A

Dissertation on

# Microwave Welding of Polymer Matrix Composites

Submitted in partial fulfillment of

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## MASTER OF TECHNOLOGY

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(With Specialization in Welding Engineering)

By

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## CANDIDATE'S DECLARATION

I hereby declare that the work carried out in this dissertation titled **"Microwave welding of polymer matrix composites**" is presented on behalf of partial fulfillment of the requirement for the award of the degree of **Master of Technology** with specialization in **Welding Engineering** submitted to the department of Mechanical & Industrial Engineering, Indian Institute of Technology Roorkee, India, under the supervision and guidance of **Dr. Inderdeep Singh**, Associate Professor MIED, IIT Roorkee and **Dr.Navneet Arora**, Professor MIED, IIT Roorkee.

I have not submitted the matter embodied in this report for the award of any other degree.

Date-24th June 2019 RAVI SAUKTA

Place -Roorkee

This is to certify that the above statement made by the candidate is correct to the best of our knowledge and belief.

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# ABSTRACT

Nowadays, natural fiber reinforced composites are being preferred over synthetic fiber reinforced composites in many engineering applications. The major contributing factor is the global concern regarding the search of biodegradable and ecofriendly materials because of the stringent policies being enforced on the manufacturers by the countries and the governments. As a result of this researchers nowadays have turned towards the development of natural fibers (jute, sisal, kenaf, bagasse etc.) based polymer matrix composites. Though it is practically not possible to replace all of synthetic based PMC's by natural fibers based PMC's because of the high strength provided by synthetic fibers, but natural fibers based PMC's can be used in areas where load bearing is not the main concern.

At present mostly thermoplastics and thermosets are being used as resin matrices for natural fibers because of good noise damping properties and their chemical resistance characteristics. By making use of natural fibers, a considerable reduction in weight of product also takes place which naturally favours reducing the carbon footprint of the component.

Most widely used thermoplastic matrices are polyvinyl chloride, polyethylene and polylactic acid. So the joining of PMC's becomes necessary to join individually processed composite parts into a usable assembly.

In the present research investigation, attention has been focused on the joining of natural fibers based PMC's using microwave welding which is a non-conventional method of joining such PMC's. By using this method the traditional problems like stress concentration due to mechanical fastening or poor strength due to adhesive bonding could be avoided, better quality weld could be produced in a faster time.

# CONTENTS

## LIST OF FIGURES

# LIST OF TABLES

# Chapter 1 INTRODUCTION

Nowadays, joining of thermoplastic based composites is becoming important since thermoplastic composite materials are increasingly replacing metallic, thermoset based composites structures in order to bear static and fatigue loads in marine industry, auto motives industry and aerospace sector. Lots of joining methods have been developed till now, in order to weld reinforced and unreinforced thermoplastic polymer based composites. But, each of the techniques developed are having only specific applications. Thermoplastic composite welding could become a fine alternative to eliminate these kinds of problems.

The main goal of here is to describe the fundamental steps required to establish bond between thermoplastic composite parts and represent various advanced thermoplastic composite welding techniques. As we knew that not a single joining technique can replace all the available joining to join the various materials, so for different types of applications, different type of method has to be used for joining purpose.

There are two types of joints in PMC's: Adhesive joints (Permanent type of Joint) and Mechanical joints (Temporary type of Joint). These two types of joining methods usually are independent of each other but for some application, these methods can be so as to get some kind of advantage based on the application for which it is being used. Adhesive bonding is found to be simplest and frequently used method for joining composites. In adhesive bonding, two adherend materials are joined by making use of an adhesive. In mechanical joints, rivets bolts, screws etc. can be used to make the joint. Apart from these joints welded joints are also there which we the focus of attention of this report.

Composites consists of one or more discontinuous phase (reinforcement) embedded in a continuous phase (matrix).Main part of composite known as matrix holds the reinforcing phases.

## 1.1 Composite materials

### Classification of composite materials:

- On the basis of matrix material
    - Polymer matrix composites(PMC)
    - Metal matrix composites(MMC)
    - Ceramic matrix composites(CMC)
- On the basis of reinforcement
    - Particulate composites
    - Fibrous composites
    - Laminate composites
    - Flake composites

This dissertation focusses on the PMC's.The reinforcement in the PMC's may be in different forms such as short fibers or long fibers or particles.In the low performance composites,the reinforcement usually is in form of short or chopped fibers i.e. particles.It provides stiffening but very little strengthening to the composite and mainly load is carried by the matrix.

In high performance composited, continuous fibers provide the desirable stiffness and strength. In this case, matrix provides protection and supports the fibers and help in redistributing the load from broken to adjacent intact fibers.Due to high specific strength and modulus, fiber reinforced polymer (FRP) composites have received widespread attention, which are usually fabricated using high strength synthetic fibers such as carbon, glass and aramid with thermoplastic resins (nylon and polyolefin), thermoset resins (epoxies etc.) and unsaturated polyester based matrices.

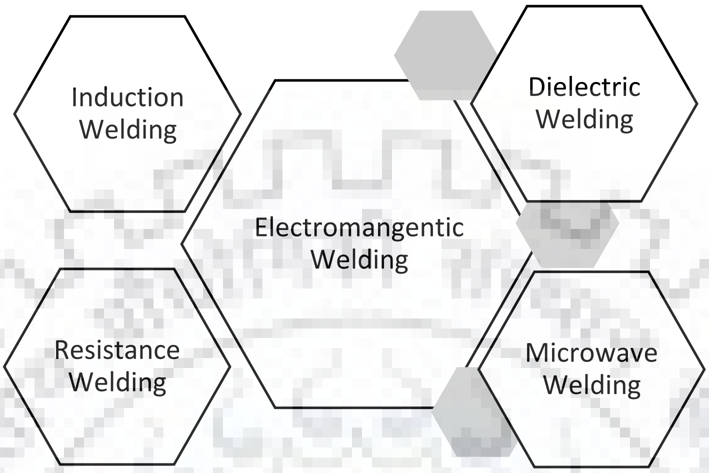


**Fig.1 Electromagnetic welding classification [63]**

### 2.1 Introduction to microwaves

The electromagnetic waves (EM) lying in frequency range of 300 MHz-300 GHz are called as microwaves. Only selective kinds of materials can be used while using this process. The properties of prime importance regarding this process are complex relative permittivity and loss tangent of the dielectric used. Higher loss tangent, dielectric loss leads to more heating and vice versa.

Microwaves are EM waves having electric and magnetic field orthogonal to each other having wavelength range from 1mm-25µm.The interaction of the material with microwaves depends on the magnetic and dielectric and property of the wave because both the electric field as well as the magnetic field component interacts on their own differently with the material during irradiation [46,47].

The PMC's are processed as well as joined by low temperature microwave processing having temperature between 500-1000°C.

Microwave welding is a type of electromagnetic welding. It is possible due to the interaction of the microwaves with the material leading to heating and the joining. Based on different type of material, many kinds of interaction takes place leading to variable core mechanisms for heating to take place. For metal based materials, this heating is influenced by magnetic field but for non-metals, this heating takes place due to electric field usually. In metals, ceramics etc. temperature gradients can be set up, also microstructure change can occur if proper attention is not paid to the process parameters.

Uniform bulk heating taking place in microwave for PMC's as compared to regular heating methods. Variable size of PMC's which include thin as well as thick specimens have been made with improved properties and better (The uniform heating characteristic of microwave yields better polymeric products than the conventionally cured. For example, thin as well as thick PMCs were processed with better mechanical properties and better joining in PMC specimen by using variable microwave heating methods to concentrate more heat at the interface of the adherend [1-8, 78].

The researchers have in the past used susceptor materials like charcoal powder, conducting particles, nanofiber coatings on composites to expose the most of the microwaves to a specific area for most of the heat to generate there, called selective heating. Using this method, processing of various composites as well as joining of various composites have taken place .In selective heating, only a selected volume of the target material is exposed to microwave radiation. This method of selective heating has lead better matrix fiber bonding [9–34].

Quite less work has been done on microwave joining and processing of natural fiber based PMC's, though the results have proved improvement in the properties of the final specimen as well as better joining strength, making it a good alternative for joining of such materials [35–41].

Microwave joining have been used in the past for various metal based materials by various researchers for metallic joining .The microwave processing of bulk metal was first reported in the form of patent for bulk metal joining [42, 43–45].

## 2.2 Principle of Microwave heating

Maxwell's equations have great importance in microwave heating phenomenon when microwave welding is taking place inside the microwave cavity.

The interaction of the microwaves with the specimen is governed by Maxwell equations [48].They take into consideration the effects of the magnetic field as well as the electric field harmonic variation on the specimen over a period of time and how its properties varying because of it. The Maxwell equations are given below:

$$\nabla \cdot \mathrm{H} = 0$$

$$\nabla \times \mathrm{E} = -j\omega\varepsilon_0\varepsilon^*\mathrm{E}$$

$$\nabla \cdot (\varepsilon\mathrm{E}) = 0$$

$$\nabla \times \mathbf{E} = j\mu\omega\mathrm{H}$$

where E- time-harmonic electric field, H-the time-harmonic magnetic field , $\varepsilon^*$ -complex permittivity of material,$\varepsilon$- permittivity, $\varepsilon_0$- permittivity in air,μ- magnetic permeability , j- imaginary unit, ω - angular frequency of microwaves

In the equation above, the complex permittivity $\varepsilon^* = \varepsilon' - j\varepsilon''$, is of prime importance which governs the heat generation due to microwaves [11,14,17,19].In this equation,$\varepsilon'$ represents the real segment of complex permittivity $\varepsilon^*$,which denotes quantity of electrical energy which could be stocked inside the specimen and is termed as dielectric constant, $\varepsilon''$ is imaginary segment termed as dielectric loss factor which signifies capacity of specimen to give away the energy it received from microwaves.

These Maxwell's equations can be solved with appropriate BC's for the electric and magnetic field distribution in the microwave applicator of a known dimension [49]. By knowing the EM field distribution, we can know the approx. position of the specimen inside microwave for better heating by providing maximum coupling of EM waves with the material[50],[51,52,49].By increasing the size of a microwave cavity ,the number of hotspots on the sample can be decreased leading to higher volume of sample capacity [50,51,52] .But with increase in size of the specimen the heating also becomes less uniform leading to formation of many hotspots and the microwave heating will take place similar to regular heating process.[51,49,78]

The power absorbed and the penetration depth to which microwaves can go in a particular material depends on its properties of EM waves, material and its mass and thickness.

Microwave penetration in a metallic material is nearly zero and termed as skin depth [53, 53,55].

### 2.3 Microwaves interaction with various materials

Depending on the material, there is variable variation of electric and magnetic field throughout the material thickness. In low loss insulator materials like Teflon and generally most of the polymers, there is almost negligible decrease in electric and magnetic fields throughout the thickness, so no need to consider skin depth because of negligible effect in case of polymers. But because of such high penetration depth which is generally because of very high dielectric loss also means that amount of energy absorbed per unit volume of the material is also very low, but as generally the polymers are low melting point materials so it is not much a problem in most of the cases. In case of polymers having moderately high dielectric constant the amount of energy absorbed per unit volume can be increased to balance the energy loss taking place due to it's moderately low dielectric loss to make it interact more with the microwaves.

Most of conducting metals possess very high dielectric loss or also called no loss materials and negligible penetration depth and reflect the microwaves.

Teflon used in this experiment is transparent to microwaves because being low loss insulator, whereas the SiC bar used is acting as absorber, which absorbs all the microwaves falling on it because of being a high loss insulator. In general the advanced materials like PMC's are considered as mixed absorbers, because of having variable dielectric loss of fiber as well as matrix.

Non-magnetic materials such as polymers, water, Al, etc. are influenced only by the electric filed and not the magnetic field component of the EM waves and heating takes place because of dipolar losses and conduction losses. Mainly dipolar losses is predominant in dielectric insulators but in case of metals and conductors conduction losses takes preference. In dielectric insulators like polymers, dipoles are produced in material due to oscillating electric filed which during reorienting themselves generate heat and increases the temperature. [48, 51, 52, 56, 57, 58].

In conduction loss, metals having free electrons moves along the direction of applied electric field and because of high conductivity ,electric field decreases through the thickness leading to induced current and magnetic field in direction opposite to external applied fields and this causes little motion because of these opposite fields leading to heating.

It is to be noted that in pure insulators, no microwave energy absorption is there because of very low dielectric loss factor whereas as in dielectric insulators like polymers they have the property to polarize (due to displacement of electrons around nuclei, due to displacement of nuclei with respect to each other and due to aligning of dipole on applying electric field) in electric field leading to heating. [52]

No matter how much a high dielectric loss factor (to absorb more power) we have, still the process can sometimes not be efficient enough because of the low penetration depth of the microwaves. This can happen in case if the size of specimen is comparatively much higher than the microwaves penetration depth inside it, which will lead only to surface heating. Penetration depth is also a function of frequency of the microwaves and with increase in frequency ,the microwave power absorption is found to increase but the penetration depth in this case will decrease[50,48 ]

This dependency of loss factor and dielectric material size on power absorbed and depth of penetration is valid only upto moderate temperature upto nearly 500°C, and when the temperature is increased further, the dielectric property of the material will start varying e.g. SiC having 1.71 loss factor at room temperature jumps to 27.99 loss factor at 695°C for a 2.45GHz microwave. [59].

