

Microwave Joining of Stainless Steel and Their Characterizations.

*A Dissertation submitted
In partial fulfillment of the
requirements*

Master of engineering

in

Production & Industrial Engineering

by

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Under the Supervision of

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THAPAR UNIVERSITY, PATIALA

JULY, 2015

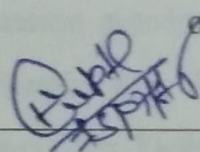
CERTIFICATE

I hereby declare that the thesis entitled "Microwave Joining of Stainless Steels and their Characterizations" is an authentic record of my work carried out as requirements for the award of the degree of **Master of Engineering in Production & Industrial Engineering** at **Thapar University, Patiala** under the supervision of **Dr. Vivek Jain & Dr. Dheeraj Gupta**, Assistant Professor, Department of Mechanical Engineering, Thapar University, Patiala during July, 2014 to December, 2014. No part of the matter embodied in this report has been submitted to any other university or institute for the award of any degree.

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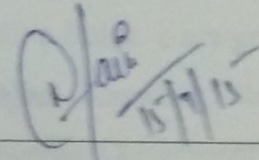
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It is certified that the above statement made by the student is correct to the best of our knowledge and belief.



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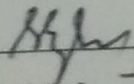
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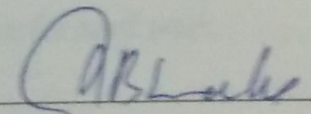
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Amit Kumar

Abstract

The application of microwave radiation in heating of materials is not a new application; only newer applications are emerging in the field of processing of materials through microwave radiations, which allowed it as a novel processing techniques. The earlier authors work was reported on sintering processing of many ceramic materials, which are the better absorbers of microwaves radiations. The domain of microwaves applications were further extended to metallic powders. In recent years, researchers have developed methods for processing of bulk metallic materials through microwave radiations such as claddings on various steels and joining of bulk metals. The present work is based on the joining of similar and dissimilar metallic materials through microwave radiations. The obtained joints were characterized by XRD, EDS and SEM. Mechanical characterizations of joints were carried in the terms of tensile testing and Vicker's microhardness. Observed results revealed that the joining of stainless steel was successfully attempted by using nickel based powder (EWAC). The metallurgical characterizations of processed joints through microwave radiations showed cellular structures with lower defects. The mechanical characterizations of joints showed that due to better metallurgical bonding and diffusion, enhancement in the mechanical strength with lower processed defects. Obtained ultimate tensile strength (425 MPa) is highest in joining of S.S 420 with S.S 420. Hardness was obtained due to the presence of carbon which was absorbed from graphite sheet, and led to the formation of carbides in the microstructures of microwave proceeds joints.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

The growth in the field of engineering and technologies led the industries to find new and improved methods/processes that can be used for processing of wide range of materials like metal, non-metal, ceramics composites etc. For sustainability the developed methods should have characteristics of lower energy consumptions and higher production rates. Novel microwave material processing is emerging as one of the promising sustainable process in manufacturing sectors. The unique characteristics of microwave radiations like volumetric heating, less power consumption, eco-friendly with environment, high quality products etc. are attracting numbers of researchers in this field. Material joining is one of the important manufacturing processes which are used widely in industries for production of complex parts. Heating of material during joining/welding is important part of process, which is still uncontrollable. This chapter contains the fundamental of heating of material through microwave radiation and its application in different fields of engineering and technologies.

1.2 Metal Joining process

Metal joining process is the process by which two or more pieces of metal form a strong metallurgical bond with and without the application of heat, with and without pressure or both. The conventional joining process includes welding, brazing, soldering, adhesive bonding etc. Whereas some advanced technologies are also employed for joining of materials and include LASER welding, electron beam welding, ultrasonic welding, microwave joining etc. However microwave joining process has some unique characteristics which are absent in other conventional and non-conventional process. The ability of heating specific areas using microwaves is one of the important parameters for joining process.

Metal joining process depends on,

a. Types of material to be joined.

- b. Physical, chemical and metallurgical properties of metal.
- c. Economy and cost effectiveness of the joining process.
- d. Properties to be obtained by the joint.

1.2.1 Types of joining process

Metal joining process is mainly divided into solid state welding, liquid state welding and solid/liquid state welding are given below.

- (a) **Solid state welding:** It can be achieved by heating the surface without causing melting and applying normal pressure on the surface of materials to be joined. For example: forge welding, friction welding, and explosion welding.
- (b) **Liquid state welding:** It can be achieved by heating the surface with causing melting the materials. For example: arc welding, resistance welding, oxyfuel gas welding.
- (c) **Solid/liquid state welding:** In this process, lower temperature joining method is used. It can't be withstand with higher temperature.

Types of material joining process are shown in figure 1.1.

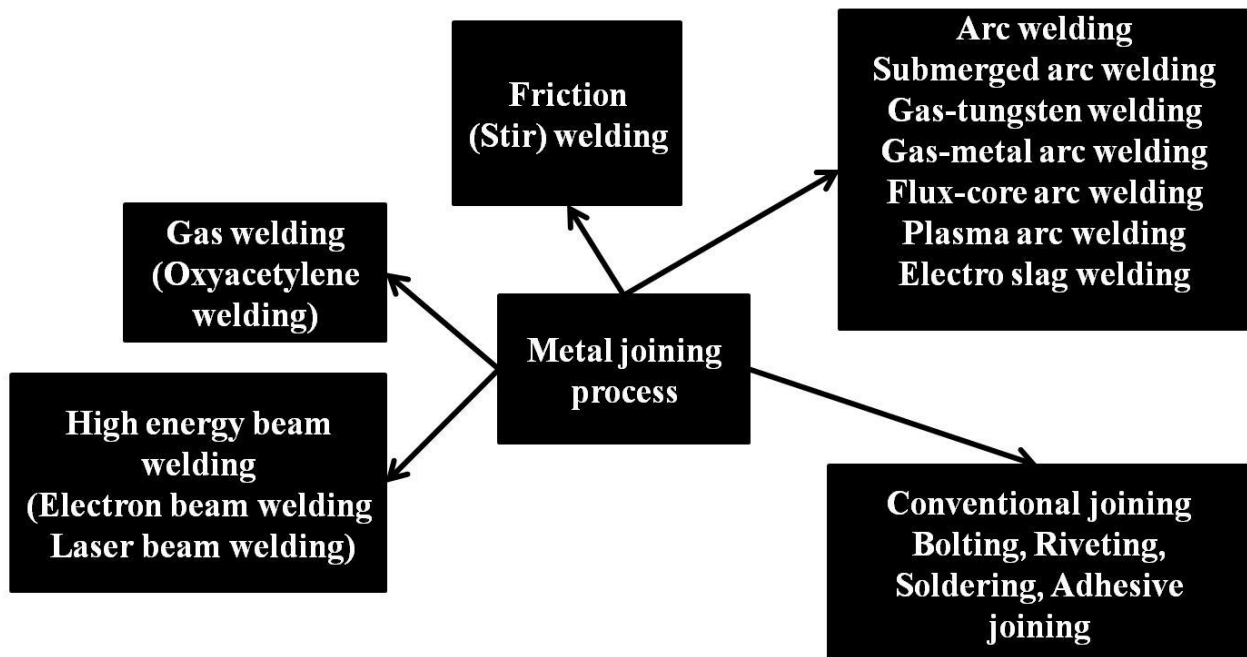


Figure 1.1: Different types of joining process

1.3 Microwave materials processing

1.3.1 Introduction to microwave materials processing

Microwave heating is a process which uses electromagnetic energy in the frequency range of 3 to 300 MHz [1]. In microwave heating the material is subjected to an electromagnetic wave that oscillates the molecules of material, thereby generating heat. Microwaves are directly absorbed by the material thus causing volumetric heating. This volumetric heating is only obtained by microwave processing and it reduces time, energy as well as it is eco-friendly. As per growing technology, industries are looking forward for new and improved technology, which can be used on a wide range of materials like metal, non-metal, ceramics, composites etc. The unique characteristics of microwave led to researchers to explore the potential of microwave in various fields and these characteristics are shown in figure 1.2. In industries developed furnaces used for material joining purposes, work on higher frequencies ranging from 915 MHz to 18 GHz [2-3] as shown in figure 1.3. Various authors reported huge savings in terms of power consumption and processing time [4-6]. Different types of ceramics by microwave processing were achieved successfully with enhanced diffusion, densifications and improved properties and positive results were reported by many researchers [7-9].

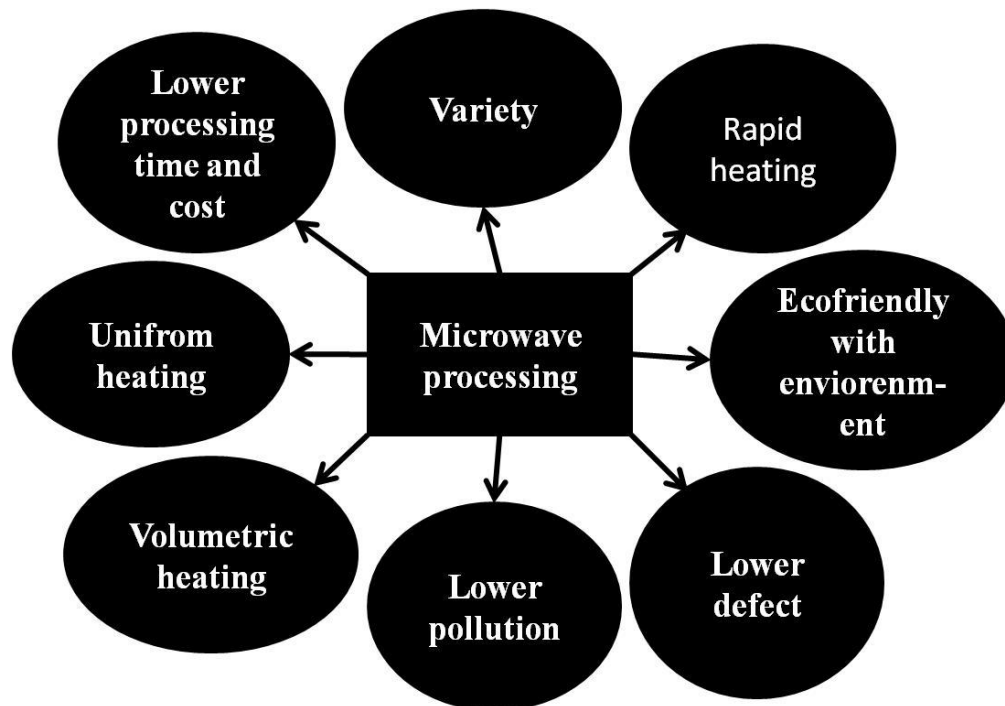


Figure 1.2: Unique characteristics of microwave processing

This chapter contains fundamentals of microwave heating phenomena's and materials properties required for microwave processing. The various applications of microwave processing of materials are discussed in this chapter.

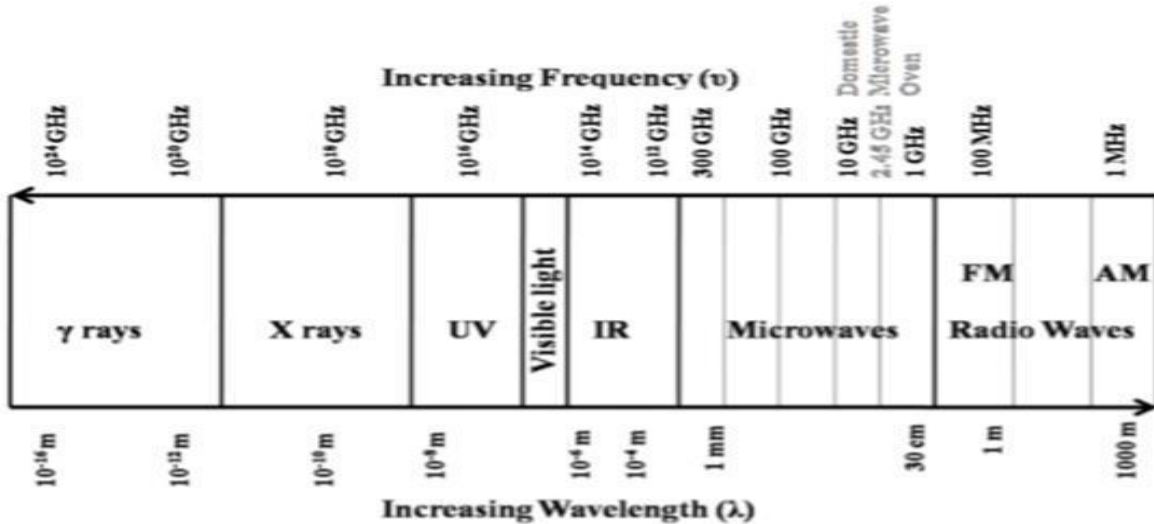


Figure 1.3: classification of electromagnetic waves [2]

1.3.2 History of microwave material processing

Microwave processing gives an alternative to high energy consumption processing methods used in material processing. The primary benefits of microwave introduces as faster heating and energy saving over conventional method of heating. As a technological growth of microwave materials processing, its different applications are revealed in front of world by researchers working in this field. The historical developments in the field of microwave processing are shown in figure 1.4, which shows that in recent times microwaves are being utilized in metallic material processing. Earlier starting development were focused on low temperature applications field such as chemical reactions, wood drying and these applications were further explored for higher temperature applications mainly by the processing of ceramic materials. In 1999, first literature was successfully present on sintering of metallic material [Roy et al] [10]. After that joining of bulk metallic material 2009 by Srinath [11], work on cladding of various metallic materials by Gupta and Sharma in 2010 [12]. Various steel parts sintered my microwave radiations are shown in figure 1.5.

