) in Ez with different powers

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 lesser 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.4.1(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 4.17×10^4 (V/m) to 7.22×10^4 (V/m).

Effect of power on melting time of the charge is shown in Fig.4.2. The increase in input power decreases the time required for melting of the charge. A mathematical correlation of the data yields the following model for power supplied (p) in terms of melting time (t):

$$t= -187.4\ln(p)+ 441.44$$

The model shows a correlation of approximately 99% (R2 = 0.994) and exhibits a hyperbolic trend. Further, it is evident from the equation that the increase in power supplied (Ps) decreases melting time (tm) and follows hyperbolic variation. Thus, the model based on the simulation data is similar to the mathematical model illustrated in the above equation.

Theoretically, increase in power reduces the required melting time of the charge by 65 % (at 3500 W) while compared to processing at 1500 W. This is attributed to faster heat generation owing to higher heat dissipation inside the bulk alloy due to more conduction loss and microwave induced eddy current generation in the bulk alloy at elevated power. Other phenomena inside the charge with increasing power, which are responsible for heating in the metallic materials during microwave irradiation, are likely chemical changes inside the alloy (for example, oxidation) and changes in thermal properties of the alloy with increase in temperature.

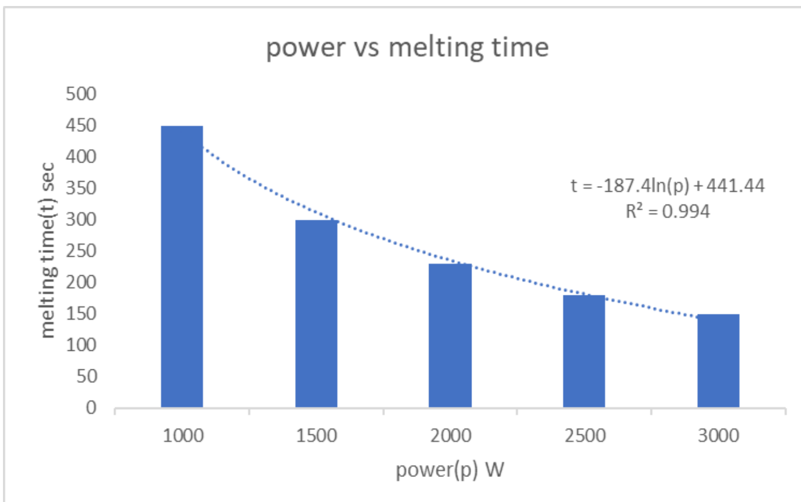


Figure 4.2: Simulation results regarding effect of power on melting time.

Effect of power on the average heating rate of the charge is shown in Fig.4.2. The average heating rate of the charge is higher at 3500 W (200.285%) in comparison to at 1500 W. The increase in power increases the rate of heat generation by enhancing the rate of heat loss inside the charge and reduces the time required to heat the charge up to melting point. Thus, the average heating rate of the charge increases with increasing power inside the microwave applicator. The effect of power on energy required for melting the charge is shown in Fig.4.2. The maximum reduction in energy is attributed to high energy generation and subsequent higher microwave energy dissipation inside the metallic charge due to enhanced E and H fields at elevated power steps. This can be interpreted for this model as the increase in power affects the charge material at atomic level and heat energy is released due to agitation in the orientation, position and movement of dipoles, free electrons by the higher intensity electric field. The increase in power also reduces time required for melting by improving the average heating rate and uniform heating of the charge due to rapid volumetric heating. This results in lower heat loss by conventional modes of heat transfer from the charge surface to the environment as the charge interacts with the environment for a very short duration comparatively at higher power.