The skin depth in case of metallic powders can be increased by making them in powder form so that their penetration depth is comparable to their own size, but in case of bulk metal rather than in powder form, the microwaves are reflected and can cause sparking too. Experimentally the nano and submicron powders have been found to absorb better microwaves and improvement in the microstructures of the specimen have been found, and a critical size of 100 micro meter has been found below which heating is uniform and above which heating becomes non uniform. [60]

In composite materials, microwave absorption is dependent on whether the fiber or the matrix phase is having high dielectric loss, which further on transfers the other one by conduction. It has been found that reinforcing with conductive particles have improved the microwave absorbing and other related properties of the constituent composite [61, 62].

For microwave joining of PMC’s, lot depends on the dielectric loss factor of fiber as well as matrix. The natural fibers have low conductivity, so low dielectric loss factor ( artificial fiber like carbon fiber have high loss factor ) ,so comparatively matrix will act as the high loss factor constituent in the composite and will get heated selectively and transfers heat by conduction to the fiber part leading to better bonding at their interfaces. [30].

There is temperature dependence of dielectric properties of fiber and polymer on temperature, which is varied during microwave joining. In case of thermosets, as they have cross linked bonds ,so during microwave heating, the viscosity increases which prevents the dipoles motion in presence of applied electric filed and consequently no heating can take place by dipole loss and only conventional heating will take place and it will get burned [32–34]. Whereas in case of thermoplastics, they have to be heated initially upto at least a critical temperature because of possessing low degree of crystallinity and dielectric loss factors . Degree of crystallinity in case of thermoplastics plays a vital role in the uniform heating of a PMC. It has been found that for more than 45% degree of crystallinity, the specimen becomes nearly transparent to the incoming microwaves because of obstruction to movement of dipoles on application of electric field [31].Thermoplastic and thermoset PMC’s way of absorption of energy is different. In case of thermoplastic based PMC’s ,mostly the energy is absorbed by fibers below the critical temperature when the PMC is having high degree of crystallinity and this heat is later on transferred by conduction to the polymer part. But if the thermoplastic PMC is possessing low degree of crystallinity then energy is absorbed by the fiber as well as the matrix too, and the more energy between the two is absorbed by the one having high value of dielectric loss factor. This energy absorption by the thermoplastic based PMC’s is also dependent on the temperature also and increases as the temperature reaches above the critical temperature which leads to even heating of the PMC having high conductive fiber reinforcement. For thermoset based PMC’s ,most of the energy is absorbed at the room temperature by the part possessing higher dielectric loss factor but when temperature increase ,then the energy absorption is affected by the conductivity of the fiber used because of the cross linked structure of the thermosets. The curing of thermoset polymer based PMCs is dominated with energy absorption by high dielectric loss factor constituent at room temperature, however at elevated temperatures energy absorption is dependent on conductivity of reinforcement fibers due to the cross linking of thermoset polymer matrix [41].

## 2.4 Microwave welding process

In microwave welding, any material in the form of a thin layer having good electromagnetic absorbing capacity has to be placed at the bond line between the parts to be joined and simultaneously welding pressure has to be applied along with high intensity microwave energy having frequency range depending upon the microwave parameters . The microwave energy will induce heating in the sample which would then lead to an increase in the temperature in the susceptor material placed between the joint and then this susceptor material will further transfer the heat by conduction to the remaining joining elements at the joint interface thus leading to formation molten polymer material at the interface.

One of the benefits of microwave joining is that it will lead to usually faster curing times when compared to the other type of the joining processes available. Due to quite faster heating rate being encountered during the usage of microwave joining could lead to reduction in the processing time of the joining process and consequently increase in the energy efficiency.

Microwave energy differs from conventional heating in the sense that, it is delivered directly to the material by the molecular interaction with electromagnetic fields produced. During heating by conventional methods causes buildup of temperature gradient only along the thickness direction of the specimen but microwaves have the capability to penetrate inside and supply energy throughout the specimen resulting in heating the material uniformly, which is referred as volumetric heating process. So microwave heating is quite helpful for fast and uniform heating of thicker materials. In conventional joining processes during heating, we have to select slow heating rates in order to prevent the setup of sharp thermal gradients which could lead to setup of induced stresses. Therefore, so it is evident that in microwave heating process, there definitely exists some kind of relationship between curing time and the joint produced. On interaction of microwaves is with different materials possessing different kinds of dielectric properties, would lead to selective coupling based upon the loss tangent of material. The material possessing high value of loss tangent will have more selective coupling with microwaves and would heat more than the other material.

So in order to generate more heat the joint interface ,a material possessing high loss material called susceptor has material has to be used at the interface for selective heating to take place.

Nowadays a lot of work is going on the natural based fiber composites and their joining. In one of the studies green sisal fiber reinforced polylactic acid composites were prepared with variable fiber content using compression moulding and joined using microwave energy process with charcoal as an accelerator. Time taken for bond formation was more for samples with lower fiber content [64].To promote green composites need and to replace the petroleum based resources have been studied. The various research work leading to development and mechanical characterization of different green composites (PLA based in detail) with varying natural fibers and biodegradable polymers has been studied [65].In another study, gully biodegradable natural fiber (grewia optiva) reinforced PLA composite has been developed and joining in lap configuration done using adhesive bonding and microwave joining and charcoal used as an susceptor and then simulation is done. Tensile strength of neat PLA resin increased by 75% by addition of grewia optiva and better joint strength obtained using microwave than adhesive joining [66]. GOF (grewia optiva) and NF (nettle fiber) were also used in combination with PLA and PP based composite producing four combinations and joining done using adhesive as well as microwave. PLA based composite shows higher failure load (may be because the failure strength of neat PLA resin was higher than PP).Joint strength was observed more in microwave than adhesive joining.

Power input, microwave exposure time, susceptor, location of specimen in microwave cavity are found to be having important roles in governing joining process[67]. Three different fibers ( nettle, grewia optiva, sisal ) used with PLA polymer to develop composite using hot compression wear and frictional characteristics of developed composite observed under varying load, sliding speed and sliding distance revealed improvement in wear behaviour and reduction in friction coefficient[68]. Processing of polymer matrix composites was done using variable frequency microwave(2-7 MHz) and compared with fixed frequency microwaves(915 MHz,2.45 MHz) by joining Nylon 66/GF (33%) in lap joint configuration using araldite as adhesive which is cured during process. Bond strength of test piece joined by VFM was found 1.5% higher than fixed frequency equipment. Also found that, the higher the power of VFM equipment, the higher will be bond strength within some limits [69].Grewia optiva and sisal fibers were used with PLA and PP as polymer matrix to obtain different composites which revealed that PLA composites shows overall better performance in terms of mechanical behaviour [70].Study of natural FRP composites to replace non-biodegradable carbon or aramid FRP was done for wind turbine parts. Problems associated with primary manufacturing of natural fibers was discussed and problem in their secondary manufacturing like drilling and joining discussed for wind turbine parts [71].

The use of lignocellulosic fiber (biodegradable natural fiber) in biopolymer matrix was studied and processes to develop it (injection moulding and compression moulding) was discussed. Various parameters affecting quality of LFBC are also discussed [72].Overview of secondary processing techniques (mainly drilling and joining) for composite materials and the major challenges were discussed [73].Reduction in tensile strength was observed due to different environment conditions on developed composite of hemp / PP, jute / PP, sisal /PP .All composites reveal increase in weight after exposure because of diffusion of liquid molecules, capillarity transport in micro voids and incomplete wettability of fiber by matrix[74].Recyclability potential of bagasse fiber reinforced polypropylene composite observed by finding tensile properties, crystallinity and aspect ratio after recycling the composite multiple times. Aspect ratio of fibers is found to increase due to crushing of fibers during recycling, crystallinity was found to increase but due to increase in surface roughness and hardness, the overall flexural properties were deteriorated [75].Natural FRPC were fabricated with microwave curing consisting of fibers-sisal, grewia optiva and thermoplastic polymers-PP and ethylene vinyl acetate. Microwave wattage and exposure time was optimized and tensile, flexural impact strength evaluated. Tensile, flexural strength was enhanced because of better interfacial bonding but impact strength reduced due to stress concentration regions [76].Investigation of tribological behaviour of hemp fiber reinforced polypropylene composite is done. Tensile strength, wear resistance increases whereas tensile modulus, flexural strength decreases due to use of hemp fiber into PP matrix [77].

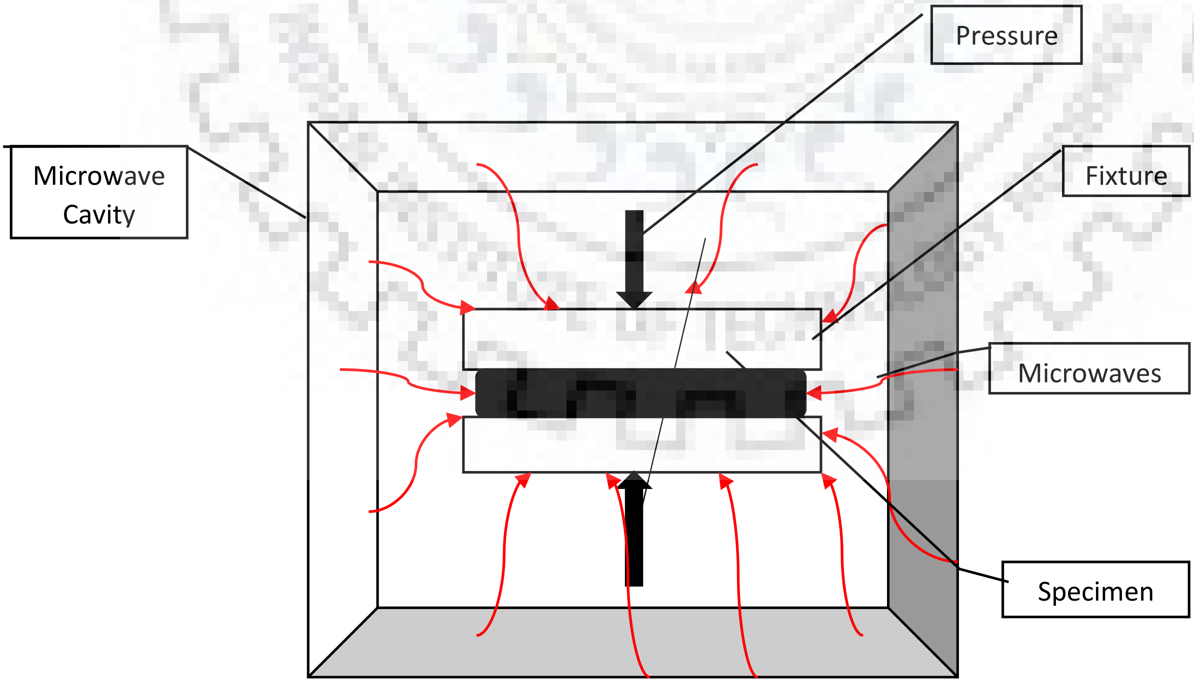


**Fig.2 Basic microwave heating setup**

## 2.5 Research gaps

When using susceptor material, then the critical size of the susceptor material used also has to be taken into consideration, leading to more complex and non-repeatable process. While making use of such micro or nano size susceptor powders just adds more to the cost of joining and in turn making the process more uneconomical. Susceptor materials while joining using microwaves use have lead to defect leading to reduction in strength of the joint produced. Very few studies have been done on the joining of natural fiber based composite, which could be the future because of being not only biodegradable but also very economical as well as readily available in abundant quantity. Very few research has been done on the joining of natural fiber based polymer matrix composites. Mostly adhesive joining has been done and its optimization is tried out rather than going for some more unconventional method like microwave joining, which could be a potential method for the future of joining of such materials.

## 2.6 Problem formulation

In the experiment done here, a natural fiber based composite is made using by making use of jute as the natural fiber and polypropylene as the polymer matrix. A lot of work can be seen on joining of natural fiber based biodegradable composites by conventional methods like adhesive bonding etc. but little work has been done on non-conventional methods like microwave joining which offer huge advantages over the traditional methods and is very important as far as the future is concerned. So, in order to conform its advantages, mechanical characterization of the obtained natural fiber based PMC’s has to be done and analyzed the reasons leading to the failure of the joint obtained by this process to develop an understanding of the process used for such kind of materials.