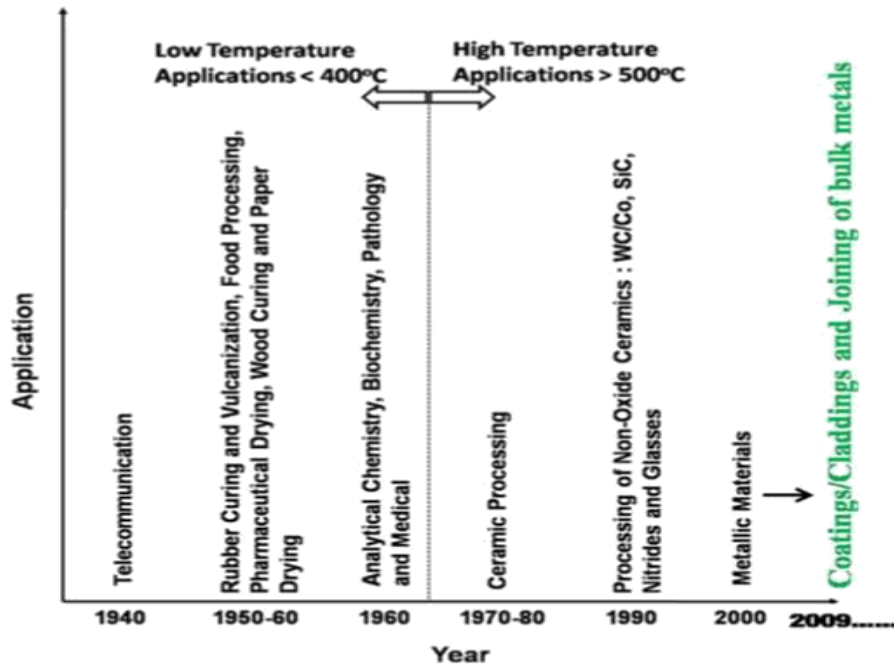


Figure 1.4: History of microwave processing.



Figure 1.5: Various steel parts sintered by microwave processing.

Chronological developments of microwave processing route for material processing are shown in figure 1.6.

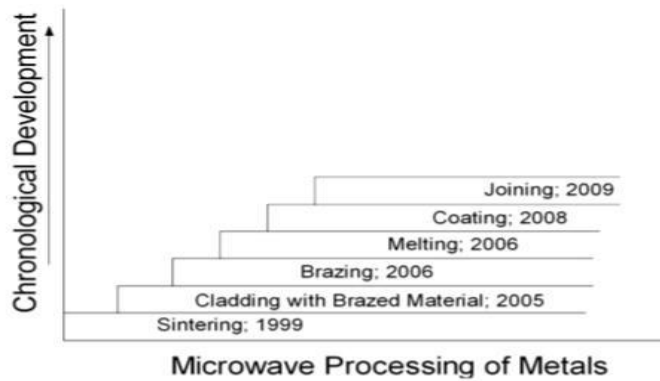


Figure 1.6: Development in microwave processing of materials

1.3.3 Theory of microwave heating

It produce heating within a material by exciting molecules to rotate, this rotation produces energy in form of heat. Microwave energy is delivered directly to material through molecular interaction with electromagnetic field. This type of heating is the transfer of electromagnetic energy to thermal energy and this conversion of energy is rather than heat transfer. It produces volumetric heating effect.

1.3.4 Microwave furnace

It consists of three major components.

- (a) **Source:** It generates electromagnetic radiations.
- (b) **Transmission lines:** Deliver electromagnetic energy from source to applicator.
- (c) **Applicator:** Energy absorbs or reflects by material in applicator. Applicator may be single mode, travelling wave and multimode, for simple geometry single or travelling mode used. Multimode mainly used in industries for large and complex components.

1.3.5 Production of microwaves in magnetron

In a microwave oven, microwaves are produced by a device called magnetron. It is in the form of a hollow tube, with cylindrical cathode running through the centre and outside of tube shaped with several cavities acting as anode. Thus, the electric fields exit in the gap inside the tube, (Gllava 2008), shown in figure 1.7.

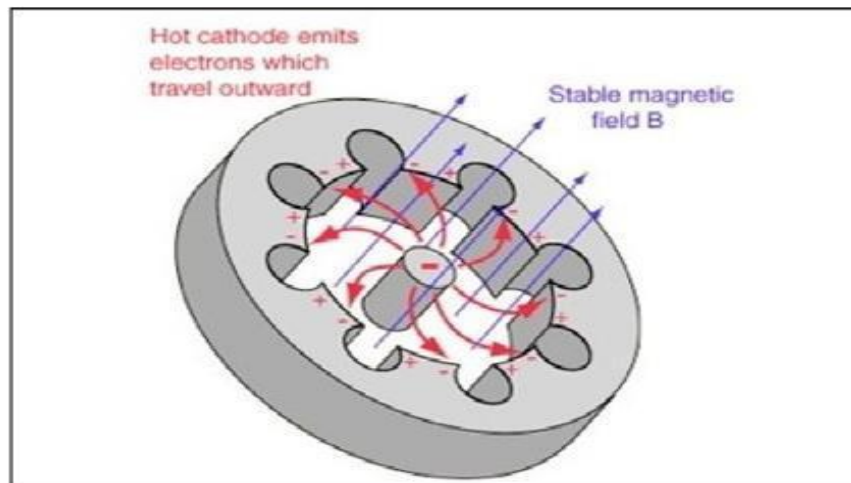


Figure 1.7: Electrons emitted from the cathode undergo curved motion towards the anode (Nave 2005)

A permanent magnetic field exists perpendicular to the electric field and parallel to length of tube. Electrons in the cathode are stripped into electric field due to thermionic emission (high temperature in the cathode causing the electrons to be excited and released). They accelerated towards anode, the outside of tube, due to force applied on them by electric field. However on their way, the magnetic field also applied a force to them which curves their motion.

Because of their curved motion, the electrons pushed towards an area where there is excess negative charge anode (one side of cavity). This excess negative charge is pushed back around the cavity, creating an oscillation of electric and magnetic field due to moving charge. The frequency at which this resonation occurs is consistent with that of microwaves, since electric and magnetic field are emitted perpendicularly to each other and perpendicular to the direction of travel at this frequency, microwaves are effectively emitted (Nave 2005).

1.3.6 Characteristics of microwave heating process

(a) **Internal heating:** Microwave will reach the object to be heated at same speed of light, then it enters into the object as a wave and by getting absorbed, the object generates heat therefore microwave heating is internal heating.

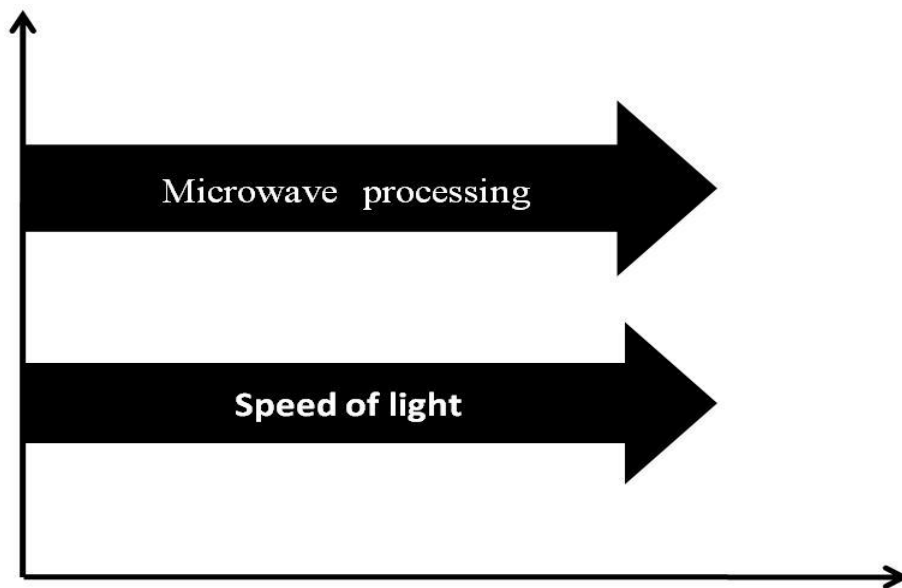


Figure 1.8: Comparison of transmission speed of microwave as same as light.

In microwave heating, the heat will be generated in the object by absorption of microwaves which has inverse heating profile. It heats the object internally and heat flows from inward

direction to outward direction which reduces heat loss and rapid heating is achieved. The heating phenomenon in microwave heating and conventional heating is shown in figure 1.9.

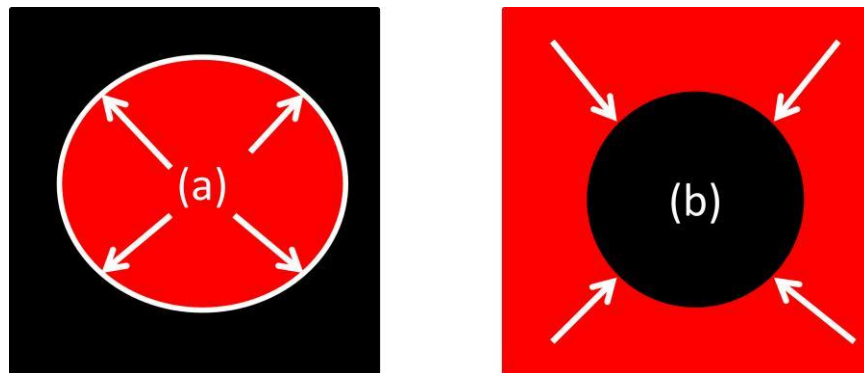


Figure 1.9: (a) Microwave radiations heat objects internally while in (b) Conventional heating externally.

b. Rapid heating: It generates heat on their own by penetration of microwaves, not necessary to consider about heat conduction that is why rapid heat is possible by microwaves, shown in figure 1.10 below.

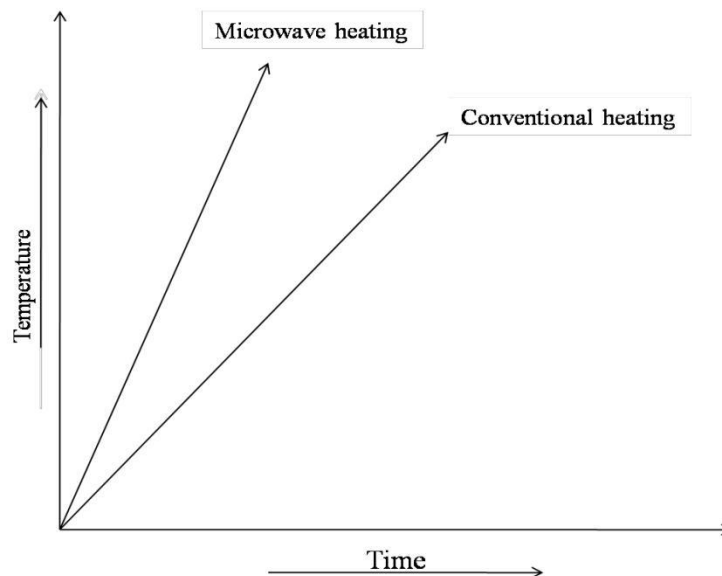


Figure 1.10: Microwave heating vs. conventional heating

c. High heating efficiency: Microwaves penetrates into object at the speed of light and the object to be heated generates heat their own. It has high efficiency due to no need to consider the heating losses of air inside the heating furnace.

d. Rapid response: Microwaves penetrates into object as the same speed of light and object generated heat their own and volumetric heating of materials so it allow rapid response. Start and stop heating instantly in case of microwave processing.

e. Heating uniformity: It heat uniformly i.e. it gives volumetric heating effect can. Each part of heated object generate heat, so even for those object with complicated shape, it can be heated relatively uniform.

f. Clean energy: It does not require medium, it propagates by only changing the electric field and magnetic field. It can propagate even in vacuum. It reaches the object and penetrates without heating air.

g. Lower power consumption: The microwave heating of material involves direct absorption of radiations by material, it provides higher rate of heat transfer in comparison of conventional methods and attains higher temperature in shorter time, this reduce overall consumption of power, shown in figure 1.11.