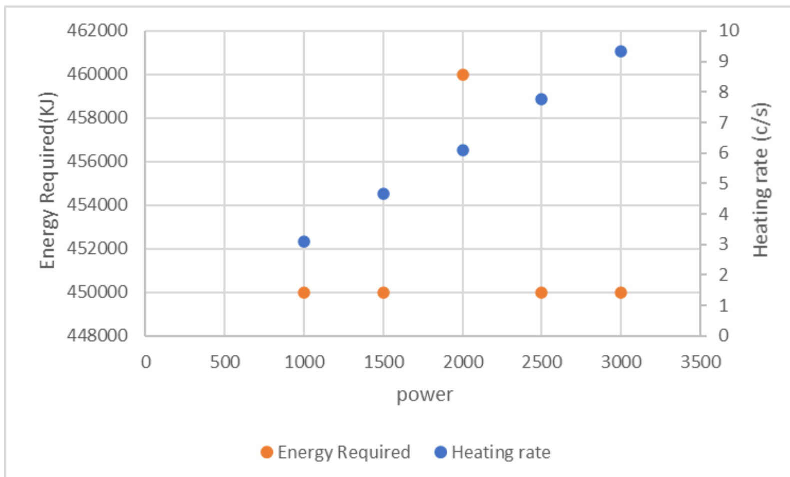
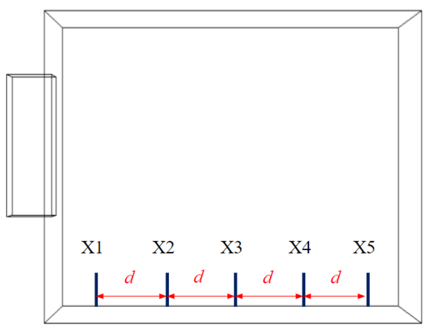


Figure 4.3: Simulation results regarding effect of power on average heating rate and energy required for melting the charge.

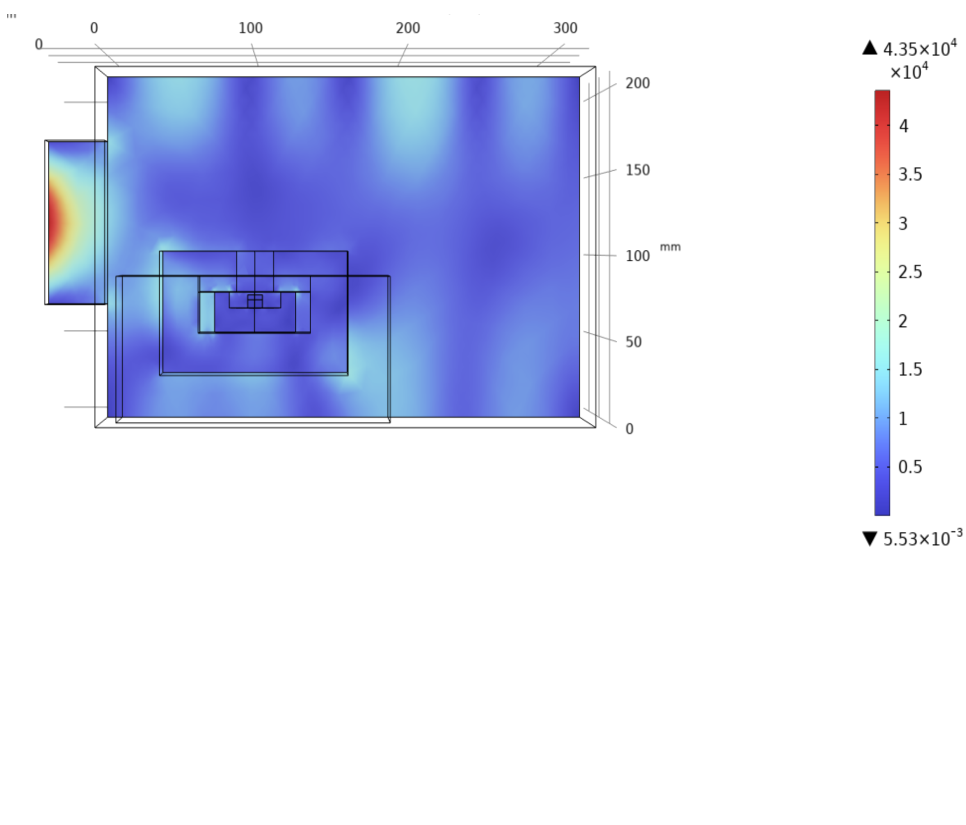
4.2 Effect of Assembly Location

It was reported that field distribution inside the cavity of multi-mode microwave applicators is always non-uniform with a pattern of high-low electric and magnetic field intensities. This pattern reorients itself in the presence of a material in the cavity during processing.Simulation of the process can provide a solution for placing the mold assembly at an optimal location (coordinates) inside the cavity.