## 3.1 Materials and methods

### 3.1.1 Fibres and matrix

Raw materials used in the experiment includes polypropylene (PP) pellets and jute fiber.PP was used as matrix material, and jute fiber (in woven fabric) was used as the reinforcement material. Polypropylene used was supplied by Reliance Industries Limited, ParcChembur, (Mumbai), India, in the form of homo-polymer pellets. Polypropylene used has a density of 0.905 g/cm$^3$ at room temperature. The melting point temperature of PP is 170°C,its glass transition temperature is 100°C it has a melt flow index of 10.5 g/10 min. Woven jute fibre used here was supplied by Women’s Development Organization (WDO), Dehradun, Uttarakhand, India. Jute is a lignocellulosic fibre i.e. a plant based fiber. The ignition temperature of jute is 193°C.

In order to fabricate composites, PP sheets of dimensions 150 mm X 80 mm X 1 mm were prepared by compressing upto 200 grams of PP pellets in the compression moulding machine at 120 kg/cm$^2$, which has been heated upto 180°C.After a time period of 20 minutes, it is then allowed to cool in the die itself ..Alternate layers of woven jute fiber and PP polymer matrix were kept one above another so that polymer can bind the fiber firmly with it. Sticking of the composite to the heaters of the compression moulding machine can be avoided by using polyethylene sheet. In the end the composite made is removed from the mould when its temperature reaches nearly 80°C. The pictorial overview of the process is shown in the figure below.

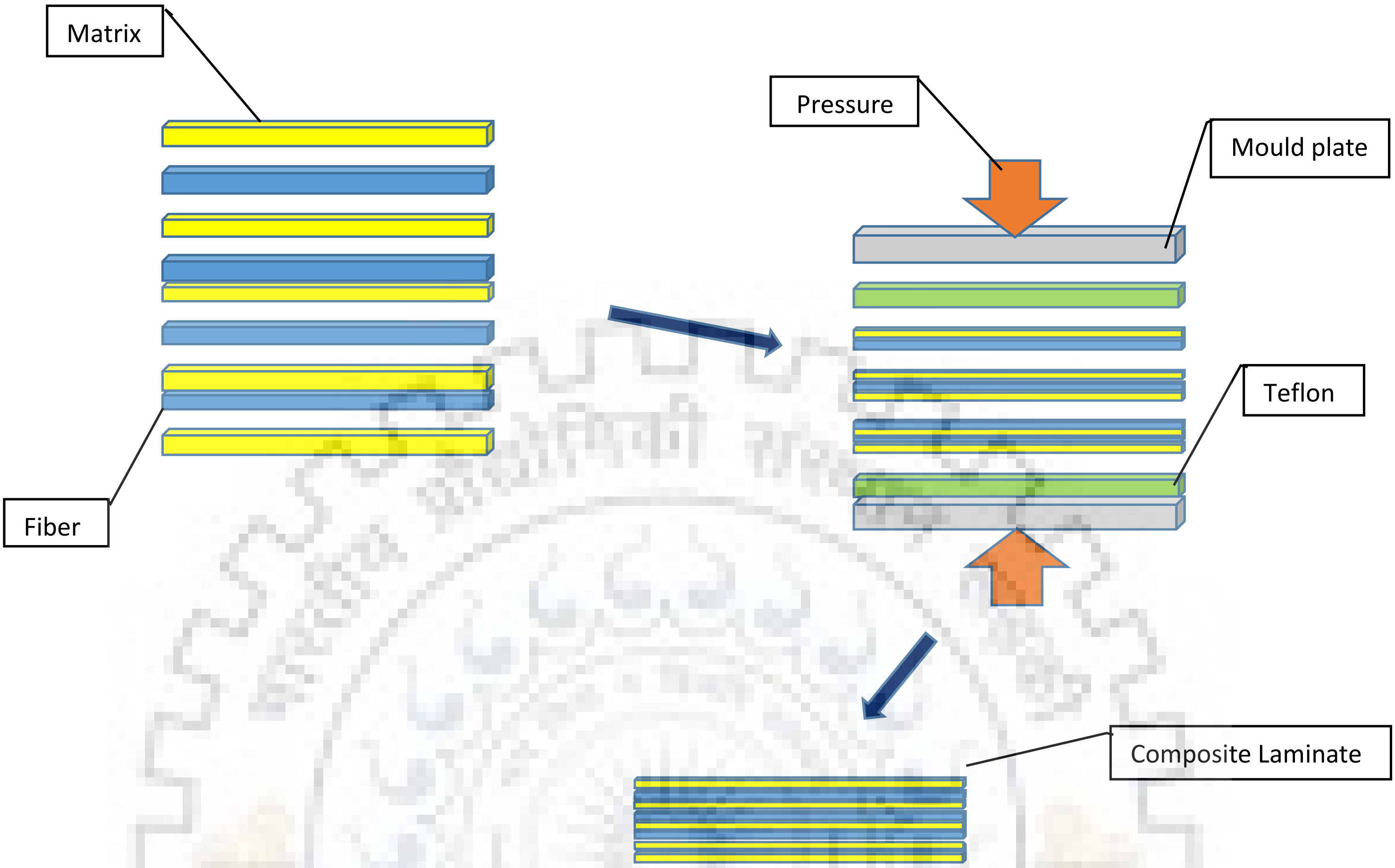


**Fig. 3 Composite preparation block diagram**

### 3.1.2 Microwave Specification

The microwave used is a domestic microwave with a fixed frequency of 2.45 GHz made by LG .The power output was kept at 900 W while doing the experimentation on the composite made. The dimensions of the inside of the microwave irradiated cavity was 527mm X 392 mm X 480 mm. In place of making a mould for the composite to keep it inside the cavity, vitrified ceramic tiles were used because of good microwave energy absorption property. The vitrified tiles used have comparatively more melting point than the polymer used in the study i.e. polypropylene and possess good surface finish. Time was varied during the joining experiments keeping all other parameters constant.

### 3.1.3 Mechanical behaviour of developed composites

The parent composite made by compression moulding is cut as per ASTM D3039 in order to perform its tensile testing. The composite specimen for lap joint is cut as per ASTM D5868 to do its tensile testing. The bonding area in the lap joint is taken as 1inch x 1inch, which is roughened using a file and emery paper in order to remove the dirt or oxide layers present on the sample and also to increase the contact area between the two samples to increase the bond strength. The tensile strength of the parent composite specimen is compared with the tensile strength of the lap joint of the composite specimen. Both the kind of specimens were tested in a 1 tonne capacity Universal Testing Machine (UTM, Make Instron). No tabs were used in order to avoid the mechanical bonding of the specimen to be tested with the tabs used. Extension rate of 3mm/min was used during the tensile testing of both the parent specimen as well as the lap joint specimen. For parent composite, seven specimen were tested and for the lap joint specimen, three specimen of three different kinds of configuration were tested. Scanning Electron Microscope was used to study the microstructures obtained in order to predict the kind of failure taking place during the testing of the specimen.

In first experiment of microwave joining done on the composite specimen, the method used is the conventional method of using charcoal powder as a susceptor material, but no Teflon cavity has been used here. It results in the burning of the specimen completely as shown below

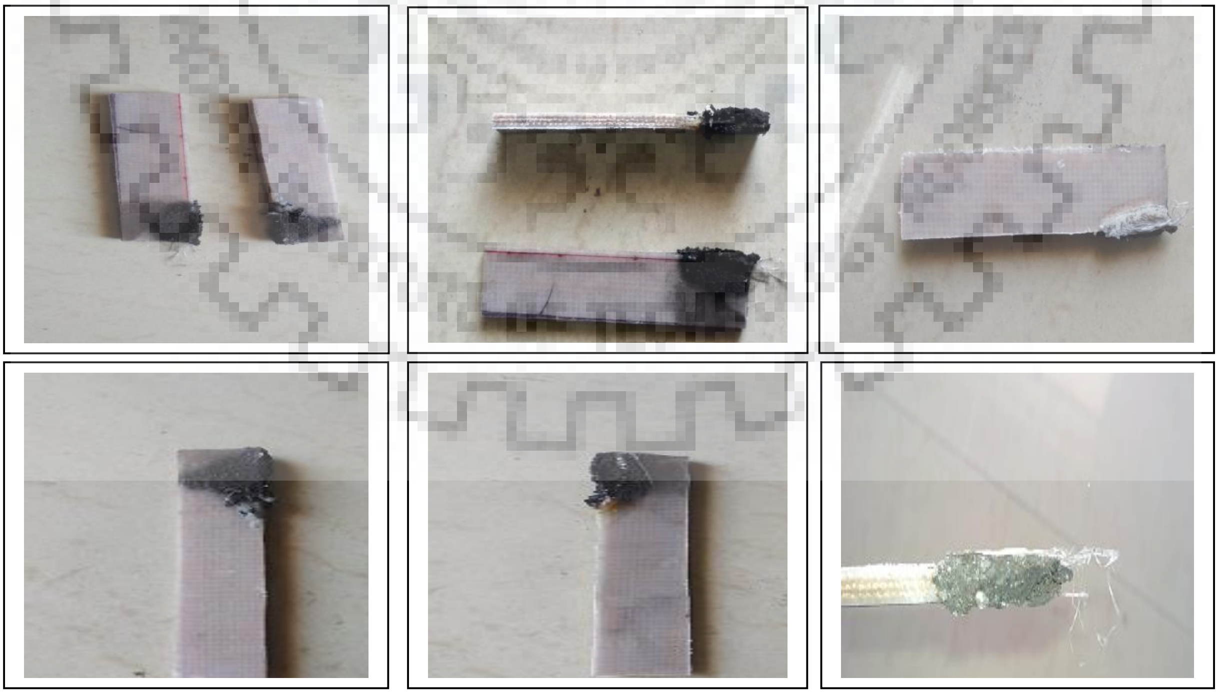

**Fig.4 Specimen heated using charcoal as a susceptor**

As can be seen in the Fig.4, a lot of charcoal has been found to be sticking with the composite where it has melted a lot of composite specimen. Though by doing different experiments, optimized parameters concerning the time required for joining of composite can be found by exhaustive experimentation, as has been found by various researches but still this method lacks in obtaining a pure welded joint i.e. joint free of any kind of impurities and also it could lead to various hot spots in the joint because of the preferential heating of the area containing the susceptor material. In this method, a lot of charcoal powder has to be used as susceptor material at the interface of the joint which later on gets accumulated inside the joint and can act as a defect and point of stress concentration leading to premature failure of the composite

Therefore, to avoid the contamination of the joint with impurity like susceptor material, it was decided to make a new kind of fixture by rather than using Teflon fixture which is used by most of the researchers in the field, the use of aluminium sheet fixture was proposed because it has melting point (660°C), which is above the melting point of the matrix material and the fiber material used in the experiment. The fixture made can be seen in Fig.5.

No kind of cavity is used here and instead of using susceptor material as charcoal powder silicon powder bar is used, which has sufficiently high melting point of 2730°C .One SiC bar is kept over the top surface of the fixture to get sufficiently heated during the microwave heating and provide additional heat to the joint for the bonding to take place.

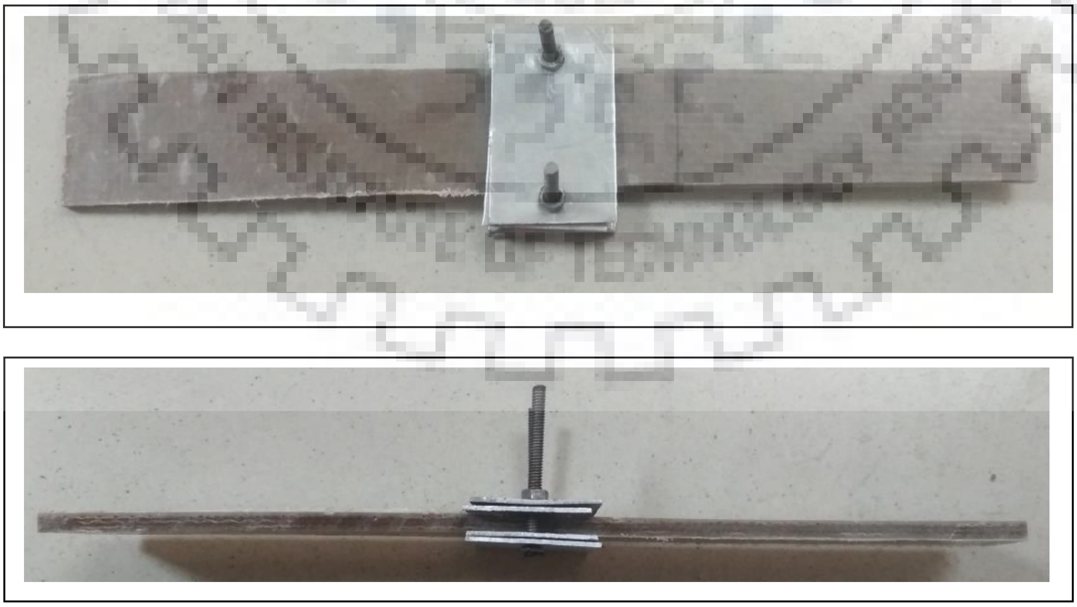

**Fig.5 Fixture for butt joint of composite**

Now joint 1 is made using the fixture shown in Fig.5. As per the experiment done on the earlier specimen the time chosen for this experiment is 1:35 min. The two composite specimen are joined in the butt joint configuration as shown in Fig.6, without using any kind of susceptor material, and just relying on the pressure forces developed due to the tightening of the screws on the fixture to aid in the joining of the interfaces of the specimen along with the heat generated due to microwave heating of the specimen as well as the aluminium plates. The joint obtained is as shown in Fig.6, which looks satisfactory in appearance, as the joint formed by visual inspection looks quite sturdy and no burning whatsoever has been found of the composites well as the fiber.