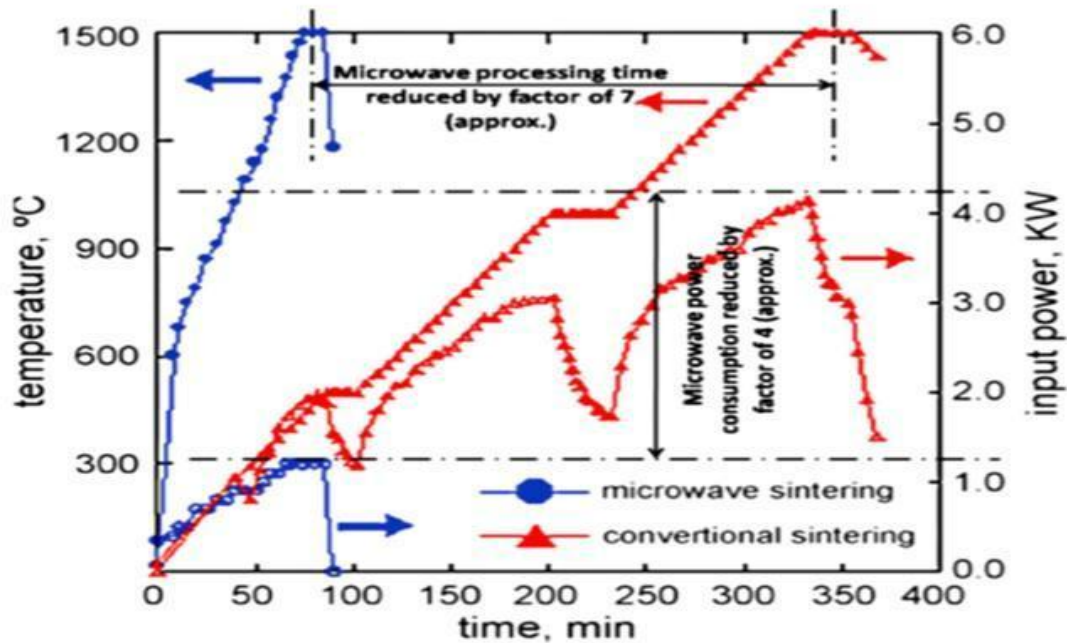


Figure 1.11: power and processing time comparison during microwave and conventional sintering process

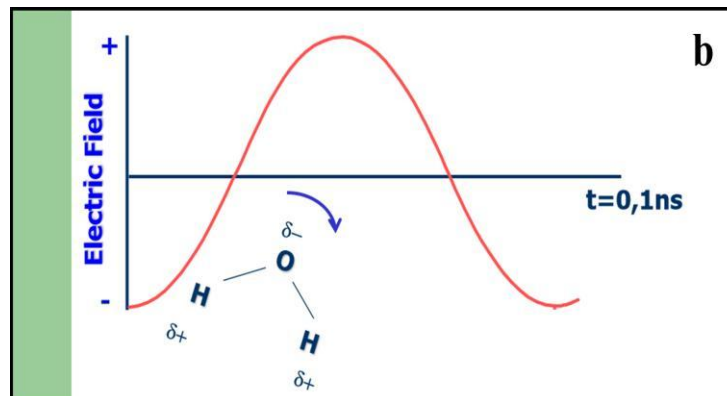
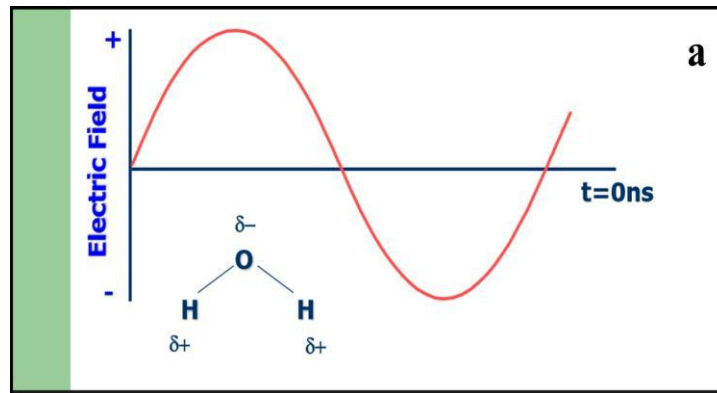
[13]

h. Good operation and working environment: It only used electricity to generate heat; there is no hazard effect and eco-friendly with environment.

1.3.7 Heat generation in microwave processing

- (a) By dipole rotation,
- (b) By ionic migration

(a) **Dipole rotation:** Molecular rotation occurs in materials containing polar molecules having electric dipole moment and they will align in an electromagnetic field. If field is oscillating, as it's an electromagnetic wave or in a rapidly oscillating electric field, these molecules rotate continuously aligning with it. This rotation is called dipole rotation or dipole polarization. As the field alternates, the molecules reverse direction. Rotating molecules push, pull, and collide with other molecules (through electrical force), distributing the energy to adjacent molecules and atoms in the material. Once distributed, this energy appears as heat. Dipole rotation of molecules is shown in figure 1.12 (a, b, c). [14].



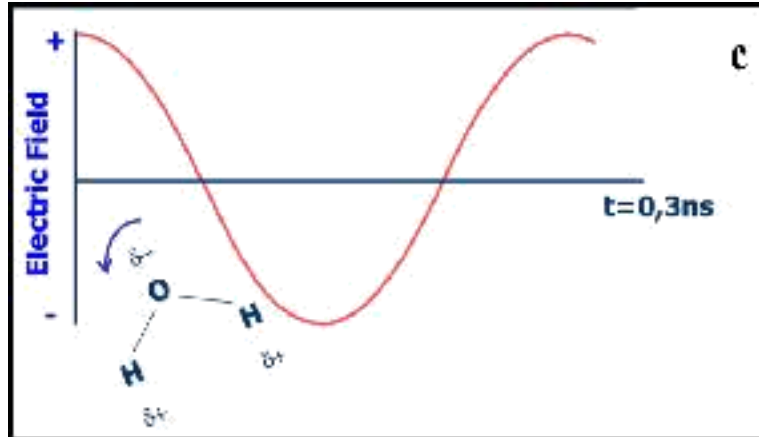
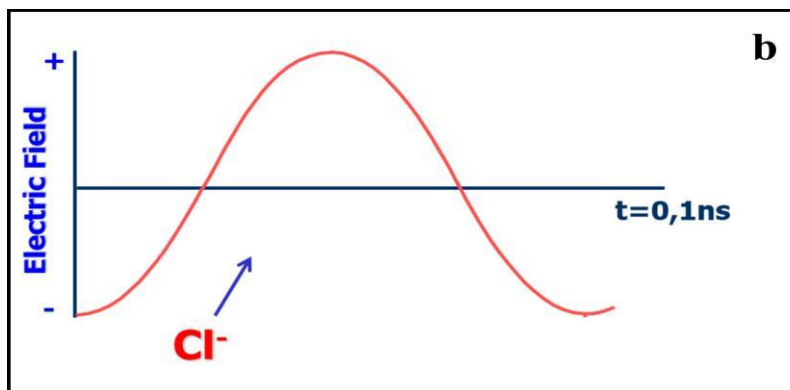
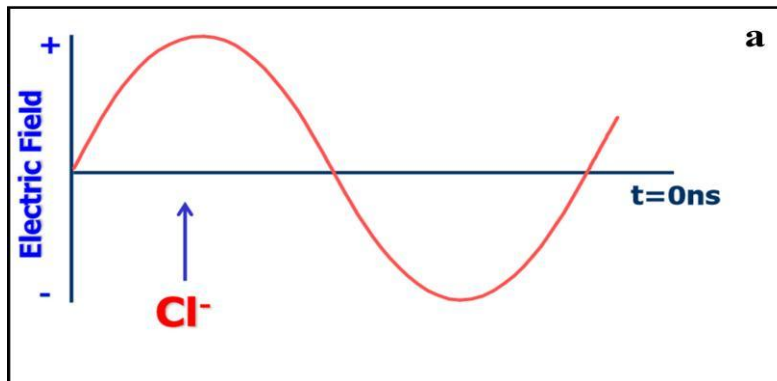


Figure 1.12: (a, b, c) shows dipole rotation of molecules.

(b) Ionic migration: Ionic migration is the transport of the material caused by the gradual movements of ions in a conductor due to momentum transfer between conducting electrons and diffusing metal atoms. It is the movement of dissolved ions due to presence of microwave's electric field. Ionic rotation of molecules shown in figure 1.13 (a, b, c). [15].



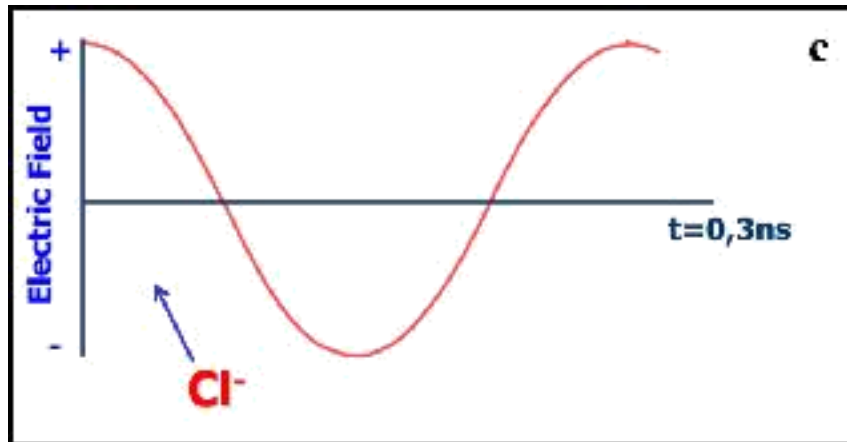


Figure-1.13. (a, b, c) shows ionic rotation of molecules.

1.3.8 Interaction of material with microwave: Interaction of microwaves radiations with different materials are shown in figure 1.14.

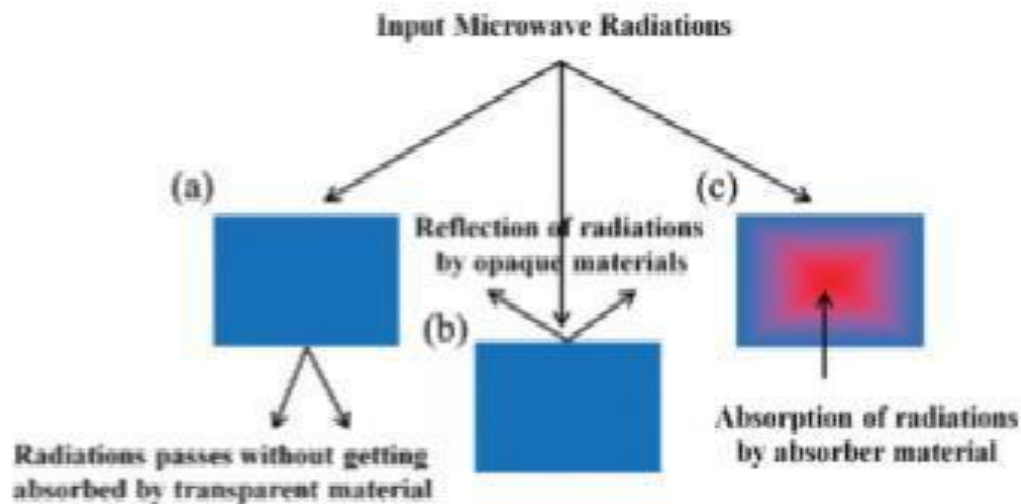


Figure 1.14: Interaction of microwaves with different materials. [16]

In figure 1.14 (a) shows radiation passes through without getting absorbed by transparent material like glass, in (b) reflection of material by opaque material i.e bulk metallic conductor neither allow to pass nor absorb but reflect from surface and produces surfacial heating of body. In last figure (c) material i.e dielectrical material absorbs radiation and converts it into heat, this occurs due to dipolar loss.

1.3.9 Material parameters of microwave processing

There are three main parameters of the microwaves materials processing.

(a) **Dielectric constant:** Polarizing level of molecule in an electromagnetic field.

(b) **Dielectric loss:** Efficiency of microwaves conversion in heat.

(c) **Tangent loss:** material of absorbing micro wave. It is calculated as dividing the dielectric loss by dielectric constant.

1.2.10 Power generation:

The generated power density per unit volume is given by equation 1.

$$= \frac{1}{2} \epsilon_0 \epsilon'' \omega^2 E^2$$

Whereas, ω - angular frequency of exciting radiation.

ϵ'' - Imaginary part of complex relative permittivity of the absorbing materials

ϵ_0 - Permittivity of free space

E - Electric field strength

1.2.11 Advantages of microwaves radiations

- (a) Better thermal efficiency.
- (b) Improved product quality.
- (c) Volumetric heating effect.
- (d) Rapid heating.
- (e) Economic advantage as saving time and energy.
- (f) Ease of operation.
- (g) Eco-friendly
- (h) Uniform heating.
- (i) Variety of heating.

Disadvantages;

- (a) Due to high heat generation, it requires careful handling.
- (b) Hazard like fire and burning occurs if proper susceptible materials and adequate amount of susceptible are not used.
- (c) Human body absorbs microwave radiations which can cause serious problems.