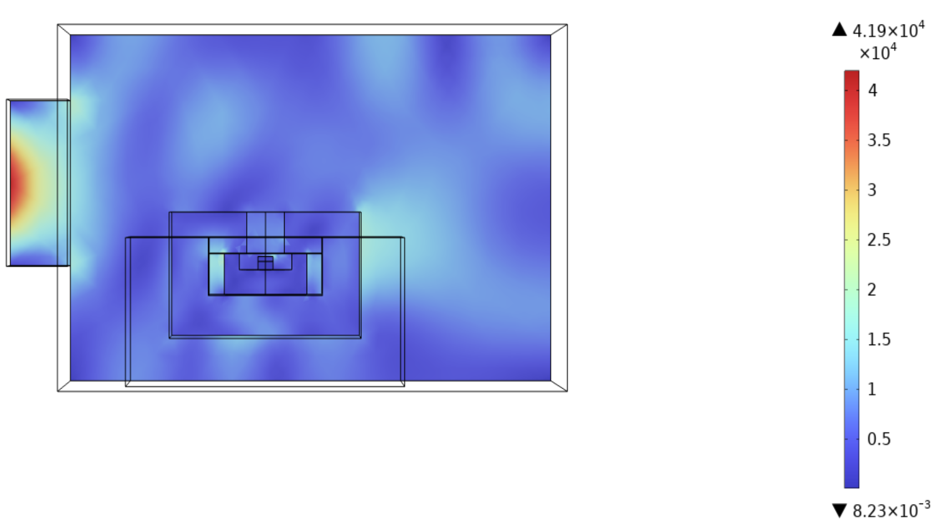
The corresponding effect of mold assembly location (at x1, x2, x3, x4 and x5) on electric field distribution in the cavity and temperature distribution inside the charge is shown in Fig. 4.4. The distribution indicates the pattern and the value of field intensity depending on location. In addition to that, the distance (L) between the source and the location of the load affects the interference pattern and positions of nodes (L=n k, where n is a positive integer) owing to possible disturbance in the absorbed and reflected microwaves. Another observation in the simulated electric field distribution (Fig. 4.4) is the reduction in field intensity near the charge as it is moved in the x-direction. On the other hand, more uniformly, the temperature marginally decreases towards the outer surface of the charge. This is attributed to the convective and radiation heat losses from the charge surface into the cavity environment.