But it has been found that maybe due to excessive pressure being applied ,at the interface of the butt joint ,the specimen are being forced out of contact during the heating process may be because of the matrix material being flowing between the interface gap resulting in pushing of the specimen in the outward direction. So the joint formed has been only joined by the matrix material in between without any strengthening provided by the fiber, which is not the desired result.

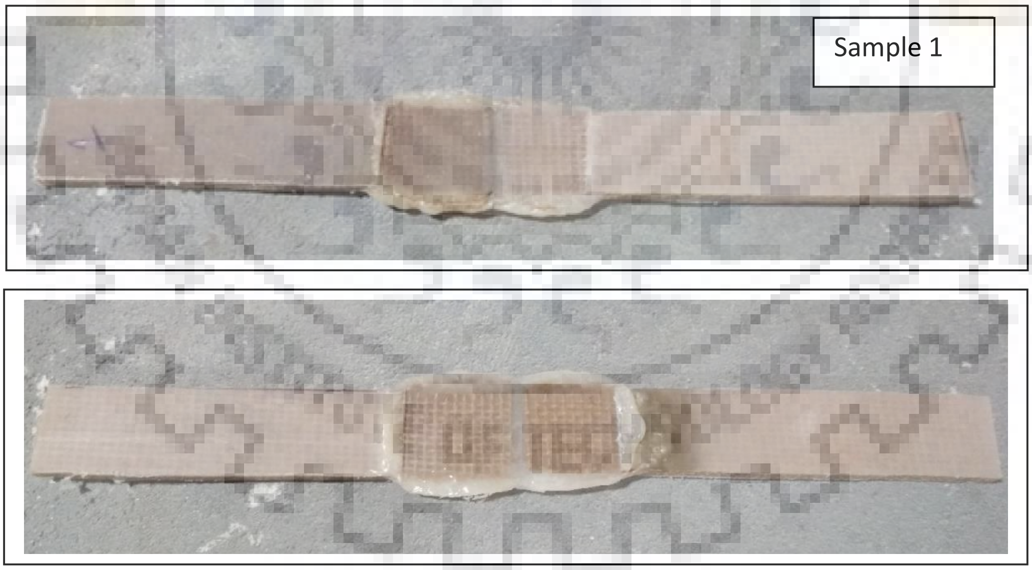


**Fig.6 Sample joint 1 (Butt joint of the composite)**

In joint 2 ,the specimen is kept again for a time period of 1:35 min, but in place of keeping a single SiC bar above the fixture, two SiC bars are kept sideways just touching the edges of the fixture to have uniform heat distribution in the whole fixture rather than just on one side of the specimen. But the microwave has to be stopped 7 sec before the desired time because of one side being burned more while one side non melted upto that extent as the other one. And in this case also the outer movement of the specimen can still be observed and here also the whole strength is just provided by matrix alone. The joint can be seen in Fig.7


**Fig.7 Sample joint 2 (Butt joint of the composite)**

Another joint was made again by placing two SiC bars kept sideways just touching the edges of the fixture and this time specimen is kept in microwave for 2 min. This time it lead to complete burning of the edges of the specimen touching the edges of the aluminium fixture, which leads to deflection of the specimen at these points at each end being kept in overhanging beams because of self-weight of the specimen, leading to near fracture conditions when hot, because of matrix as well as fiber being completely burned. So in order to prevent this the fixture has to be redesigned.

So in order to overcome the weakness of the overhanging beam because of melted condition of matrix being quite weak, the beam is made simply supported to provide sufficient support to it by making use of ceramic bricks as the supports. Also in this case to avoid the weakening of the joint area due to being compressed leading to stress concentration points in the geometry of the specimen, matrix material i.e. PP (polypropylene) sheets are used as a filler material both above and below the butt joint surface area which is being compressed, which could possibly hold the outward movement of the specimens. The adherends are kept for a time period of 1:30 min in the microwave cavity.

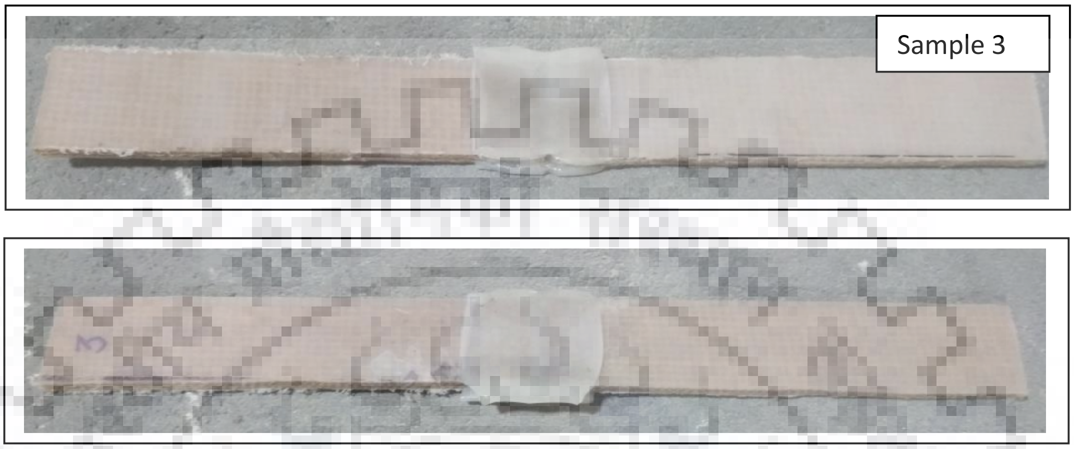


**Fig.8 Sample joint 3 (Butt joint of the composite)**

From joint 3 in Fig.8 ,it can be seen that the outward movement of the joint is considerably reduced by making use of the matrix material as the filler material as well as the shape of the composite specimen is retained leading to no stress concentration points. Also this thin matrix material will further strengthen the butt joint formed.


**Fig.9 Sample joint 4 (Butt joint of the composite)**

Joint 4 in Fig.9 is also prepared using matrix thin sheets as the filler material and by keeping the specimen for 1:30 min in the microwave cavity. In this joint also, the observations are quite similar to the joint 3, which gives nearly a perfect butt joint as far as from appearance point of view.

**Fig.10 Lap joint fixture configuration for microwave welding**

Now a lap joint is made using the same fixture as used for butt joint .The configuration of the fixture along with the composite specimen is shown above, having three supports. Two supports are at end and one support in the middle of the joints. The end supports are provide to prevent bending of each adherend during the heating due to its own weight and middle support is provided to support the joint at middle as well as to place the SiC carbide bar on it for preferential heating of the joint at the interface.

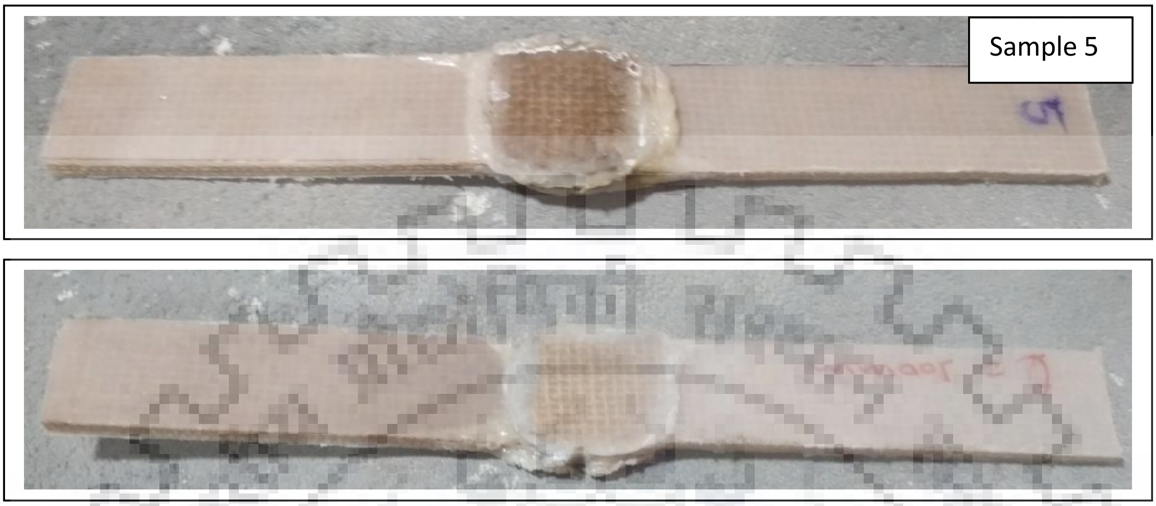


**Fig.11 Sample joint 5 (Lap joint of the composite)**

Joint 5 as shown in Fig.11 is a lap joint which is prepared using fixture shown above without using any susceptor material or filler material by keeping the specimen for a time period of 1:30 min. As can be seen for joint 5, the joint made is nearly perfect from visual inspection point of view as far as no burning of fiber or matrix is concerned but there is distortion in the shape of the joint because of slight deflection of the joint when the composite was in melted state leading to deflection due to the self-weight of composite as well as the weight of the fixture. This deflection can later on be removed by applying low pressure manually or automatically, but in order to avoid this kind of defect completely joint 6 is made.

Joint 6 was made by using end tabs between the composite specimen and the aluminium plates so as to avoid distortion of the joint produced. The setup is as shown in Fig.12

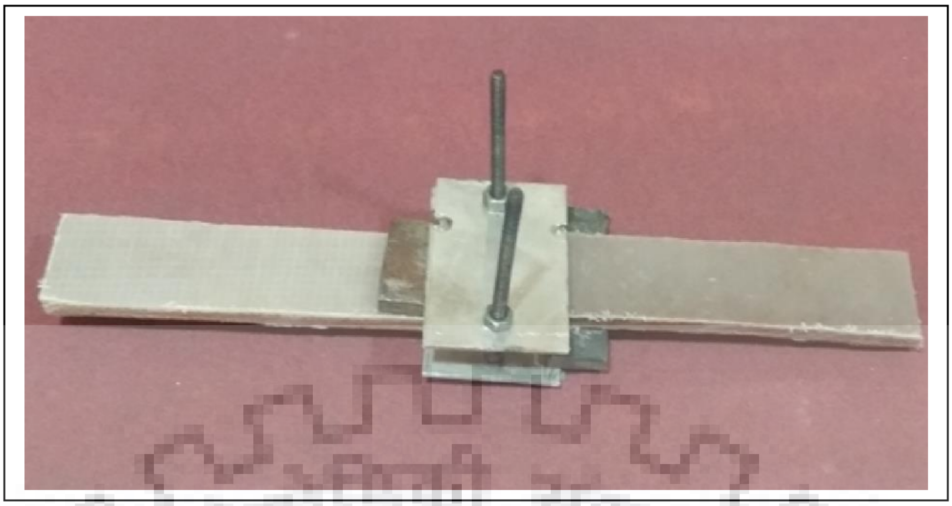

**Fig.12 Lap joint fixture configuration with metal tabs support**


**Fig.13 Sample joint 6 (Lap joint of composite)**

Joint 6 shown in Fig.13 is produced by keeping the specimen in the microwave for a time period of 1 min duration .From joint 6 above it can be seen that the joint produced is nearly perfect from visual inspection in terms of every parameter. But during the microwave joining of the specimen small sparks have been observed because of the interaction of the SiC occasionally with the aluminium tabs used resulting in the production of sparks which could be a potential threat and is a very crucial thing to be looked into as far as safety is concerned.