CHAPTER 2

Literature survey

2.1 Literature review :

In this chapter, the literatures on the basis of different materials processing through microwave materials processing routes are elaborated. Literature contains the different metal processes including cladding, joining, sintering, melting the material etc.

Sharma and Gupta., 2012 [17] Investigated to develop carbide reinforced (tungsten based) metal matrix composite cladding on austenitic stainless steel (SS316) by domestic multimode microwave applicator. Cladding was developed through microwave irradiation of the prepared clad material at 2.45 GHz for 420 sec. Clad shows metallurgical bonding with substrate by partial dilution of material and distribution of particles uniformly in metallic matrix. Clad exhibit good stiffness and adhesion with substrate and introduced mechanism of clad development has been introduced.

Bansal et al., 2014 [18] Investigated joining of stainless steel 316 to stainless steel 316 in bulk form has been carried out by placing stainless steel 316 at interface by microwave hybrid heating. The developed joints characterized using X-ray diffraction (XRD), field emission scanning electron microscopy equipped with energy dispersive X-ray spectroscope and measurement of vicker's micro hardness, porosity and tensile strength. The XRD spectrum shows presence of chromium carbide, iron carbide, iron silicates that contribute to enhancement of microhardness of joint. Evaluation of tensile strength of joints showed an average ultimate tensile strength of 425MPa with an average elongation 9.44%.

M.S.Srinath et al., 2011 [19] Focused on microwave joining of stainless steel 316 to mild steel in bulk form has been successfully carried out using multimode applicator at 2.45GHz, 900 W. Nickel based powder used as sandwich layer between the bulk pieces and exposed to microwave radiation at atmospheric condition. The average vicker's hardness observed 346.6 MPa with 13.58% elongation.

Gupta and Kumar., 2014 [20] Focused the joining of stainless steel 316 by using microwave joining was carried by using Nickel based powder (Ewac 1002 ET) as a sandwich layer and applied microwave hybrid heating in domestic microwave oven. Developed joints were crack free however small porosity is observed during microstructural investigation and observed that with increase in Nickel content and exposure time, the joint tensile strength increase significantly.

Lin et al., 2011 [21] Investigated the processing of nitride layers on biomedical stainless steel substrate by microwave plasma system. Layer of nitrides produced by using microwave plasma in an AST-M.W 1200 plasma reactor. The microwave plasma was generated by using constant power of 700 W at frequency of 2.45GHz microwave radiation. Coating layers have high microhardness and also showed antibacterial properties.

Bansal et al., 2012 [22] Investigated the joining of inconel 718 plates by using Nickel powder of mesh size 0.2 mm in interface layer. The joining process was carried out at 2.45 GHz domestic microwave applicator at 900 W powers. It was observed that faying surface were well melted and fused with good metallurgical bonding on both sides of the base material. The joint strength analysis shows that average tensile strength was 400 MPa with 6% elongation.

M.S.Srinath et al., 2011 [23] Investigated a novel method of joining bulk metallic material through microwave heating at 2.45 GHz and powers 900 W. Charcoal is used as susceptor material. Copper (in coin and plate form) has been joined successfully through microwave joining within 900 second. Hardness of joint area was observed to be 78 Hv while porosity of joint to be 1.92%, elongation 29.2% with an average ultimate tensile strength of 164MPa.

D.Loganathan. 2014 [24] Focused on heat treatment of A1-6061 sheet by multimode applicator at 2.45 GHz and power 850 watt. The specimen are masked with alumina oxide layer as a heat insulator and then covered with graphite layer as susceptor. By microwave heat treatment material strength has been enhanced. Tensile and yield strength increase with shorter duration of heat treatment and less power consumption due to heat transfer in the form of heat conversion and increase of strain hardening coefficient value indicates with productivity. Heat transfer is uniform. Stress – strain curves for microwave heating and convention heating shown in figure 2.1.

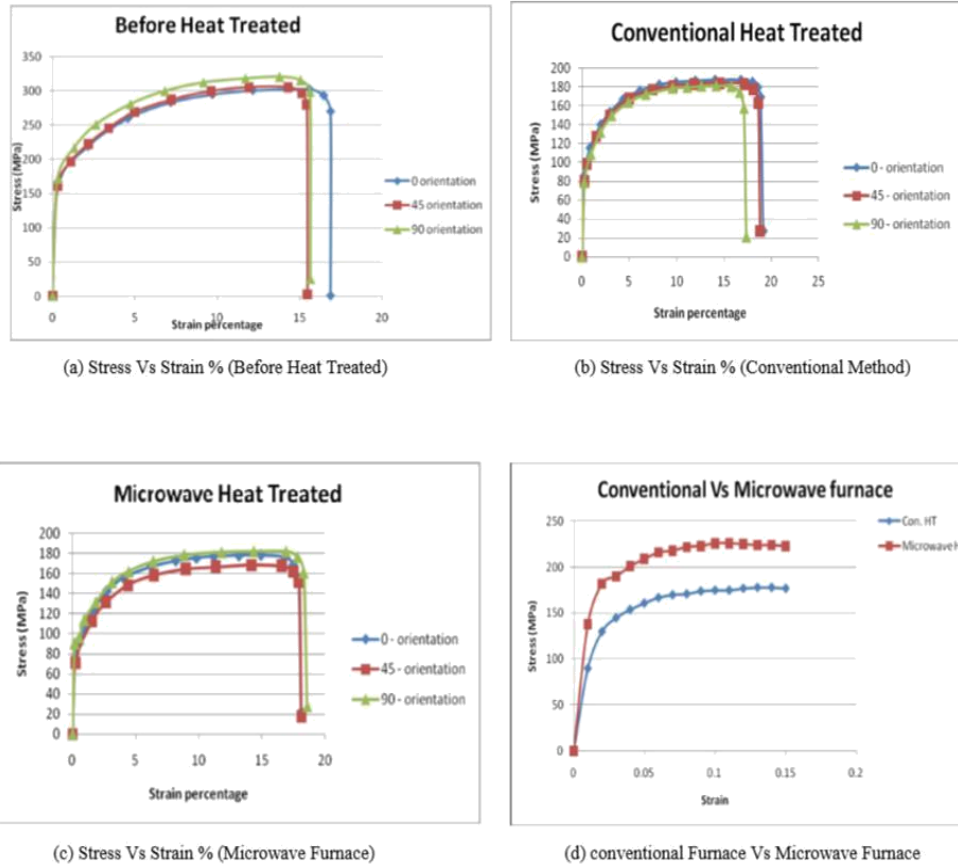


Figure 2.1 – Stress-strain graph between microwave processing and conventional processing

Gupta and Sharma, 2011 [25] Investigated sliding wear of cladding developed through novel processing technology. Wear resistance WC10Co2Ni cladding using microwave irradiation on austenitic stainless steel (SS 316). The developed clads exhibit an average microhardness 1064

± 99 HV and the porosity of developed clads has been approximately 0.89%. Tribological properties of cladding have been analysed through pin and disc sliding method against EN-31(HRC 70) counter surface. Wear resistance was observed to be better at lower sliding speed.

Gupta et al., 2012 [26] Investigated development of cladding through microwave radiation, EWAC (Ni based +20% Cr23C6 powder) composite cladding has been developed on substrate Austenitic stainless steel (S.S 316) by 2.45 GHz microwave applicator at 900 watts in exposure time 360 second. The obtained Vicker's hardness is 425 ± 140 HV and porosity 0.90%. The developed microwave clad can be effectively used in wear resistant applications.

Mishra, 2014 [27] Investigated the neck formation and growth that is associated with diffusion during sintering of pure metal powder and dynamic of stable neck growth summarized in the form of mathematical equations. The smoother surface of powder compact is developed in short time by microwave sintering than conventional sintering. In case of pure copper powder microwave sintering occurs at lower temperature. Thermal profile during microwave sintering in multimode microwave furnace depends on particles size and porosity present in compacted powder metal. The effect of oxidation on sintering of metal powder by microwave is less effective phenomenon in comparison to conventional heating.

H.S.Ku. 2006 [28] Focused on two kind of microwave processing material variable frequency microwave facilities (V.F.M.F) and fixed frequency microwave facilities (FFMF) and observed that V.F.M.F is superior to F.F.M.F. For both curing time composites has been largely reduced with the enhanced or comparable material properties.

Ammar Ahmad. 2001 [29] Investigated the characterisation of Alumina (48%), Zirconia (32%), and Silica (20%) at high temperature at different power through microwave processing and observed that strength of joint greater than base metal. The better joining properties like distribution of microwave radiations and blow holes occur at lower power density.

Prakash et al., 2014 [30] Focused on tensile strength of mild steel 1018 plates joined by microwave processing at three different power (800W, 850W and 900W) with same frequency 2.45 GHz. Nickel based metallic powder with mesh size 50 micrometer used as a interfacing material and observed that as increase in power, tensile strength decreases while welding time increases, tensile strength increases. Microstructures of 1018 mild steel plate are shown below.

Bansal et al., 2013 [31] Investigated the joint fabricated of mild steel-mild steel through microwave hybrid heating route and their characterization through scanning electron microscope (SEM), X-ray diffraction (XRD) and electron probe micro analyzer (EPMA). Nickel powder used as an interfacing material. The measured Vicker's microhardness is 420 ± 30 Hv which is higher than hardness of substrate (230 ± 10 Hv) and the measured tensile strength is 240 MPa that is about 50% of base material.

2.2 Literature Gap

The literature survey on microwave processing of material revealed that microwave irradiations are now used for high temperature applications in the manufacturing field. The work has been carried out on cladding of metallic materials, joining of metallic materials to enhance the research scope of microwave processing. The following gaps are follows,

- (a) The literature shows that very less work has been reported on joining of stainless steel grades of 304 and 420 through microwave processing route.
- (b) Very less work has been reported on microstructural analysis of microwave processed joints.
- (c) Analysis of literature shows that less work has been carried out on mechanical characterization of stainless steel joint through microwave processing.

2.3 Objective

From literature review, analysis of gaps in literature and to full-fill the above stated gaps. The following objective has been found,

- (a) To join commercial available stainless steel 304 and 420 through microwave heating using microwave applicator working at 2.45 GHz frequency.
- (b) Microstructural characterization of joints sample through microwave processing by using scanning microscopy (SEM), energy dispersive X-ray spectroscopy (EDS) and X-ray diffraction (XRD).
- (c) Study the mechanical properties of joints by Vicker's microhardness and tensile testing.

CHAPTER 3

METHODOLOGY

3.1 Methodology

The joining experiments were conducted in microwave applicator working at frequency of 2.45GHz. The process was carried out at a power of 900 watts. The optimization of joining time was carried out before conducting final experiments and it was found that 7 minutes were sufficient for joining. The slurry of Nickel based powder EWAC was introduced between faying surface and joint was protected from susceptor (charcoal) by using thin sheet of graphite. The present work comprises of three main phases:

Phase 1

In the first phase of research proper material selection was carried out which satisfies the gaps mentioned in literature review chapter.

Phase 2

In the second phase microwave exposure time was calculated for various similar and dissimilar materials by carrying out trials.

Phase 3

The joints developed through microwave processing were characterized by microstructural characterization and mechanical characterizations. The samples were polished by emery paper 800, 1000, 1500, 2000, 3000, 4000, and 5000. Various techniques of XRD, SEM and EDS were used for characterizations. The main objective of this phase to obtained defect free material. For tensile testing specimens prepared as per ASTM designation E8/E8-09 standard with length 18 and width 3 mm. In the final phase of work analysis of results of joined sample was done by microstructural and mechanical characterizations.

The process flow chart showing the step wise procedure used in present work is shown in figure 3.1.