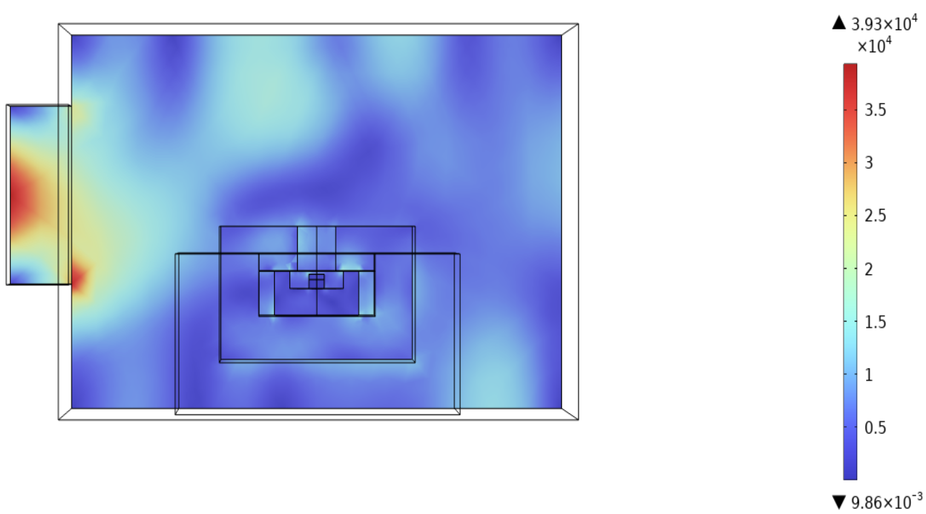
d=30mm



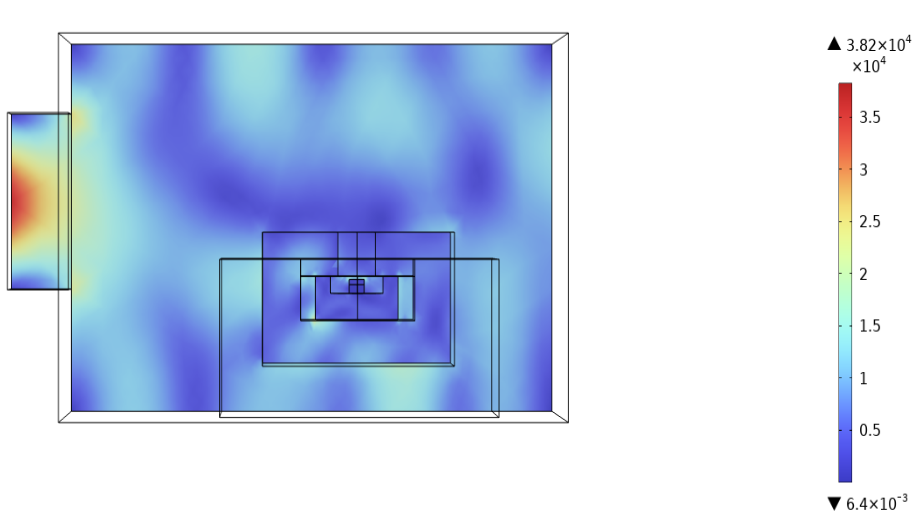
At X1



At X2



At X3



At X4

At X5

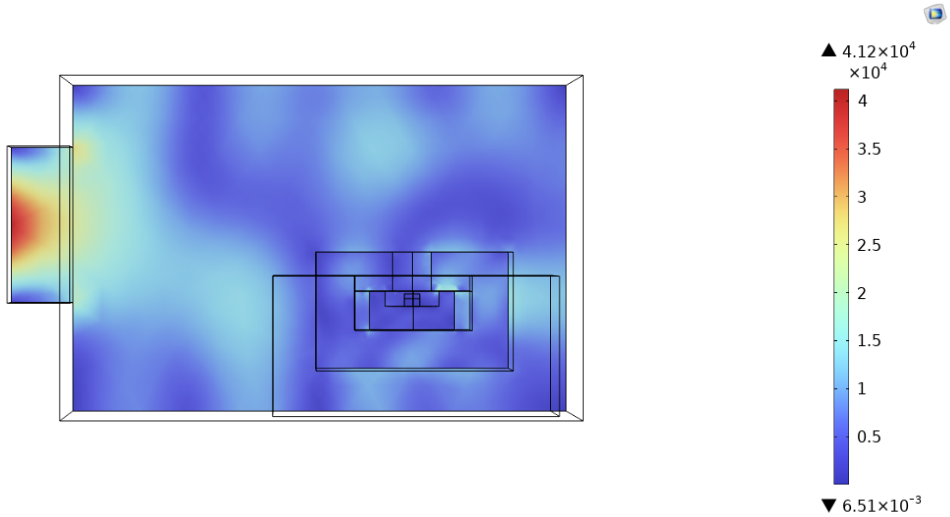


Figure 4.4:. Effect of location on electric field distribution inside microwave applicator

The effect of mold assembly location on melting time during heating of the charge is shown in Fig.4.5. The variation in electric field intensity while placing the mold assembly and the charge at different locations affects heating characteristics of the charge. Higher electric field enhances polarization of molecules in the hastelloy and the susceptor; which also enhances mobility of the free electrons in the charge compared to low electric field locations. The quick heating of the hastelloy and the susceptor decreases conventional heating time of the charge to attain the critical temperature. The charge couples with microwaves and gets heated up above the critical temperature. The rapid heating of the charge, thus reduces overall melting time.

The distribution of nodes and their field intensities affect the melting time. The rapid heating of the charge at the location x4 results in the shortest melting time and the lowest non-uniformity in the charge. Less non-uniformity in the charge at location x4 offers more uniform heating of the charge and hence less heat transfer takes place through conduction mode inside the charge. Therefore, melting time of the charge gets reduced with reduced degree of non-uniformity (Fig. 4.5). The melting time of the charge was reduced by 51.61% and 40.3% at locations x4 and x5, respectively, in comparison to at x2. Thus, placing the mold assembly and the charge at a suitable location ensures less microwave energy utilization to melt the charge with reduced melting time.