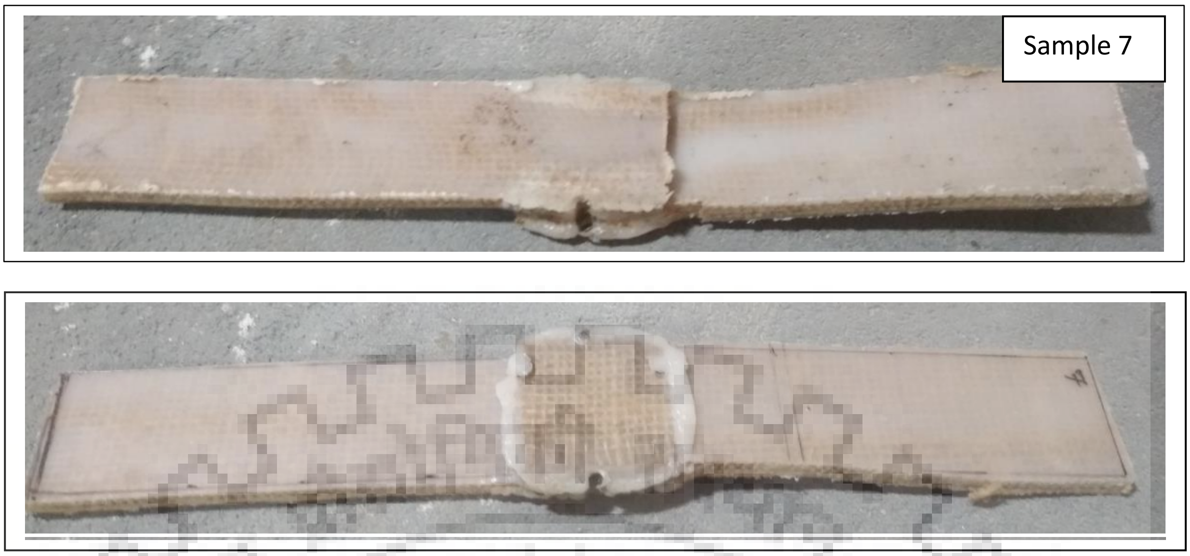


**Fig.14 Sample joint 7 (Lap joint of composite)**

Joint 7 as shown in Fig.14 is made without using any kind of tabs and at a time period of 1:30 min and the joint made is satisfactory from visual inspection except a little distortion, which can later on be corrected by applying little pressure on the joint manually to align it properly.


**Fig.15 Sample joint 8 (Lap joint of composite)**

Joint 8 shown in Fig.15 is also made without any tabs at a time period of 1:20 min. As can be seen that one side of the joint (on the upper side)  and little bit of the sides got burnt which could be due to combined effect of excessive pressure applied and some matrix material coming in direct contact with the SiC bar leading to burning .

After doing joining of various parts and inspecting them manually for perfect joints, now the joints are made using the best method as obtained from above methodology which can further be tested by doing tensile testing and FESEM microstructural examination. The various visual observations along with curing time taken for above eight samples is shown in Table 1.

**Table 1: Samples visual observations after microwave joining**

| Sample no. | Sample type | Curing time (in min) | Observation |
|---|---|---|---|
| 1 | Without using any filler material and one SiC bar used (Butt joint) | 1:35 | Only matrix is providing strength to joint due to outward movement of specimen during heating |
| 2 | Without using any filler material and two SiC bars used (Butt joint) | 1:35 | Only matrix is providing strength to joint, some burning also took place |
| 3 | Two PP layers ,one above and one below the specimen interface used (Butt joint) | 1:30 | Joining took place ,outward movement of specimens restricted |
| 4 | Two PP layers ,one above and one below the specimen interface used (Butt joint) | 1:30 | Joining took place ,outward movement of specimens restricted |
| 5 | Without using any filler material and two SiC bars used (Lap joint) | 1:30 | Good joint obtained ,slightly deflection at ends as joint was not provide any supports at the end of specimen |
| 6 | Without using any filler material and two SiC bars used (Lap joint),and additional end tabs made of metal used to support specimen at the fixture ends | 1:00 | Good joint obtained with no deflection at all. But little sparking took during joining because of tabs coming in contact with SiC bars |
| 7 | Without using any filler material and two SiC bars used (Lap joint) | 1:30 | Good joint obtained ,slightly deflection at ends as joint was not provide any supports at the end of specimen |
| 8 | Without using any filler material and two SiC bars used (Lap joint) | 1:20 | Burning took place on one side of specimen along with little deflection which may be due to improper orientation of SiC bar |

Now different types of configurations of joints with or without fiber, polymer and composite combinations is tried to find the joint for which maximum strength of bond can be formed. The curing time is taken in accordance with the curing time obtained for the samples joined earlier to get an approximate idea for the optimum time.

Three types of configurations of the joints were investigated. In one of the joints type, lap joint is made between the parent composite specimens without using any kind of filler material. In this type of configuration the joints were made simply by using combination of heat generated during microwave curing as well as applying the pressure with the help of fixture. These types of composite lap joints were referred in this study as Type 1 composite joints.

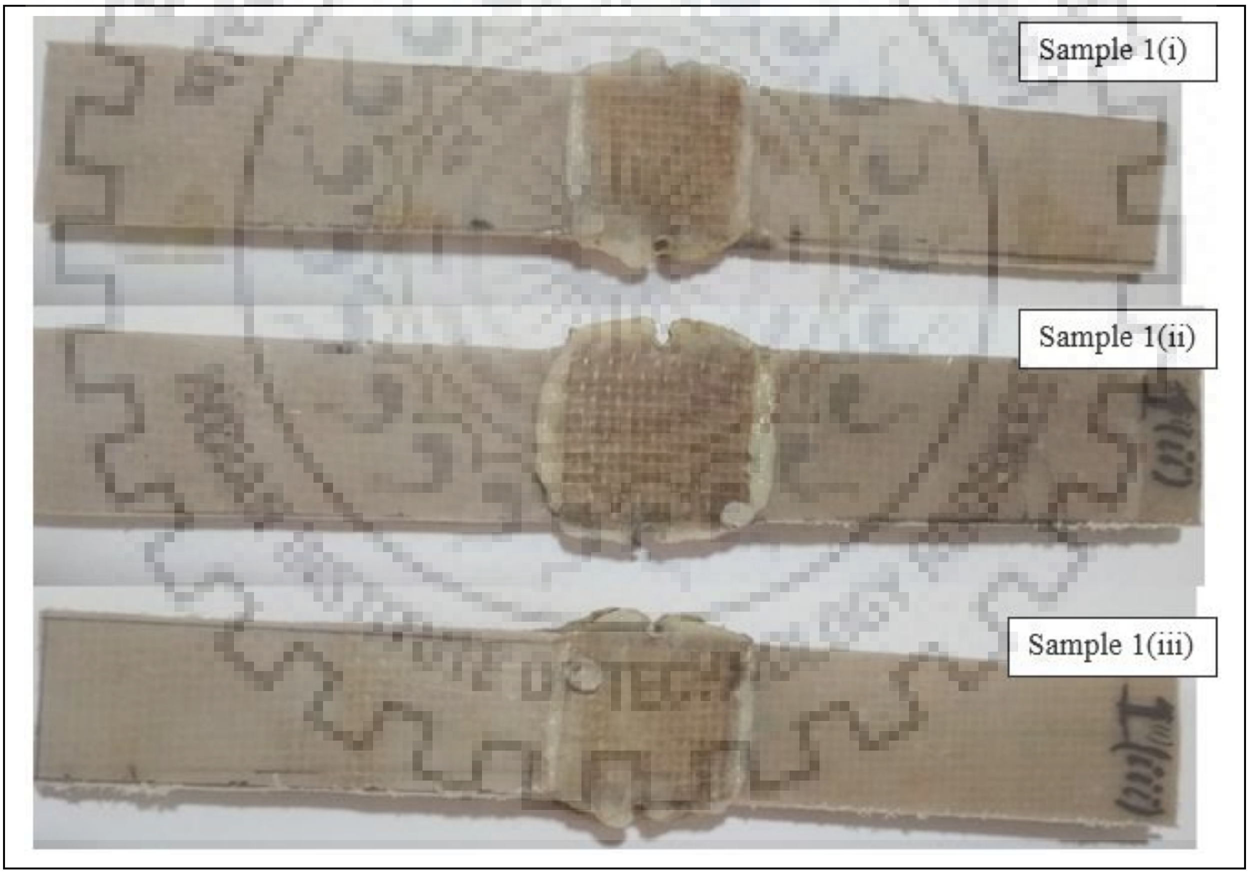


**Fig.16 Type 1 Lap joints of the composite**

In another kind of configuration, the lap joints were made using a thin polymer layer, which is PP of 1mm thickness in between the parent composite specimen to make the joint. In this type of joint, along with the pressure and heat energy, the polymer layer in between the interface is expected to provide further strengthening to the joint obtained. These types of lap joints of the composite specimen in this study were referred as the Type 2 composite joints.


**Fig.17 Type 2 Lap joints of the composite**

In the third kind of configuration, two thin polymer layers each of 1mm along with a layer of the fiber i.e. jute is used as filler between the joint interface, the fiber layer was expected to provide additional strength and the polymer layer was expected to hold this fiber layer to the rest of the parent composite specimen. These types of lap joints were referred in this study as Type 3 composite lap joints as shown in Fig.18

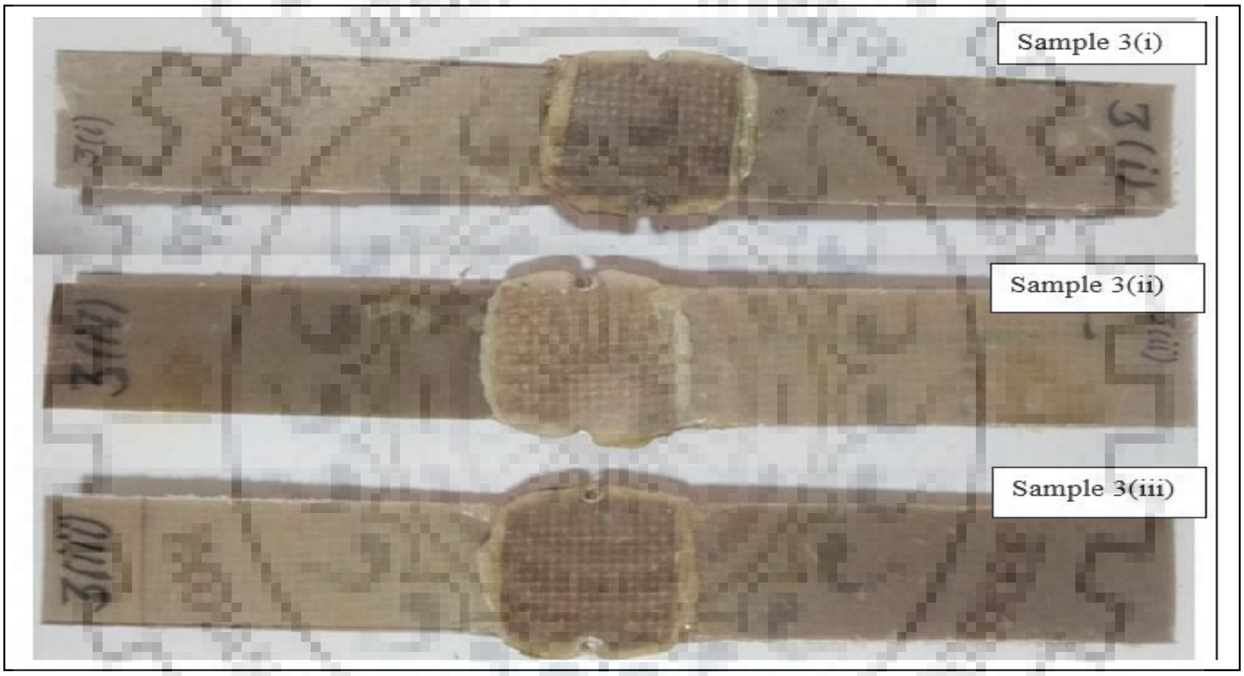


**Fig.18 Type 3 Lap joints of the composite**

**Table 2. Time taken for microwave heating of composite specimen lap joints**

| Sample no. | Type of joint | Curing time | Remarks |
|---|---|---|---|
| 1(i) | Lap Joint with no filler material | 1min 10 seconds | Burn up of the polymer because of improper alignment of SiC bar with respect to specimen |
| 1(ii) | Lap Joint with no filler material | 1minute 10 seconds | Burn up of the polymer because of improper alignment of SiC bar with respect to specimen |
| 1(iii) | Lap Joint with no filler material | 1 minute 15 seconds | Maximum heat transferred to only one side of specimen because of the another SiC carbide bar not being in proper contact with the fixture |
| 2(i) | Lap Joint with PP sheet at the interface of the joint | 1 minute 19 seconds | Satisfactory joint. Note: The SiC bar should not touch the fixture physically. It should be kept at an optimum distance from it, neither too far otherwise it will not transfer its heat to the specimen and nor to near otherwise it would burn the polymer as well as fiber |
| 2(ii) | Lap Joint with PP sheet at the interface of the joint | 1 minute 10 seconds | Satisfactory joint |
| 2(iii) | Lap Joint with PP sheet at the interface of the joint | 1 minute 10 seconds | Satisfactory joint |
| 3(i) | Lap Joint with two PP sheets along with a fiber layer between them inserted at the interface of the joint | 1 minute 20 seconds | Satisfactory joint, but proper cleaning of the fixture has to be done before next joining in order to prevent residue material on the fixture to initiate fire inside microwave cavity during curing process |
| 3(ii) | Lap Joint with two PP sheets along with a fiber layer between them inserted at the interface of the joint | 1 minute 16 seconds | Satisfactory joint, same precaution as above has to be followed |
| 3(iii) | Lap Joint with two PP sheets along with a fiber layer between them inserted at the interface of the joint | 1 minute 20 seconds | Satisfactory joint, same precaution as above has to be followed |