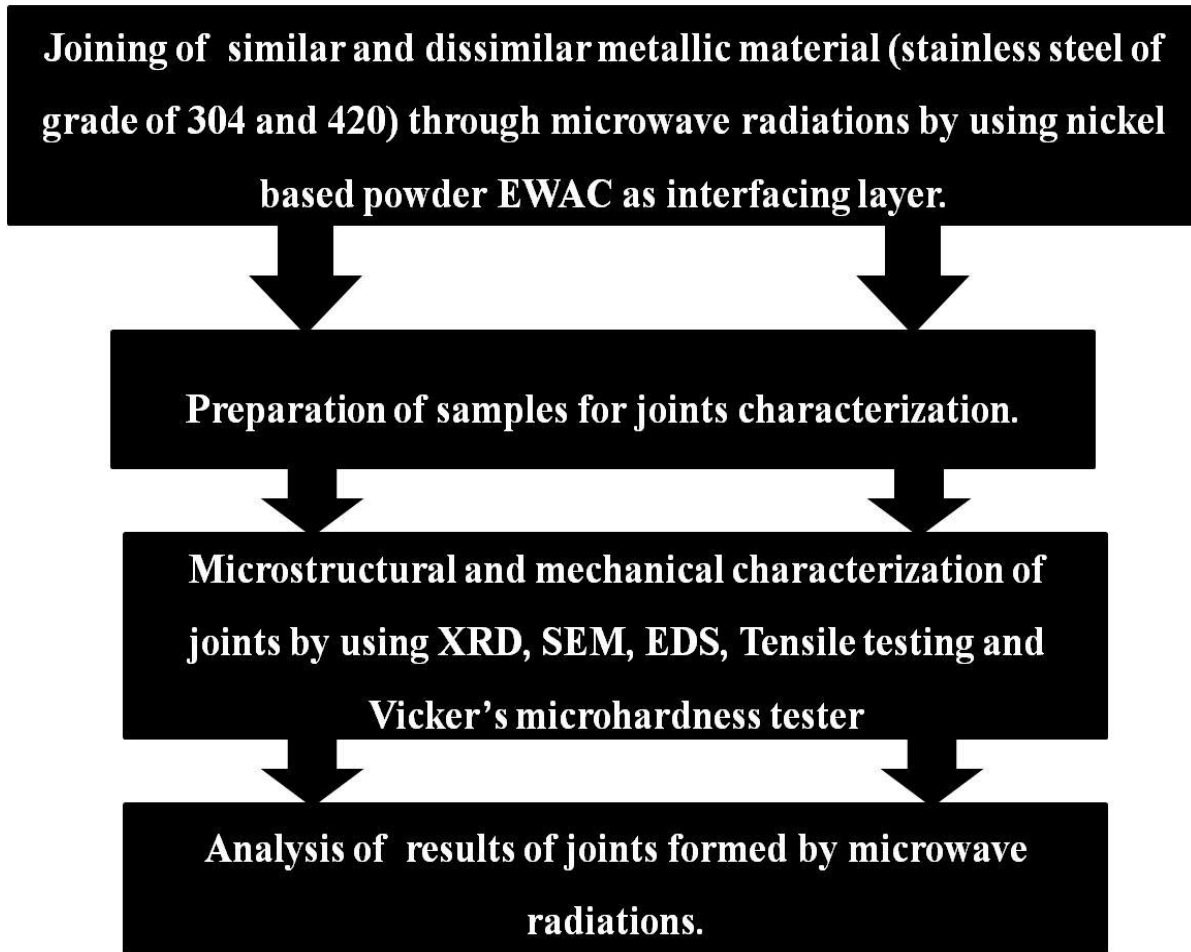


Figure 3.1- Flow chart showing step wise work procedure used in present work

3.2 Selection of materials

3.2.1 Material selection

The selection of material is proposed by reviewing the literature. It was found that stainless steels of grade SS304 and SS420 are used for many industrial applications such as in surgical equipments, automobile sectors, marine applications etc. Further joining of these stainless steel grades of 304 and 420 is difficult and no work is reported on microwave joining of selected work material.

Stainless steel: In metallurgy it is also known as asinox steel is a steel alloy with minimum 10.5% chromium content. It has high resistance towards corrode, rust or stain. Grade of stainless 304 is known as austentic stainless steel and used for food processing equipments, chemical

equipments etc. Stainless steel of grade of 420 is known as martensitic stainless steel and used for rifile barrel, jet engines etc. Chemical constituents of S.S 304 and S.S 420 are given in table 3.1.

Table 3.1- Chemical composition of selected materials.

Grade	Cr	C	Si	Mn	S	N	Ni	P
304	18-20	<0.08 or 0.08	<0.75 or 0.75	<2 or 2	< 0.03 or 0.03	< 0.11 or 0.11	8-10.5	< 0.045 or 0.045
420	12-14	0.16- 0.25	< 1 or 1	< 1.50 or 1.50	< 0.03 or 0.03	-	-	-

3.3 Experimental equipments and facilities

3.3.1 Microwave applicator

In microwave processing energy supplied by an electromagnetic field directly to material, this result in rapid heating throughout the material thickness with reduced thermal gradient. Volumetric heating reduced time and energy, microwave processing shown in figure 3.2.

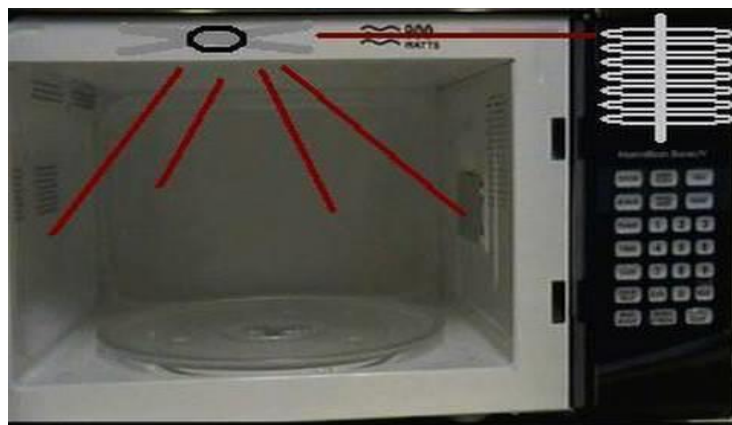


Figure 3.2 A microwave processing applicator.

3.3.2 Development of joint by microwave equipment

The process parameters of microwave joining process are given below in table 3.2.

Table 3.2: The process parameters of microwave joining processing.

Process parameter	Description
Microwave applicator	Domestic multimode (Model: LG, Model: charcoal)
Working frequency	2.45 GHz
Power rating	900 watts
Exposure time	420 second
Work piece material	S.S 420 and 304
Interfacial powder	Ni based powder (EWAC)
Susceptor material	Fine grained charcoal
Separation material	99.9% pure thin graphite sheet

Exposure time is obtained through numbers of experimental trails at different time periods and optimal period was selected based on the quality of joint produced. The schematic diagram of microwave hybrid heating processing of joints in microwave cavity is shown in figure 3.3. Microwave hybrid heating concept was utilized by using charcoal as susceptor material, which increases the temperature of nickel conventionally such that at elevated temperature nickel starts absorbing microwaves. The actual processing of microwave joints in domestic applicator during experimentation work is shown below in figure 3.4.

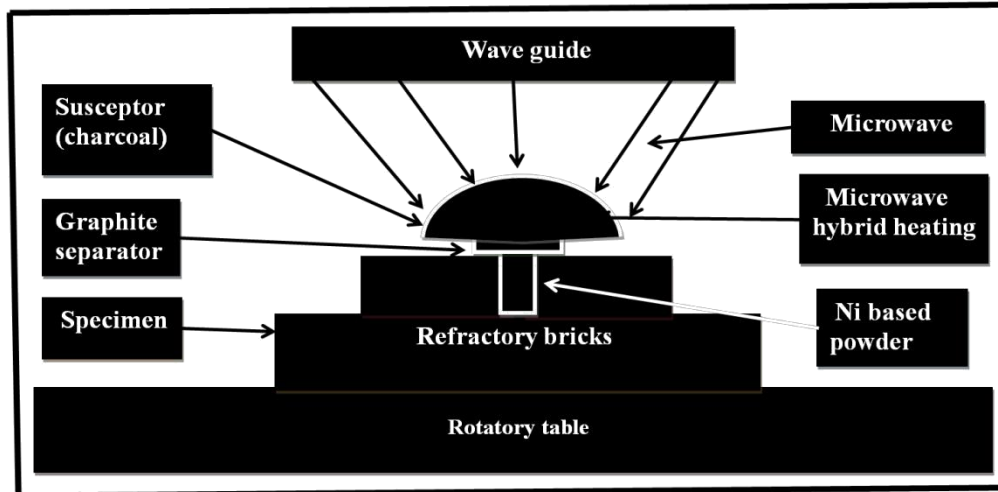


Figure 3.3- A schematic microwave hybrid heating processing.



Figure 3.4 – Actual microwave processing.

3.4 Characterization

3.4.1 XRD (X-ray diffraction)

X-rays are electromagnetic radiation of wavelength about 1 \AA (10^{-10}m), which is about same size of atom. It is non-destructive analytical technique which can yield the unique finger print of

Bragg reflection associated with crystal structure. It is based on constructive interference of monochromatic x-rays and crystalline sample. The x-rays are generated by cathode ray tubes, filtered to produce monochromatic radiation, collimated to concentrate and directed towards sample. Interaction of incident rays with sample produces constructive interference (diffracted rays) when condition satisfied Bragg's law ($n\lambda=2d\sin\theta$). This law relates wavelength of electromagnetic radiation to diffraction angle and lattice spacing in crystalline sample.



Figure 3.4- XRD machine (T.U Patiala)

3.4.2 Scanning electron microscopy (SEM):

SEM used a focused beam of high energy electrons to generate a variety of signals at the surface of solid specimens. A schematic principle of scanning electron microscopy is shown in figure 3.5. In SEM accelerated electrons carries significant amount of kinetic energy and this energy dissipated in solid samples. Signals in SEM include secondary electrons that provide SEM images. Secondary electrons are electrons in specimen that are ejected by beam of electrons, if electrons are ejected from an inner shell by the energy released when an ionized atoms returns to the ground state, then these secondary electrons are called angular electrons. In Thapar University SEM is available in SAI lab and is used to analyse microstructural characterization. Figure 3.6 shows the SEM machine.

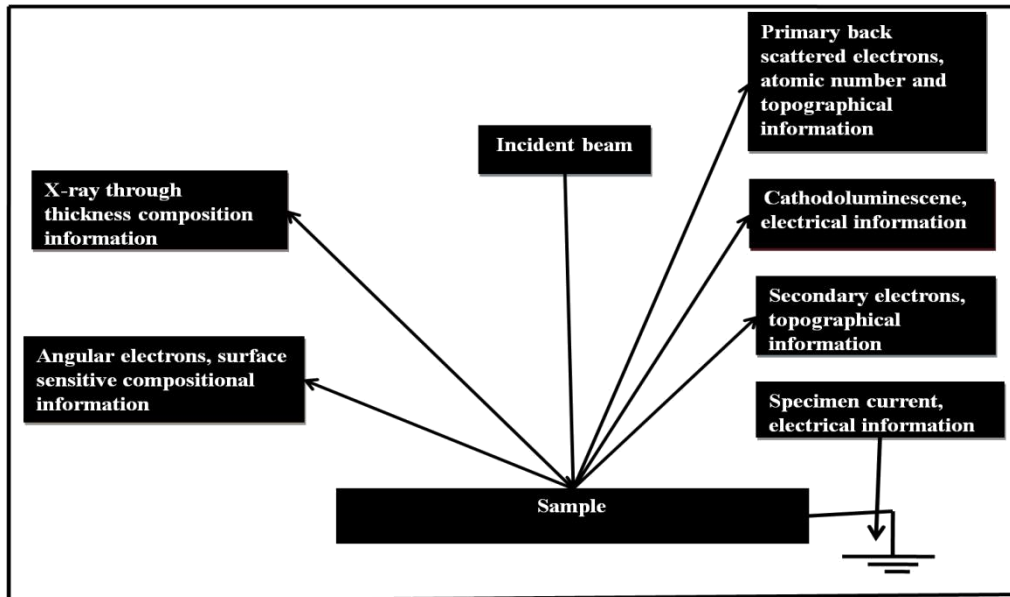


Figure 3.5- A schematic principles of scanning electron microscopy.



Figure 3.6 – SEM machine, (T.U Patiala)

3.4.3 Energy dispersive spectrum (EDS)

It makes uses of X-ray spectrum emitted by a solid sample bombarded with a focused beam of electrons to obtain a localized chemical analysis. This analysis may be qualitative analysis or quantitative analysis. Qualitative analysis involves the identification of the lines in the spectrum

and it is fairly straight forward owing to the simplicity of X-ray spectra. Quantitative analysis (determination of the concentrations of the elements present) entails measuring line intensities for each elements in the sample and same elements in calibrations standard of known composition. It provides rapid, quantitative, qualitative analysis of elemental composition with a sampling depth 1-2 microns.

3.4.4 Tensile testing

It is also known as tension testing, is a fundamental material science test in which sample is subjected to controlled tension until failure. The results from the test are commonly used to select a material for an application of quality control and to predict how a material will react under other type of forces. The tensile testing carried out by applying longitudinal or axial load at the specific extension rate to a standard tensile specimen with known dimension (Gauge length and cross section area perpendicular to the load direction) till failure. The applied tensile load and extension are recorded during test for calculation of stress and strain. Range of the sample standard, provided by the professional societies like American society of testing and material (ASTM), British standard, Jis standard etc. The tensile testing specimen prepared as per ASTM designation E8/E8-09 standard with length 18 mm and width 3 mm, as shown in figure 3.7, with tensile testing equipment.