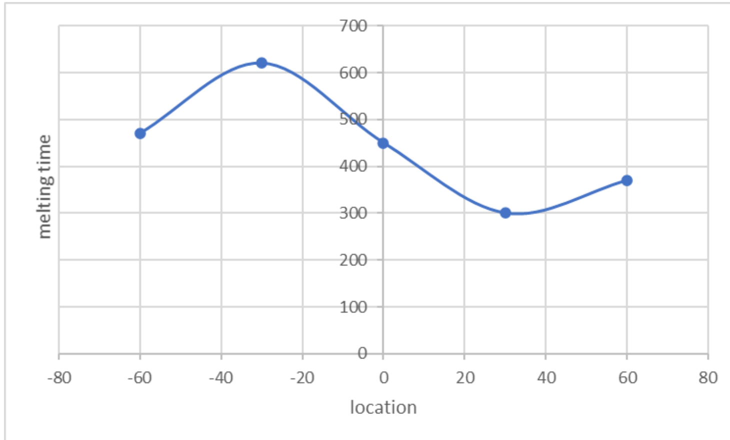


Figure 4.5: Simulation results regarding effect of location on melting time

4.3 Temperature Distribution

The temperature distribution in Hastelloy is shown in Fig. 4.6. 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 (fig 4.7). The temperature of the bottom layer, i.eGraphite 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 the electrical conductivity for simulation and also various thermal properties also required for the study.

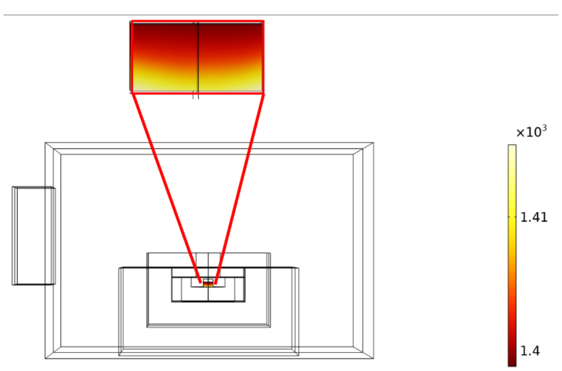


Figure 4.6: Temperature distribution

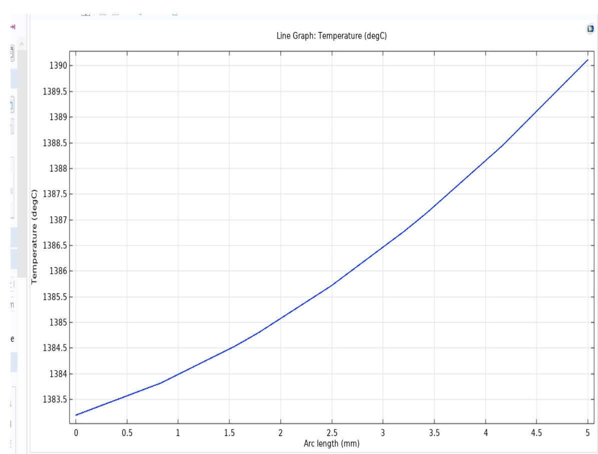


Figure 4.7: Temperature v/s distance plot

4.4 Resistive Losses

It is observed from the Fig. 4.8 The resistive losses are not uniform throughout the assembly. Mostly it is concentrated at corners of the graphite cylinder and graphite plate, this may be due to the effect of conduction of heat by interface layer or it might be microwave energy absorption.