### 4.1 Mechanical testing

For testing purpose, the parent composite is made as per ASTM D3039.The composite specimen for lap joint is made as per ASTM D5868. The tensile testing was done on the universal testing machine (Make: INSTRON, Model: 5982).The sample was having a gauge length of 50 mm and the crosshead speed used was 2 mm/min. The extension rate was kept at 3mm/min for the tensile testing of both the parent composite as well as the lap joint configuration of the composite specimen. The machine used for tensile testing is as shown in Fig.19


**Fig.19 Universal Testing Machine (Make: INSTRON, Model: 5892)**

**Table 3. Tensile testing of parent material**

| Sample no. | Maximum Load [kN] | Stress at Maximum Load [MPa] |
|---|---|---|
| 1 | 3.16366 | 31.637 |
| 2 | 3.20635 | 32.063 |
| 3 | 2.39358 | 23.936 |
| 4 | 1.86923 | 18.692 |
| 5 | 3.17309 | 31.731 |
| 6 | 1.79079 | 17.908 |
| 7 | 2.89752 | 28.975 |

**Table 4. Tensile test results of the lap joint configuration of composite**

| Sample no. | Maximum Load [kN] | Stress at Maximum Load [MPa] |
|---|---|---|
| 1(i) | 1.67250 | 16.725 |
| 1(ii) | 1.22497 | 12.250 |
| 1(iii) | 2.14131 | 21.413 |
| 2(i) | 1.39837 | 13.984 |
| 2(ii) | 1.29280 | 12.928 |
| 2(iii) | 1.35298 | 13.530 |
| 3(i) | 0.66985 | 6.699 |
| 3(ii) | 0.70182 | 7.018 |
| 3(iii) | 1.73442 | 17.344 |

**Table 5. Joint efficiency of the lap joint configuration of composite**

| Sample no. | Stress at maximum load [MPa] | Average tensile strength of parent composite [MPa] | Lap joint efficiency [%] |
|---|---|---|---|
| 1(i) | 16.7250 | 26.42 | 63.30 |
| 1(ii) | 12.2497 | 26.42 | 46.36 |
| 1(iii) | 21.4131 | 26.42 | 81.05 |
| 2(i) | 13.9837 | 26.42 | 52.93 |
| 2(ii) | 12.9280 | 26.42 | 48.93 |
| 2(iii) | 13.5298 | 26.42 | 51.21 |
| 3(i) | 6.6985 | 26.42 | 25.35 |
| 3(ii) | 7.0182 | 26.42 | 26.56 |
| 3(iii) | 17.3442 | 26.42 | 65.65 |

## 4.2 Lap joint strength under tensile loading of Type 1 composite joint

In Type 1 composite joints, lap joints were made between the two parent composite specimen without using any kind of filler material and simply roughening of the adherend surfaces was done in order to have better surface to surface bonding between the specimens.


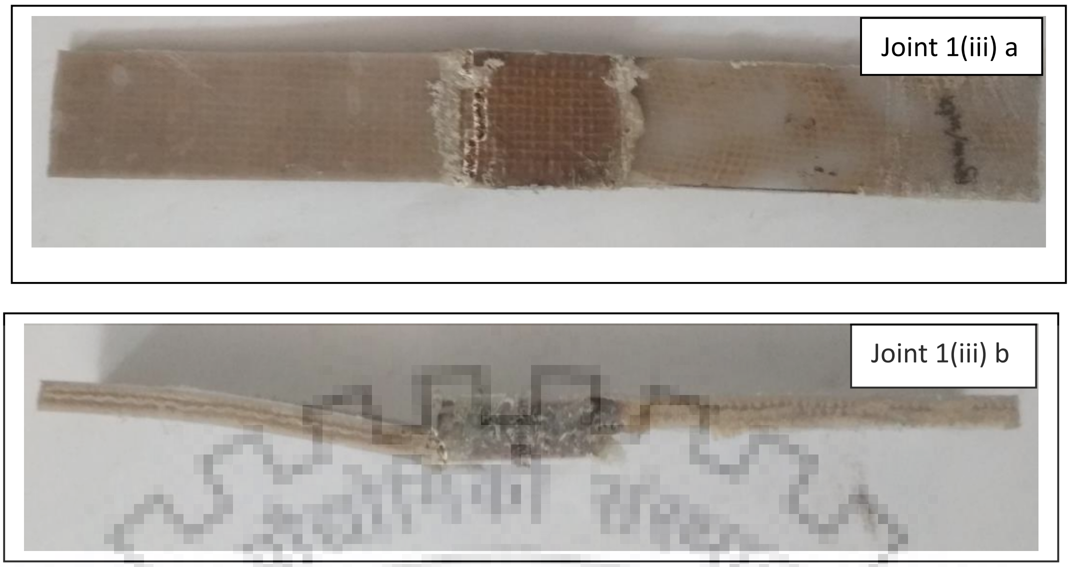


**Fig.20. Fracture of Type 1 lap joints configuration of composite**

As can be seen from Fig.20, that the Type 1 type of joints have quite good strength as the joints were breaking most of the time from whole of the bonded area or area near to the parent material rather than the interface of the bonded area. Therefore, the joint is giving maximum efficiency as high as 81.05%.

### 4.3 Lap joint strength under tensile loading of Type 2 composite joint

In Type 2 lap joints configuration, a filler material has been used, which is the matrix material i.e. PP itself. But as can be seen from the figure that rather than providing the strength to the joint by binding the fiber it on the contrary, is becoming the site, most susceptible to fail during the tensile loading. And sometimes when the heat is not proper, in that case the filler material layer i.e. PP is not even getting sufficient heat to even melt up and is remaining as it was before, leading to reduction in the bonding area, as can be seen for joint 2(ii) b in Fig.21

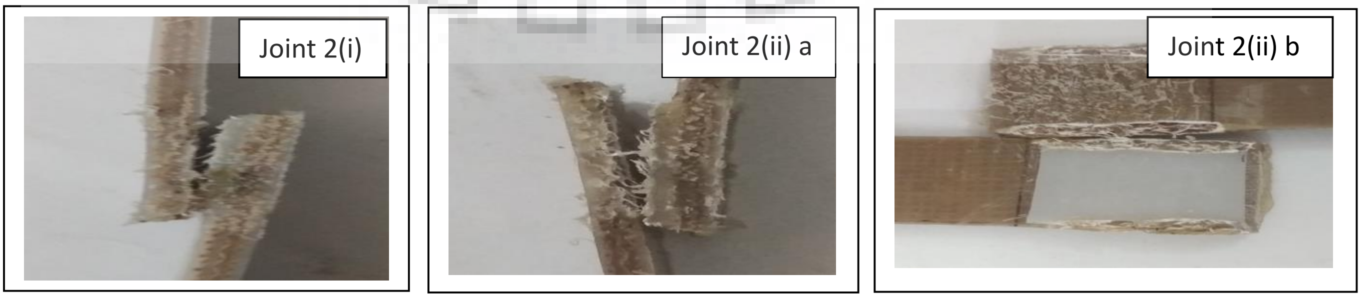


**Fig.21 Fracture of Type 2 lap joints configuration of composite**

### 4.4 Lap joint strength under tensile loading of Type 3 composite joint

In Type 3 type lap joints configuration as shown in Fig.22, two PP layers and a jute fiber is used as the additional filler material to fill up the space between the joint to increase the strength of the joint. But in most of the cases, the strength obtained is only 25% of parent composite, which is significantly less than the strength as compared to joints of Type 1 and Type 2.This is mainly due to improper heating of the PP layers in between the adherend, because of which they are not fully able to bind the fiber with it. But in one case the strength obtained is 65.65%, which is significantly higher than the others in Type 2, which may be due to more manual pressure and time allowed for the specimen to get heated inside the cavity.

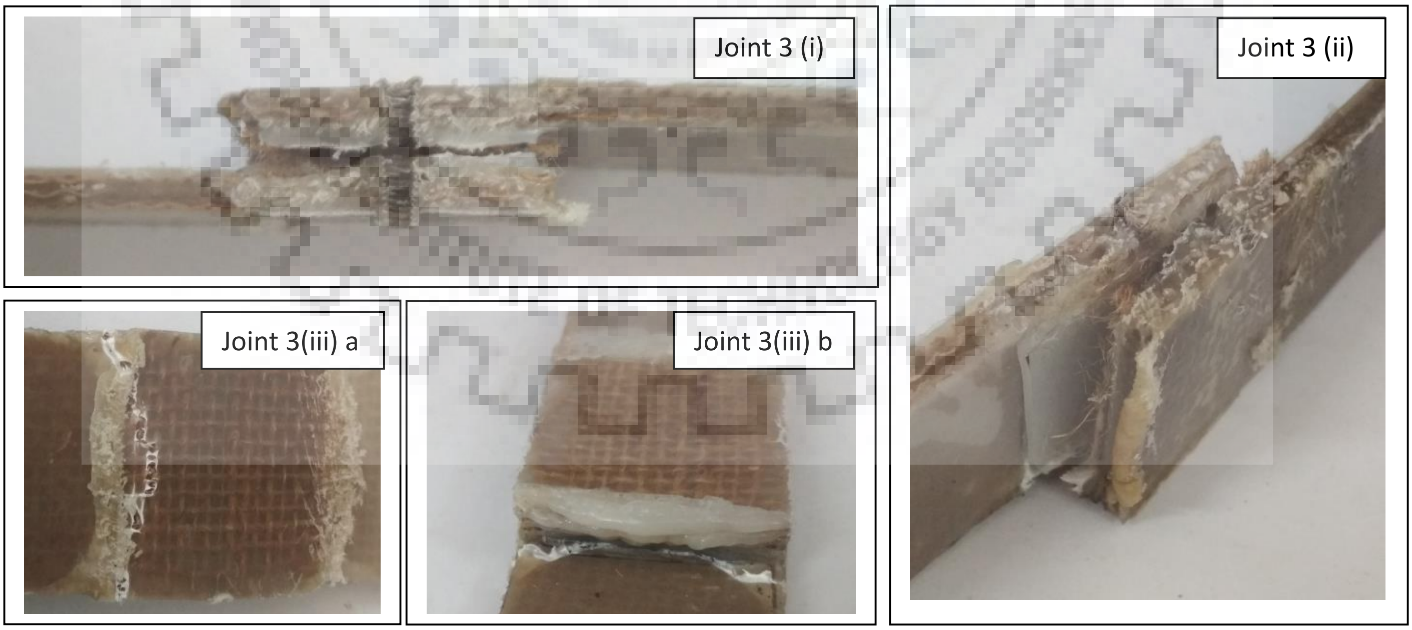


**Fig.22 Fracture of Type 3 lap joints configuration of composite**

Therefore, from above experimental results and observations, it can be concluded that the strength obtained for lap joints in case of Type 1 composites is better than in Type 2 and Type 3 composite ,and in between Type 2 and Type 3 composite ,better strength is obtained in Type 2 in most of the cases, though more strength can be obtained in Type 3 composite if the pressure can be increased to some optimized value to increases the binding force, so that more heat can easily reach to the PP layers for binding the jute layer in between them.

### 4.5 Microstructural analysis using FESEM

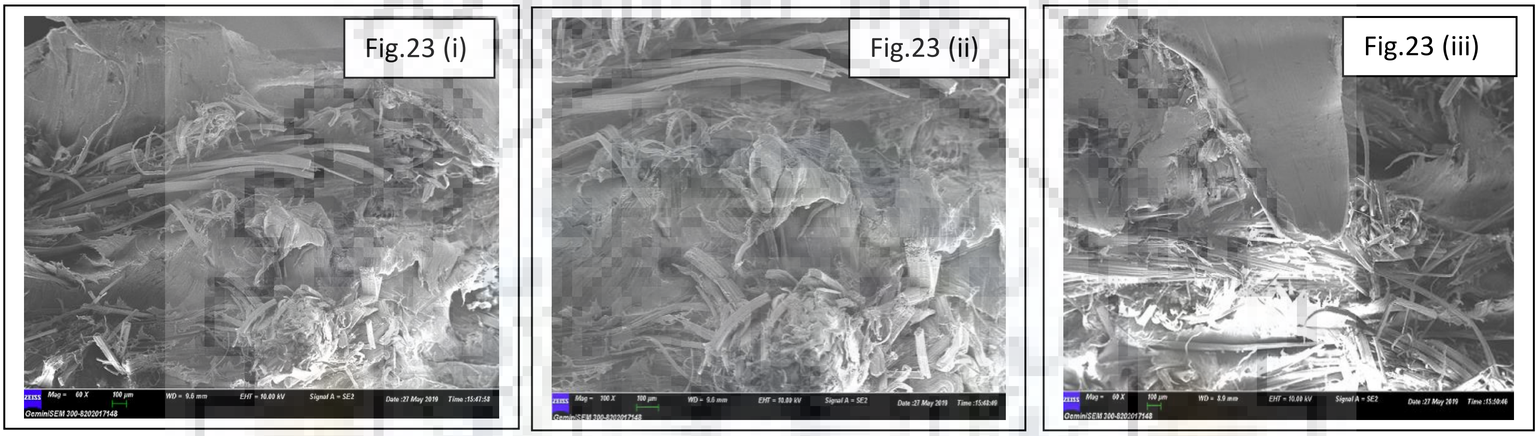


**Fig.23 FESEM of sample 3 of parent composite specimen**

As can be seen for FESEM of sample 3 of parent composite specimen in Fig.23 (i) at 60X,that it is having weak interfacial adhesion, which is leading to its weak strength as compared with other composite specimen because of the lack for proper adhesion bonding between the matrix and the fiber at some regions in the composite. The interfacial region between the fiber and the matrix denotes absence of adhesion between these materials. Lignocellulosic fibers generally have –OH groups in their structure, so does the jute fiber. These bonds makes these fibers hydrophilic leading to moisture absorption and disturbing the structure of the composite. Also such kind of polar type of bonding repulses the bonding between polar and non-polar fiber and matrix, leading to weakening of the adhesion forces between them. Therefore for ensuring good bonding between fibers ad matrix, coupling agents should be used.