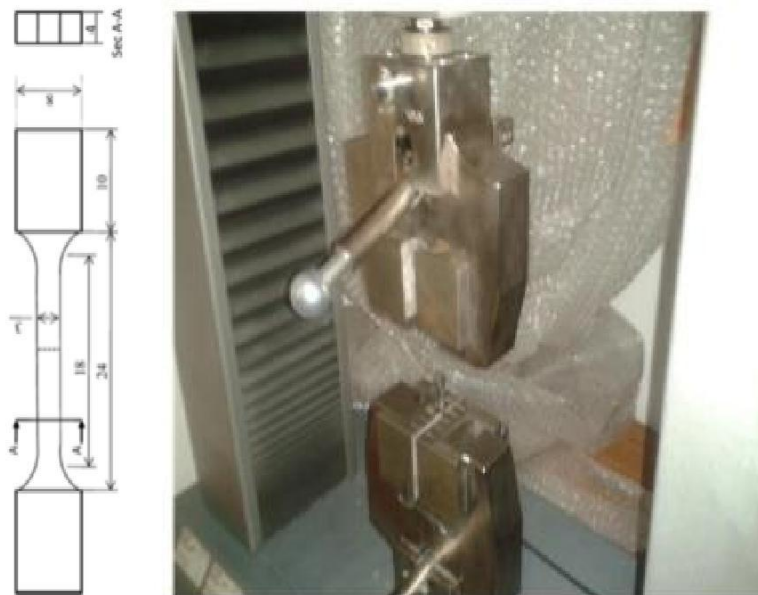


Figure 3.7 – (a) Standard tensile testing specimen, (b) Zwick-Roell Z10 tensile testing machine (T.U Patiala)

By tensile testing we can directly measured an ultimate tensile strength, maximum elongation and reduction in area, yield strength, Young's modulus, Poisson's ratio and strain hardening.

3.4.5 Vicker's microhardness

This method consist of indenting the test material with diamond identator , in the form of pyramid with a square base and an angle of 136 degrees between opposites faces subjected to test force between 1 gf- 100 Kgf. The full load normally applied to 10-15 seconds. The two diagonals of the indentation left in square of material after removal of load, are measured using microscope and their average calculation. The area of the sloping surfaces of the indentation is calculated.

The Vicker's hardness is quotient obtained by dividing the Kgf load by the square mm area of the indentation. Vicker's microhardness testing machine is shown in figure 3.8 below.



Figure 3.8 – Vicker's microhardness tester (T.U Patiala)

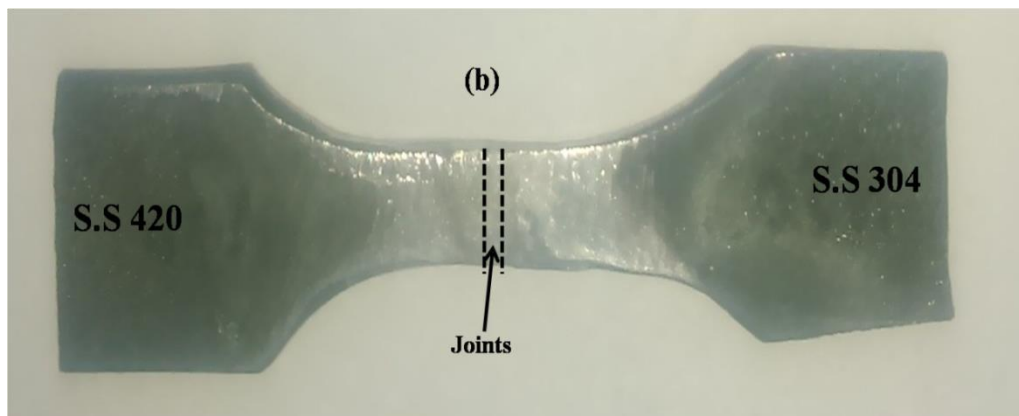
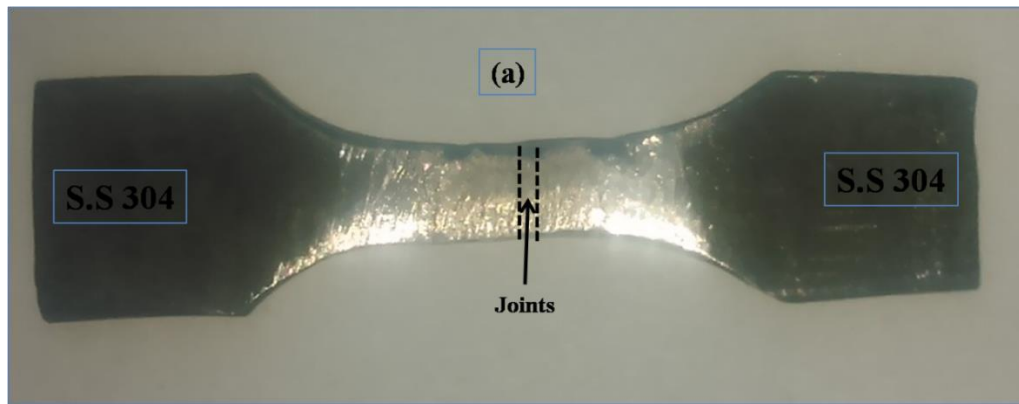
CHAPTER 4

Results and discussions

This chapter contains experimental and characterization results of joints of stainless steel of grade of 304 and 420 by microwave processing route. An attempt has been made to study of microstructure and joint strength obtained by microwave radiations. Its usefulness is evaluated and the failure mechanism of joined samples under tensile testing.

4.1 Characterisation of joints

The microwave proceed similar and dissimilar joints of stainless steel of grade of 304 and 420 are shown in figure 4.1 (a- c).



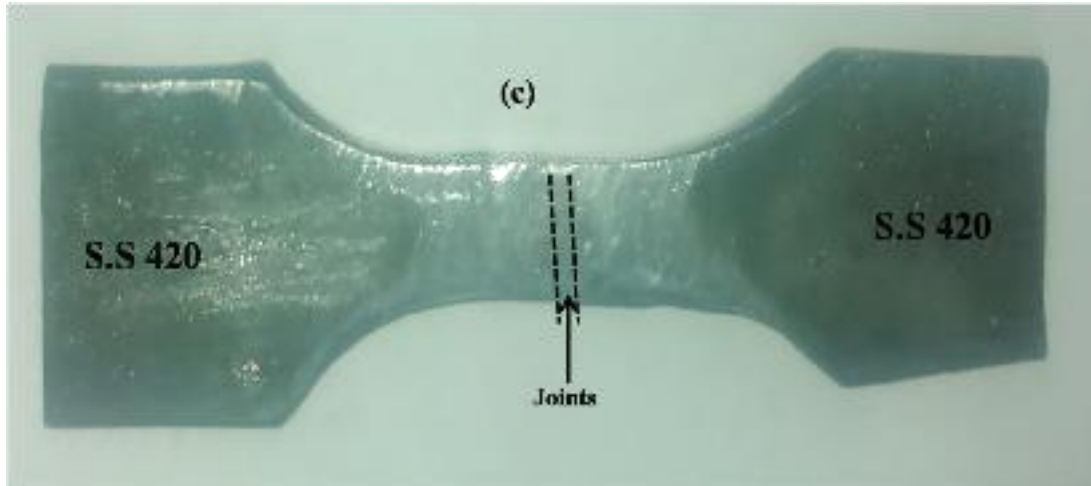


Figure 4.1 - (a, b, c) shows the joining of similar and dissimilar stainless steel through microwave radiations.

Above figure shows that joints are free from defects and also shows that metallurgical bonding. Samples were prepared by cutting the joints cross section using low speed diamond cutter for the characterization. The samples were polished properly as stated in methodology section and kept in plastic bags to prevent from any unwanted contamination of joints.

4.1.1 XRD analysis of joints

The typical XRD spectrum of microwave proceed similar and dissimilar joints of stainless steel grade of 304 and 420 are shown in figure 4.2 (a, b, c) below, which are obtained by Nickel based powder (EWAC) at the interface. Compounds formed during microwave processing are also described below the figure 4.2.

XRD scans were obtained for scanning angle of 0° to 110° at a scan rate of $1^{\circ}/\text{min}$ using Cu K rays.

Figure 4.2 (a-c) shows the XRD spectrum of similar and dissimilar joining of metallic material by microwave processing route. The result obtained by XRD test shows the presence of free Nickel mainly in microwave processing of similar and dissimilar joints of stainless steel of grade of 304 and 420, which are the major constituents of interfacial powder. The formation of compounds Fe_2Si , Ni_3Si , Ni_3Si_2 , C_6Cr_{23} , Fe_3Ni_2 , Cr_3Si , and $\text{Cr}_{13}\text{Si}_2$ mainly observed.

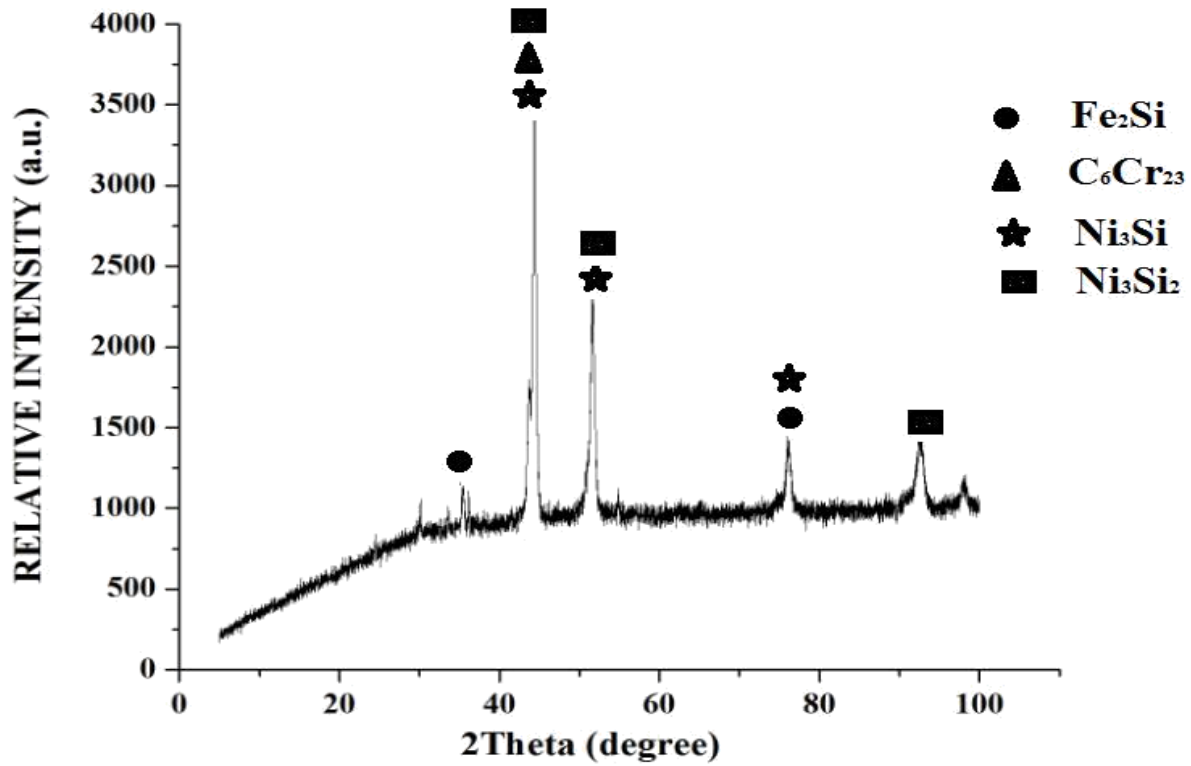


Figure 4.2(a) - Shows the XRD spectrum of joining of stainless of grade of 304-304 through microwave radiations.

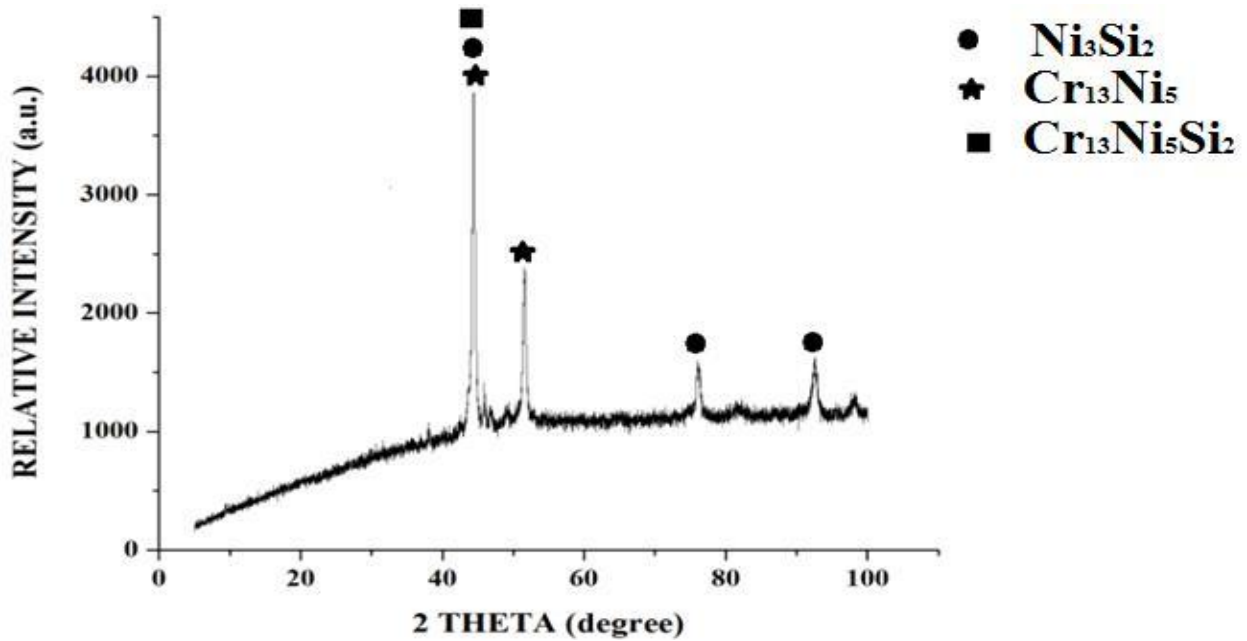


Figure 4.2 (b) shows the XRD spectrum of joining of stainless of grade of 304-420 through microwave radiations.