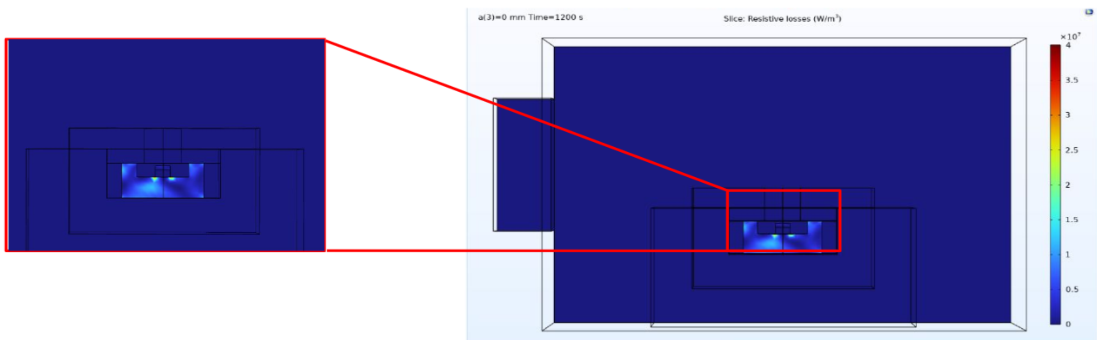


Figure 4.8: Resistive losses

4.5 Experimental Study

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 Hastelloy was placed inside the cylinder, susceptor was also placed on the Hastelloy and then the Hastelloy and susceptor was covered with charcoal powder. This whole setup was placed inside the microwave oven and the experiment was done for 470 seconds.

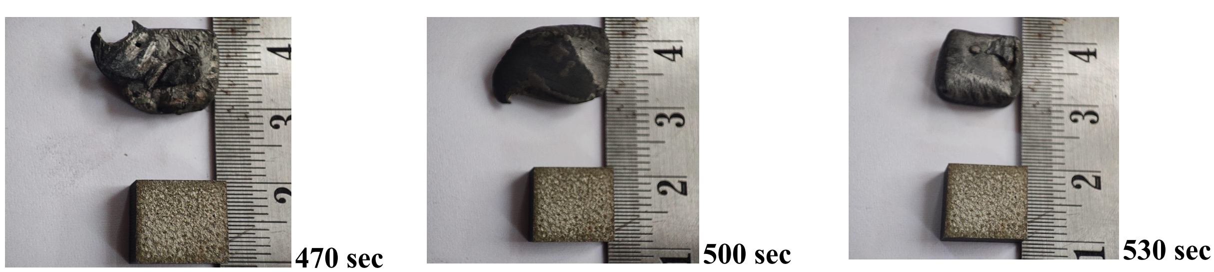


Figure 4.9: Melting time of Hastelloy during experiment

Chapter 5
SUMMARY AND CONCLUSIONS

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

Melting of the bulk Hastelloy during in-situ microwave casting was investigated through experimental trials in a multi-mode applicator cavity at 2.45 GHz and numerical simulation using COMSOL multiphysics software tool. The experimentally obtained temperature profile was in good agreement with the simulated temperature profile (error within ±5%). charge.

The amount of microwave power supplied and the location of the assembly inside the microwave cavity have significant effects on melting time, non-uniformity, average heating rate and energy required to melt the Hastelloy during in-situ microwave casting. The distribution of electric field inside the cavity affects the charge heating and temperature distribution inside it. The time and energy required for the melting of the hastelloy reduces at high power and suitable locations due to higher average heating rates and more uniform heating of the Hastelloy.

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

When power input increases, melting time decreases. To get the lowest melting time , x4 is the suitable location and x2 is 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 4.17×10^4 (V/m) to 7.22×10^4 (V/m) when power varies from 1000W to 3000W.

Chapter 6
SCOPE OF FUTURE WORK

Challenges:

1. Without the use of susceptors, thermal damage is likely to occur in microwave-processed materials due to non-uniform heating characteristics.
2. A rise in temperature during heating results in a change in material properties and alters the absorption of microwaves. These material properties need to be measured in real-time to accurately model the heating.
3. The physics behind the phenomenon is still not understood well. Certain phenomena called “Microwave effects” are still under the black box.
4. The existing microwave applicators have a standard size which limits the size of the part which can be produced. Customized microwave applicators may be designed but it requires high investment.

All these challenges limit the use of microwave processing for industrial applications. They need to be overcome and hence, they also provide opportunities for future research and development in the field of microwave processing.

This present work was only done on the melting characteristics of Hastelloy. This can be further extended for casting in microwave and Thin sheet rolling.

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