In Fig.23 (ii) at 100X, it can be seen clearly that the matrix in certain regions is amalgamating leading to weakening of fiber in that region and in turn reduction in the strength in that region.

In Fig.22. (iii) at 60X,it can be seen that improper wetting of the fiber has taken place with the matrix leading to reduction in the overall strength of the developed composite joints.

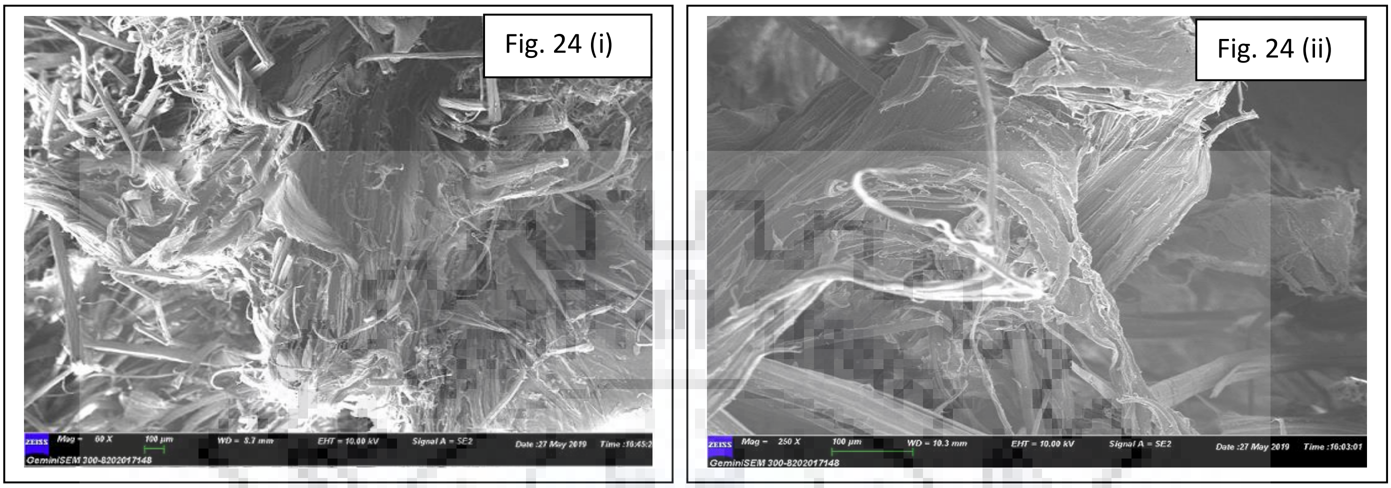


**Fig.24 Figure of FESEM of sample 2 and sample 1 of parent composite specimen**

From Fig.24 (i), it can be seen that in FESEM of sample 2 of the parent composite specimen at 60X, there is proper wetting of the fiber with the matrix, therefore, an increase in strength has been observed as compared to sample 3 of the parent specimen.

The same thing can be observed in Fig.24 (ii), which is the FESEM of sample 1 of parent composite specimen at 250 X possessing better fiber matrix wetting than that of specimen 3.

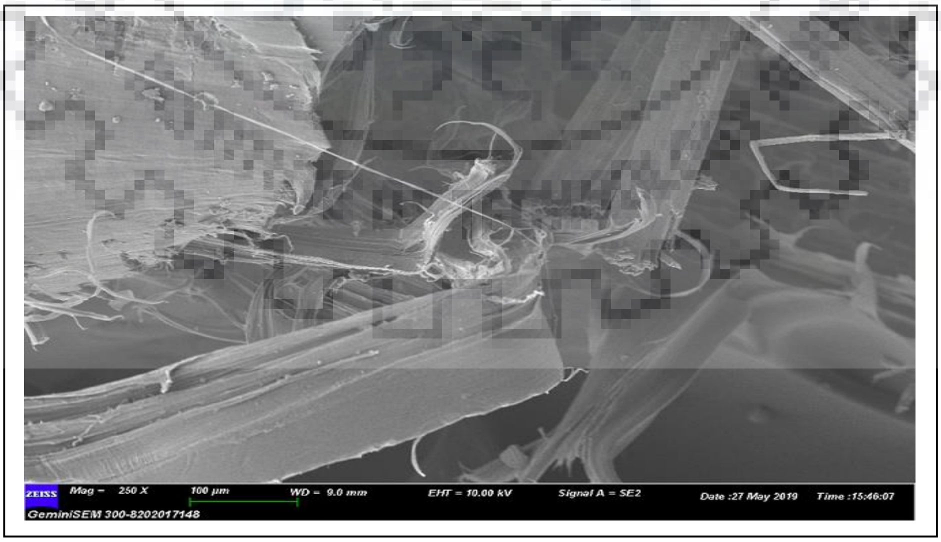


**Fig.25 Figure of FESEM of fractured lap joint of Type 1 joint 1(ii)**

From Fig.25, FESEM of fractured lap joint of Type 1 joint 1(ii) can be seen at 250X .It can be observed that there is fiber misalignment which is weakening the bonding and reducing the tensile strength in a given direction and thus leading to poor stress transfer capability. This misalignment of the fibers with the loading direction could have occurred during the preparation of the composite by compression molding itself.


**Fig.26 FESEM of fractured lap joint of Type 1 joint 1(iii)**

From Fig.26, FESEM of fractured lap joint of Type 1 joint 1(iii) can be seen at 250X.It can be observed that little bit of fiber pull out is taking place during the tensile loading of the specimen, which is indicating little weak bonding between matrix and fiber.

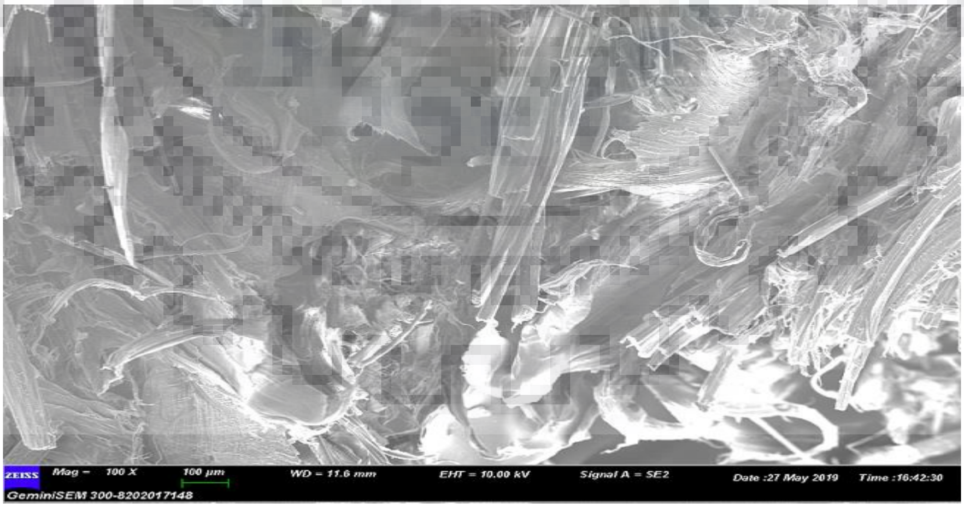


**Fig.27 FESEM of fractured lap joint of Type 3 joint 3 (i)**

From Fig.27, FESEM of fractured lap joint of Type 3 joint 3(i) can be seen at 100X.It can be seen that there is misalignment of fiber as well as improper wetting of the matrix with the fiber, which is leading to the reduction in the strength of the joint.

In the present experimental investigation, three different kinds of lap joints were made of natural fiber based polymer matrix composite, where PP is the matrix material and jute is the fiber. Microwave heating is used as the source for the joining to take place by melting the interface in between the adherends. The lap joints strength of the three different kind of joints were compared with the tensile strength of parent composite material for assessing the applicability of the obtained joints.

Based on the experiments, following conclusions can be drawn:

1. In this study as no susceptor material is used, therefore no external impurity defects are observed which has led to significant increase in joint strength as compared to earlier obtained joint strength by other researchers.

2. During the microwave joining of composite specimens, Type 1 lap joints configuration have shown most reliable and repeatable results as compared to Type 2 and Type 3 lap joints configuration. In order to have good lap joint, no filler material should be used, as without filler, it is giving as high as 81.05% joint efficiency.

3. For joining of Type 1 lap joints configuration, the optimum time for microwave heating is 1 minute 15 seconds, which gives 81.05% joint efficiency. For Type 2 lap joints configuration, the optimum time for microwave heating is 1 minute 19 seconds, which gives 52.93% efficiency. For Type 3 lap joints configuration, the optimum time for microwave heating is 1 minute 20 seconds, which gives 65.65% joint efficiency.

4. No hotspots are observed in microwave joining which were normally observed when using charcoal as a susceptor material, and the burned composite can be removed by either filing or by cutting to give good finishing to the joint.

5. Microwave joining using specific fixtures has been proved to be a feasible solution for joining of natural fiber based partially biodegradable composites because of the better strength, rapid joining time as compared to conventional adhesive joining of thermoplastics and very less thermal gradients because of bulk heating phenomenon taking place.

## 5.1 Scope of future work

Further investigation can be done on the study of pressure on the joint strength obtained, which has not been taken into consideration in the present study. As earlier has been observed that for Type 3 lap joints configuration for composite, joint 3(iii), which has been found to have unexpectedly higher strength as compared to other Type 3 lap joints of the composite, which could be contributed to more manual pressure applied during the experimentation. Also fixture can be designed differently so that in addition to providing the support to the specimen, it can also be used to apply the pressure on the specimen during the joining process. Further work can also be done to simulate the variation of thermal gradients being setup between each matrix layer and the fiber layer to know about how much thickness of the composite, the thermal gradients can be ignored or are minimal enough to be ignored. Also variable thickness of composite can be joined by changing the number of matrix material layers and the fiber material layers in order to determine the extent of thickness upto which the composite can be joined in the microwave joining process.

## References

[1] Boey FYC, Lee WL. Microwave radiation curing of a thermosetting composite. Journal of Material Science Letters 1990; 9(10):1172-1173

[2] Yue CY, Looi HC. Influence of thermal and microwave processing on the mechanical and interfacial properties of a glass/epoxy composite. Composites 1995; 26(11):767–73.

[3] Nightingale C, Day RJ. Flexural and inter laminar shear strength properties of carbon fibre/epoxy composites cured thermally and with microwave radiation. Composites Part A 2002; 33(7):1021–30.

[4] Marand E, Baker KR, Graybeal JD. Comparison of reaction mechanisms of epoxy resins undergoing thermal and microwave cure from in situ measurements of microwave dielectric properties and infrared spectroscopy. Macromolecules 1992; 25(8):2243–52.

[5] Rao R, Rao S, Sridhara B. Studies on tensile and inter laminar shear strength properties of thermally cured and microwave cured glass epoxy composites. Journal of Reinforced Plastics and Composites 2006; 25(7):783–95.

[6] Varaporn T, Kaew S. Comparison of microwave and thermal cure of epoxy-anhydride resins: mechanical properties and dynamic characteristics. Journal of Applied Polymer Science 2005; 97(4):1442–61.

[7] Varaporn T, Dumrong J. Comparison between microwave and thermal curing of glass fiber-epoxy composites: effect of microwave heating cycle on mechanical properties. Journal of Applied Polymer Science 2006; 102(2):1059–70.

[8] Thostenson ET, Chou TW. Microwave and conventional curing of thick-section thermoset composite laminates: experiment and simulation. Polymer Composites 2001; 22(2):197–212.

[9] Boey FYC, Lee TH. Electromagnetic radiation curing of an epoxy/fibre glass reinforced composite. International Journal of Radiation Applications and Instrumentation Part C Radiation Physics and Chemistry 1991; 38(4):419–23.

[10] Mooteri PS, Sridhara B, Rao S. Studies on mechanical behaviour of microwave and thermally cured glass fiber reinforced polymer composites. Journal of Reinforced Plastics and Composites 2006; 25(5):503–12.