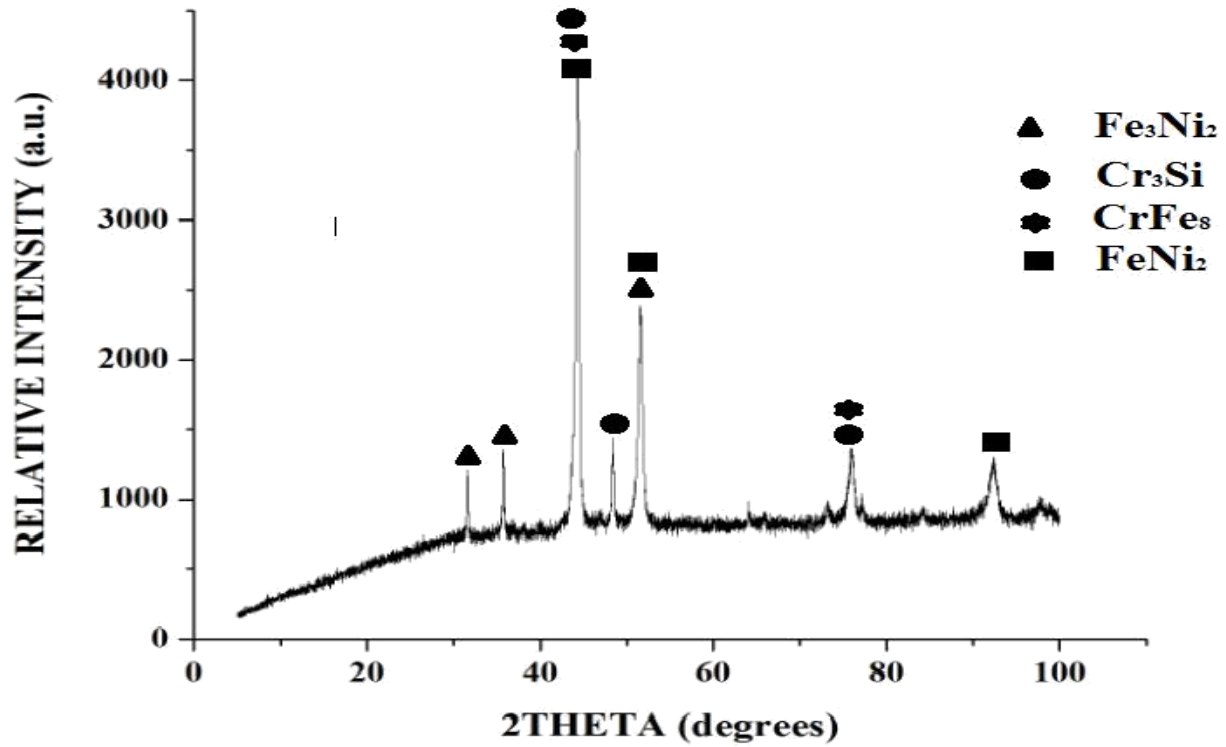


Figure 4.2(c) shows the XRD spectrum of joining of stainless of grade of 420-420 through microwave processing.

4.1.2 Microstructural analysis of joints:

The SEM images of similar and dissimilar joints formed by microwave processing route of stainless steel of grade of 304 and 420 are shown in figure 4.3 (a-c).

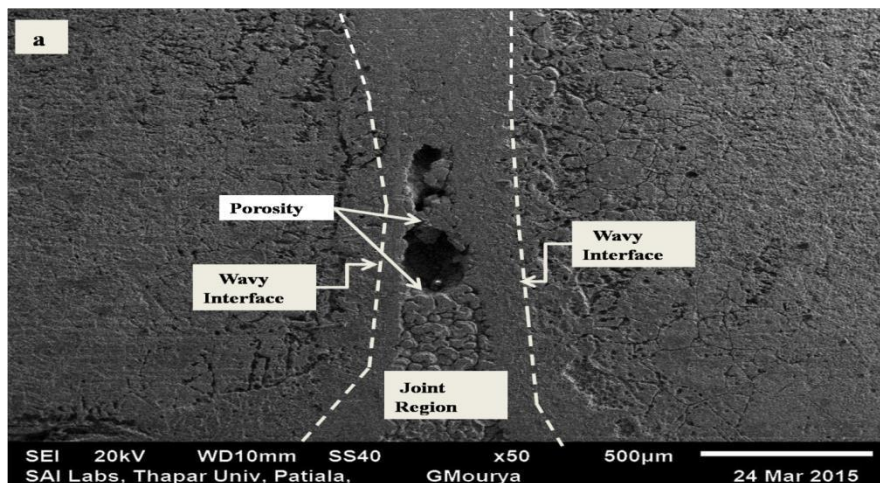


Figure 4.3(a): Microwave processed similar joint of stainless of 304-304

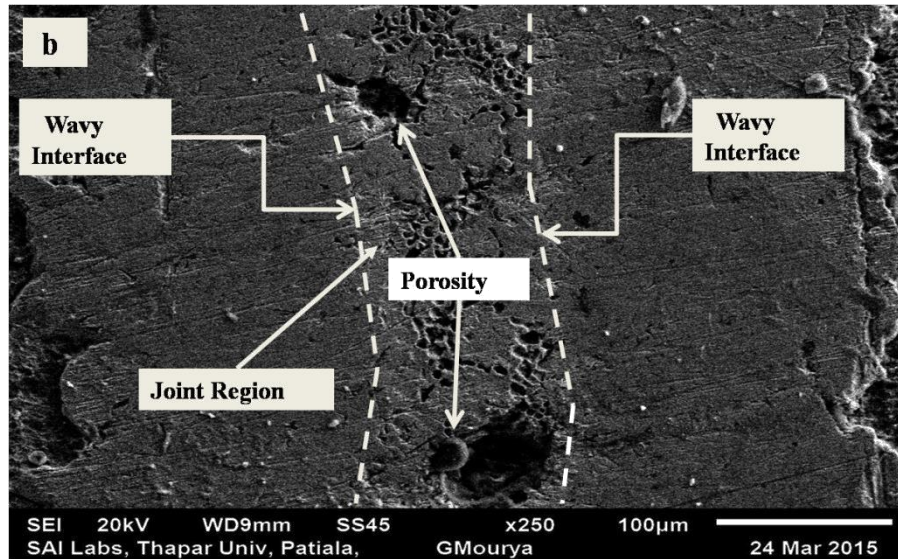


Figure 4.3 (b): Microwave processed dissimilar joint of stainless of 304-420

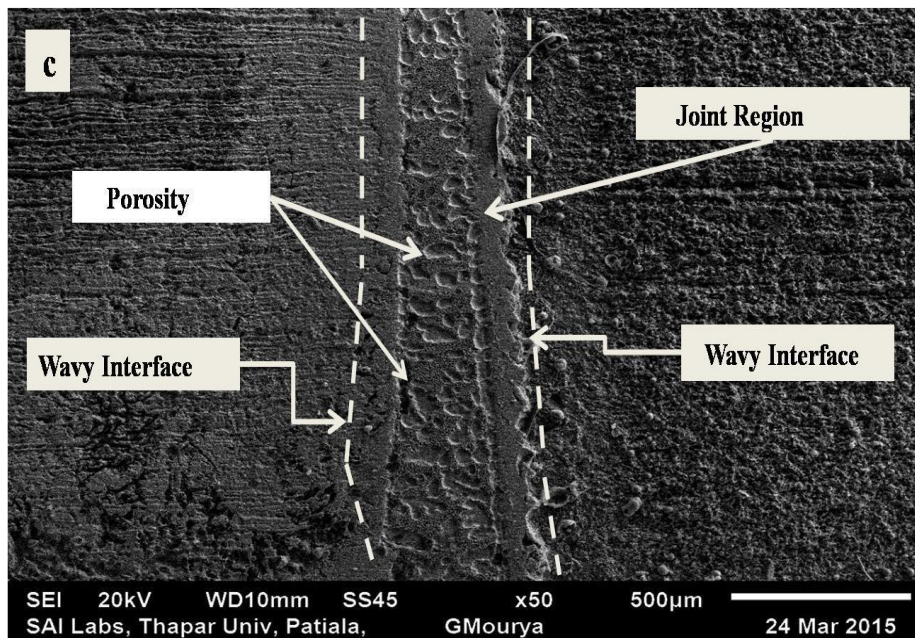


Figure 4.3 (c): Microwave processed similar joint of stainless of grade of 420

The obtained joint region by microwave processing shows wavy interface which confirms the mutual diffusion of interface powder and base materials. SEM images of joint zone, which shows metallurgical bonding and mutual diffusion of material. Similar joints of S.S 304-304 and dissimilar joints S.S 304-420 shows the lower porosity levels, while in similar joints of S.S 420-420 clean joints were obtained. In figure 4.4 (a-c) the microstructure shows rich cellular structure

of nickel in the joint region. Joints obtained through microwave processing leads to lower defect formation in joint region which is due to volumetric heating coupled with lower thermal gradients in the joint region. Though some carbide formation was observed which was justified by EDS analysis. The presence of carbon was due to the contamination of joint by separator sheet made of pure graphite.

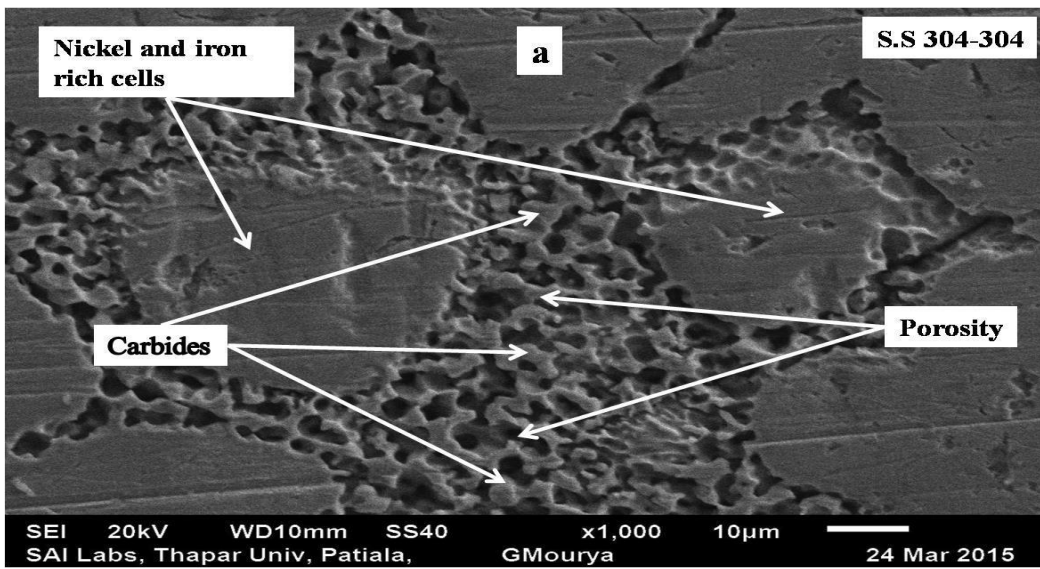


Figure 4.4 (a): SEM images joining of S.S 304-304 through microwave radiations.