[11] Johnson MS, Rudd CD, Hill DJ. Microwave assisted resin transfer moulding. Composites Part A 1998; 29(1–2):71–86.

[12] Lee WI, Springer GS. Microwave curing of composites. Journal of Composite Materials 1984; 189(4):387–409.

[13] Wei J, Hawley M, Assmussen J. Microwave power absorption model for composite processing in a tunable resonant cavity. Journal of Microwave Power Electromagnetic Energy 1993; 28(4):234–42.

[14] Papargyris DA, Day RJ, Nesbitt A, Bakavos D. Comparison of the mechanical and physical properties of a carbon fibre epoxy composite manufactured by resin transfer moulding using conventional and microwave heating. Composites Science and Technology 2008; 68(7):1854–61.

[15] Jordan C, Galy J, Pascault JP. Comparison of microwave and thermal cure of an epoxy/amine matrix. Polymer Engineering and Science 1995; 35(3):233–9.

[16] Mijovic J, Corso WV, Nicolais L, d'Ambrosio G. In-situ real-time study of cross linking kinetics in thermal and microwave fields. Polymers for Advanced Technologies 1998; 9 (4):231–43.

[17] Mijovic J, Wijaya J. Comparative calorimetric study of epoxy cure by microwave vs. thermal energy. Macromolecules 1990; 23(15):3671–4.

[18] Saccone G, Amendola E, Acierno D. Conventional and microwave curing process of epoxy systems: kinetic analysis and characterization. Microwave and Optical Technology Letters 2009; 51(11):2777–83.

[19] Bai SL, Djafari V, Andreani M, Francois D. A comparative study of the mechanical behaviour of an epoxy resin cured by microwaves with one cured thermally. European Polymer Journal 1995; 31(9):875–84

[20] Bai SL, Djafari V. Interfacial properties of microwave cured composites. Composites 1995; 26(9):645–51.

[21] Boey FYC, Gosling I, Lye SW. High-pressure microwave curing for epoxy– matrix/glass–fibre composite. Journal of Material Processing Technology 1992; 29(1):311–9.

[22] Lye SW, Boey FYC. PC-based monitoring and control for microwave curing of polymer composites. Material and Manufacturing Process 1992; 9(5):851–68.

[23] Joshi SC, Bhudolia SK. Microwave–thermal technique for energy and time efficient curing of carbon fiber reinforced polymer prepreg composites. Journal of Composite Materials 2014; 48(24):3035–48.

[24] Tanmay B. Role of metallic, ceramic and composite plates on microwave processing of composite dielectric materials. Materials Science and Engineering A 2007; 457 (1):261–74.

[25] Chaowasakoo T, Sombatsompop N. Mechanical and morphological properties of fly ash/epoxy composites using conventional thermal and microwave curing methods. Composites Science and Technology 2007; 67(11):2282–91.

[26] Ramajo LA, Cristóbal AA, Botta PM, López JMP, Reboredo MM, Castro MS. Dielectric and magnetic response of Fe3O4/epoxy composites. Composites Part A 2009; 40(4):388–93.

[27] Park KY, Han JH, Lee SB, Yi JW. Microwave absorbing hybrid composites containing Ni–Fe coated carbon nanofibers prepared by electroless plating. Composites Part A 2011; 142(5):573–8.

[28] Rangari VK, Bhuyan MS, Jeelani S. Microwave curing of CNFs/EPON-862 nano composites and their thermal and mechanical properties. Composites Part A 2011; 42(7):849–58.

[29] Ageorges C, Ye L, Hou M. Advances in fusion bonding techniques for joining thermoplastic matrix composites: a review. Composites Part A 2001; 32 (6):839–57.

[30] Drzal LT, Hook KJ, Agrawal RK. Enhanced chemical bonding at the fiber– matrix interphase in microwave processed composites. In: Snyder Jr WB, Sutton WH, Iskander MF,

Johnson DL, editors. Microwave processing of materials II, materials research society proceedings. Pittsburgh: Materials Research Society 1991; p. 449–54.

[31] Chen M, Siochi EJ, Ward TC, McGrath JE. Basic ideas of microwave processing of polymers. Polymer Engineering Science 1993; 33(7):1092–109.

[32] Martinelli M, Rolla PA, Tombari E. A method for dynamic dielectric measurements at microwave frequencies: applications to polymerization process studies. IEEE Transactions on Instrumentation and Measurement 1985; 34(3):417–21.

[33] Kranbuel D, Delos S, Yi E, Mayer J, Jarvie T, Winfree W. Dynamic dielectric analysis: nondestructive material evaluation and cure cycle monitoring. Polymer Engineering and Science 1986; 26(5):338–45.

[34] Mijovic J, Kenney JM, Maffezzoli A, Bellucci F, Nicolais L. The principles of dielectric measurements for in-situ monitoring of composite processing. Composites Science and Technology 1993; 49(3):277–90.

[35] Singh I, Bajpai PK, Malik D, Sharma AK, Kumar P. Feasibility study on microwave joining of green composites. Akademeia 2011; 1(1):1–6.

[36] Singh I, Bajpai PK, Malik D, Madaan J, Bhatnagar N. Microwave joining of natural fiber reinforced green composites. Advanced Materials Research 2012; 410:102–5.

[37] Bajpai PK, Singh I, Madaan J. Joining of natural fiber reinforced composites using microwave energy: experimental and finite element study. Materials and Design 2012; 35:596–602.

[38] Ali S, Bajpai PK, Singh I, Sharma AK. Curing of natural fibre-reinforced thermoplastic composites using microwave energy. Journal of Reinforced Plastics and Composites 2014.

[39] Mali A, Sharma AK, Singh I. Microwave curing of natural fiber and synthetic fiber reinforced polymer matrix composites. imanager's Journal on Material Science 2013;1(1):8–14.

[40] Sgriccia N, Hawley MC. Thermal, morphological, and electrical characterization of microwave processed natural fiber composites. Composites Science and Technology 2007; 67(9):1986–91.

[41] Sgriccia N, Hawley MC, Misra M. Characterization of natural fiber surfaces and natural fiber composites. Composites Part A 2008; 39(10):1632–7.

[42] Sharma AK, Srinath MS, Kumar P. Microwave joining of metallic materials. Indian patent application no. 1994/Del/20092009

[43] Bansal A, Sharma AK, Kumar P, Das S. Characterization of bulk stainless steel joints developed through microwave hybrid heating. Materials Characterization 2014; 91:34–41.

[44] Srinath MS, Sharma AK, Kumar P. Investigation on microstructural and mechanical properties of microwave processed dissimilar joints. Journal of Manufacturing Processes 2011; 13(2):141–6.

[45] Bansal A, Sharma AK, Kumar P, Das S. Investigation on microstructure and mechanical properties of the dissimilar weld between mild steel and stainless steel-316 formed using microwave energy. Proceedings of the Institution of Mechanical Engineers Part B Journal of Engineering Manufacture 2014:1–10. 0954405414558694.

[46] Clark DE, Sutton WH. Microwave processing of materials. Annual Review of Materials Science 1996; 26:299–331.

[47] Sharma AK, Kumar P. Advanced manufacturing processes, NPTEL e-learning course. [retrieved on date 28.03.2015 at 10 PM]

[48] Zhang H, Datta AK. Microwave power absorption in single-and multiple item foods. Food and Bioproducts Processing 2003; 81(3):257–65.

[49] Sturm GSJ, Stefanidis GD, Verweij MD, Van Gerven TDT, Stankiewicz AI. Design principles of microwave applicators for small-scale process equipment. Chemical Engineering and Processing: Process Intensification 2010; 49(9):912–22.

[50] Thostenson ET, Chou TW. Microwave processing: fundamentals and applications. Composites Part A 1999; 30:1055–71.

[51] Saltiel C, Datta AK. Heat and mass transfer in microwave processing. Advances in Heat Transfer 1999; 33(1):1–94.

[52] Metaxas AC, Meredith RJ. Industrial microwave heating, Series 4. Institution of Engineering Technology 1983.

[53] Gupta M, Leong EWW, Wong WL. Microwaves and metals. Asia: John Wiley and Sons; 2007.

[54] Kubel E. Advancement in microwave heating technology. Industrial Heating 2005; 62:43–53.

[55] Sparks M. Ferromagnetic-relaxation theory. New York: McGraw Hill; 1964.

[56] Clark DE, Folz DC, West JK. Processing materials with microwave energy. Journal of Material Science and Engineering A 2000; 287:153–8.

[57] Pozar DM. Microwave engineering. 2nd edition Toronto: John Wiley and Sons; 2001. p. 1–49.

[58] Moulson AJ, Herbert JM. Electroceramics: Materials, Properties, Applications. 2nd edition Toronto: John Wiley and Sons 2003.

[59] Sutton WH. Microwave processing of ceramics—an overview. In: Beatty RL, Iskander MF, Sutton WH, editors. Microwave processing of materials III, materials research society proceedings. Pittsburgh: Materials Research Society 1992; p. 3.

[60] Anklekar RM, Bauer K, Agrawal DK, Roy R. Improved mechanical properties and microstructural development of microwave sintered copper and nickel steel. Powder Metallurgy 2005; 48(1):39–46.

[61] Moulart A, Marrett C, Colton J. Polymeric composites for use in electronic and microwave devices. Polymer Engineering and Science 2004; 44(3):588–97.

[62] Pramila D, Nair DSA, Jabin T, Kutty SK. Mechanical, thermal, and microwave properties of conducting composites of polypyrrole/polypyrrole-coated short nylon fibers with acrylonitrile butadiene rubber. Journal of Applied Polymer Science 2012; 126 (6):1965–76

[63] Yousefpour. A, Hojjati M , Jean-Pierre I. Fusion Bonding/Welding of Thermoplastic Composites 2004

[64] Singh I, Bajpai P.K, Malik D, Sharma A.K, Kumar P. Feasibility study on microwave joining of green composites, Journal of Akademeia, 2011

[65] Singh I, Bajpai P.K, Madaan .J. Development and characterization of PLA-based green composites, Journal of Thermoplastic Composite Materials 2014; 27(1) 52–81

[66] Singh I, Bajpai P.K, Malik D, Madaan J, Bhatnagar N. Microwave Joining of Natural Fiber Reinforced Green Composites, Advanced Materials Research 2012;410:102-105

[67] Bajpai P.K, Singh I, Madaan J. Joining of natural fiber reinforced composites using microwave energy: Experimental and finite element study, Materials and Design 2012; 35: 596–602

[68] Bajpai P.K, Singh I, Madaan J, Tribological behaviour of natural fiber reinforced PLA composites, Wear-An International Journal on the Science and Technology of Friction, Lubrication and Wear 2013;297:829–840

[69] Ku H.S, Siores E, Elias ,Ball J.A.R, Siu F. Processing of polymer matrix composites using variable frequency microwave, 13th International Conference on Composite Materials (ICCM-13) 2001, Beijing, China

[70] Bajpai P.K, Singh I, Madaan J. Comparative studies of mechanical and morphological properties of polylactic acid and polypropylene based natural fiber composites, Journal of Reinforced Plastics and Composites 2012; 31(24): 1712–1724

[71] Debnath K, Singh I, Dvivedi A, Kumar P. Natural Fiber-Reinforced Polymer Composites for Wind Turbine Blades: Challenges and Opportunities, Recent Advances in Composite Materials for Wind Turbine Blades(Book) Chapter 2 2013 ; p.25-39,The World Academic Publishing Co. Ltd.

[72] Chaitanya S, Singh A.P, Singh I. Processing of lignocellulosic fiber-reinforced biodegradable composites, Natural Fiber, Reinforced Biodegradable and Bioresorbable Polymer Composites(Book) Chapter 9 2017 ; p.163-181,Woodhead Publishing

[73] Lilaa M.K, Komal U.K, Chaitanya S, Singh I. Secondary Processing of Polymer Matrix Composites: Challenges and Opportunities, International Conference on Latest Development in Material, Manufacturing and Quality Control. MMQC 2016, Bathinda, India

[74] Yallew T.B, Aregawi S, Kumar P, Singh I. Response of natural fiber reinforced polymer composites when subjected to various environments, International Journal of Plastic Technology 2018

[75] Lila M.K, Singhal A, Banwait S.S, Singh I. A recyclability study of bagasse fiber reinforced polypropylene composites, Polymer Degradation and Stability 2018; 152: p. 272-279

[76] Ali S, Bajpai P.K, Singh I, Sharma A.K. Curing of natural fiber-reinforced thermoplastic composites using microwave energy, Journal of Reinforced Plastics and Composites 2014; 33(11):p.993-999

[77] Yallew T.B, Kumar P, Singh I. Sliding behaviour of woven industrial hemp fabric reinforced thermoplastic polymer composites, International Journal of Plastic Technology 2015 ;19(2), p.347–362

[78] Mishra R.R, Sharma A.K. Microwave material interaction phenomena: heating mechanisms, challenges and opportunities in material processing, Composites Part A : Applied Science and Manufacturing 2016;81:p.78-97