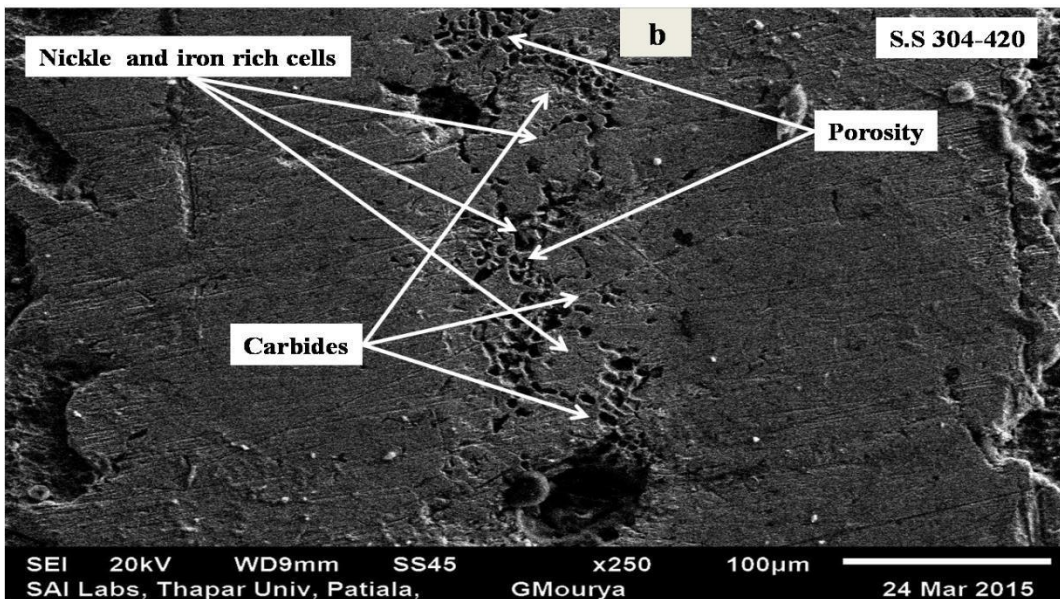


Figure 4.4 (b): SEM images joining of S.S of grade of 304 and 420 through microwave radiations.

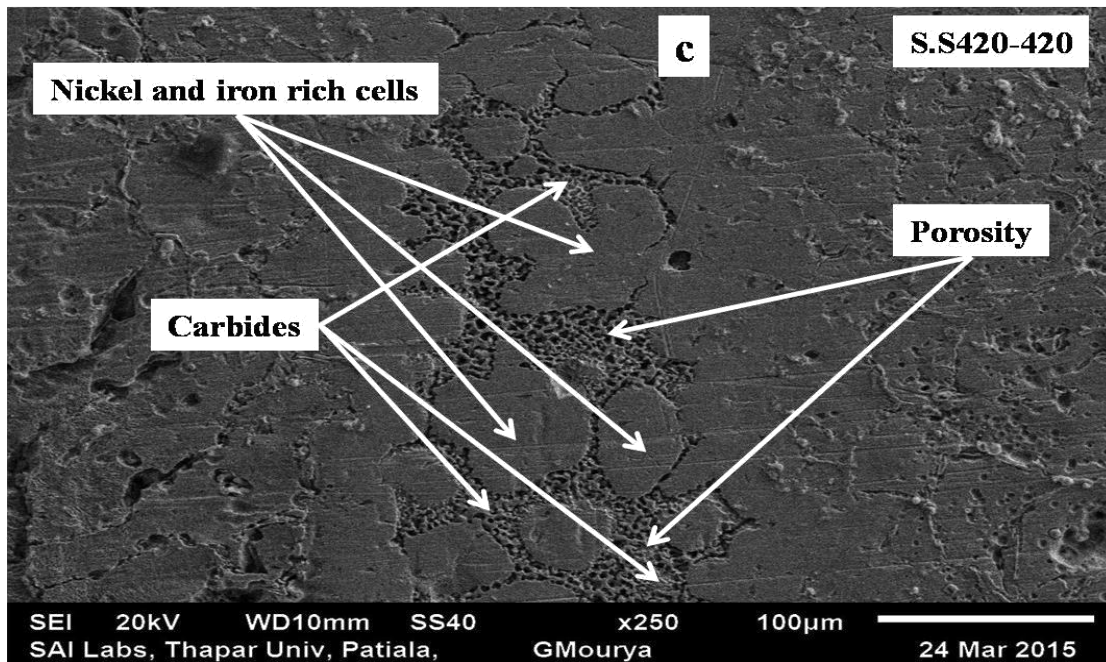
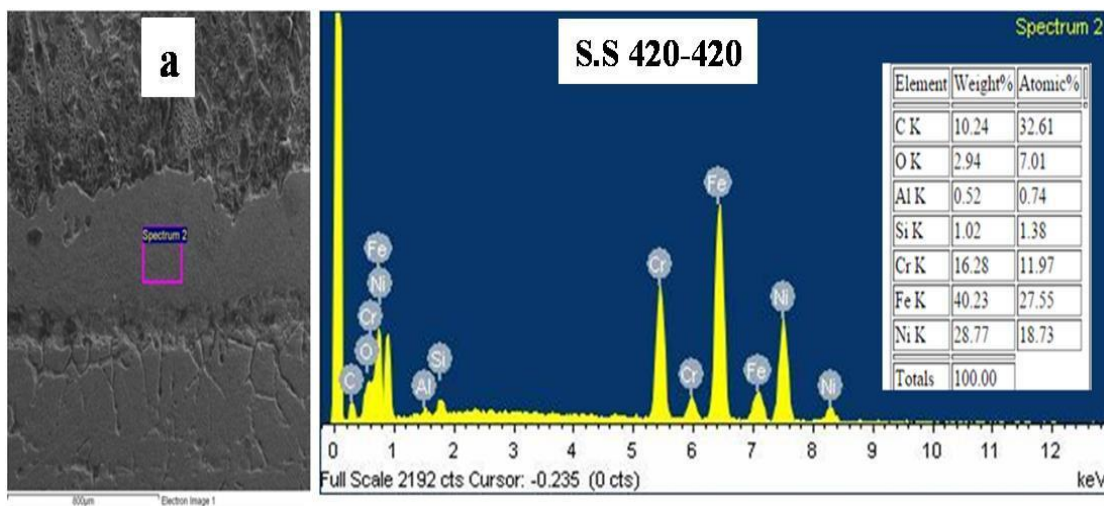


Figure 4.4 (c): Joining of S.S 420-420 by microwave radiations.

The EDS analysis of microstructures revealed that cells in the joint region are mainly of nickel and iron. The presence of iron is due to the mutual diffusion of elements from joint to parent and from steel to joint region. The presence of carbides (chromium and iron) was at the grain boundaries. This is due to the precipitation of carbides near the grain boundaries owing to the difference in solidification time. The results of EDS analysis of microwave processed steel joints are shown in figure 4.5 (a-c).



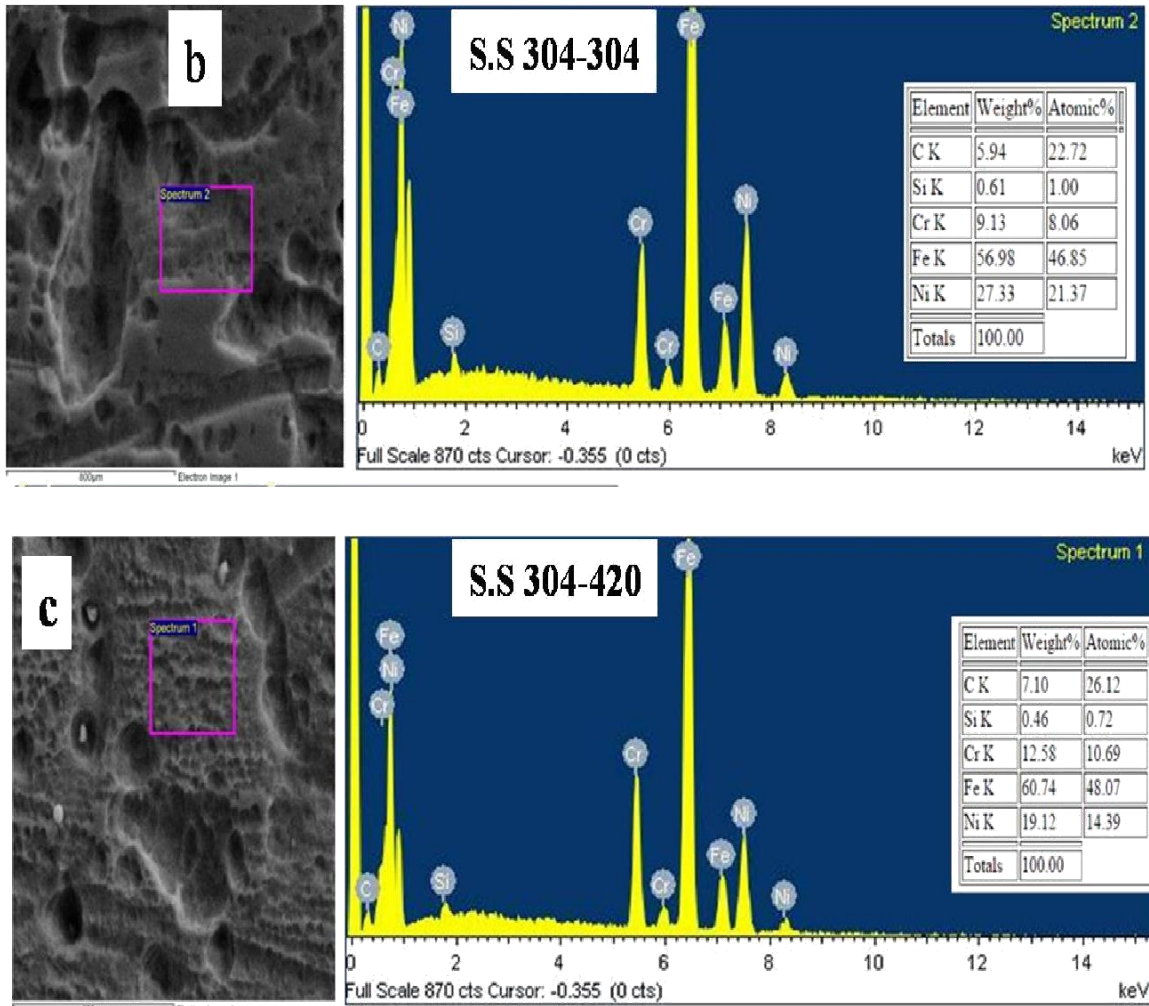


Figure 4.5: (a, b, c) shows EDS analysis of joints.

As the figures 4.5 (a,b,c) shows that percentage of chromium is more in case of similar joining of stainless steel of grade of 420 and minimum in similar joining of stainless steel of grade of 304. Due to presence of more percentage of chromium in similar joining of stainless steel of grade of 420 in joining region, which increases the strength than other joints because of formation of chromium carbides and hence chromium carbide increase the joints strength in case of similar joining of stainless steel of grade of 420.

4.1.3 Mechanical characterization of joints:

The developed joints are characterized by mechanical testing of joints. Vickers microhardness and tensile testing was carried out on joints develop by microwave processing. The obtained value of Vickers microhardness are shown in Table 4.1,

Table 4.1: Results of Vicker's microhardness tests

Material	Vickers Microhardness (HV)		
	Base Metal	Microwave Processed	
		Interface	Joint
SS: 304-304	250±5	282±10	330±15
SS:304-420	290±5	380±20	320±15
SS:420-420	330±5	370±15	425±10

The microhardness results shows that in the joint region the value increased significantly due to presence of chromium and iron carbides. Hardness of base metal was lower than the hardness of interface and joint. The highest microhardness (425 Hv) was obtained for SS420 steels due to higher amount of chromium content in parent metal, which diffuses into joint region and forms chromium carbide. The obtained results of tensile tests of joints are shown in table 4.2, and results revealed that the ultimate tensile strength (UTM) was highest for SS420 (368 MPa) but percentage elongation was lower due to higher percentage of carbide formation. The carbide presence hinders in the higher order deformation which leads to lower elongation percentages.

Table 4.2: Results of tensile strength of joints

Material	Microwave Processed Joint	
	UTM (MPa)	% elongation
SS: 304-304	301	2.86
SS: 304-420	315	2.24
SS: 420-420	368	1.62

Chapter 5

Conclusions and future scope

5.1 Conclusion

The processing of materials through microwave energy has emerged as a novel material processing technique for joining, which has extended its domain from sintering of ceramics to joining of metallic materials. Further, high temperature applications using microwaves were carried out such as claddings on the bulk metallic substrate and joining of bulk materials. The present work was based on joining of similar and dissimilar stainless steels of grade of 304 and 420 through microwave energy. Following are the major conclusions drawn from the work:

1. The joining of similar and dissimilar steels was successfully attempted by the using of nickel based powder at the faying surfaces in domestic multimode microwave oven through microwaves processing route.
2. The joints characterizations were carried out and it was showed that microwave processed joint have cellular structure and lower defects.
3. The mechanical characterizations of microwave proceeds joints showed that the joints formed by microwave processing shows metallurgical bonding which enhanced the mechanical strength. The joints further revealed lower defects due to volumetric heating by microwave radiations.
4. Due to the absorption of carbon from graphite sheet, it led to the formation of carbides in the microstructures hence higher hardness was obtained in microwave processed joints.

5.2 Future Scope

Following points can be considered as future work in the field of microwave material joining technique:

1. Evaluation of microstructure elemental composition by using different separator like silicon carbide sheets or alumina, that will be prevent the addition of carbon in the joint

2. To study the effect of exposure time of microwave on ductility of joint in terms of percentage elongation percentage.
3. The joining of hard to weld materials can be carried out by using microwaves.
4. Optimization of the welding parameters can be carried out.
5. To study the ultrasonic peening treatment on microwave proceeds joints for enhancement of fatigue strength.
6. Computational work on microwave processing of metallic materials can be attempted through multi physics software's such as ANSYS and COMSOL.

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