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Technical Report

Joining of natural fiber reinforced composites using microwave energy: Experimental and finite element study

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ABSTRACT

The development of natural fiber reinforced polymer composites has received widespread attention due to their environment friendly characteristics over the synthetic fiber based polymer composites. Although, different categories of natural fiber reinforced composites have been developed, their joining has not been explored extensively. In the current article, natural fibers (nettle and grewia optiva) reinforced polylactic acid green composites and polypropylene based partially biodegradable composites have been developed. These composites have been joined with an innovative microwave heating process in the presence of suitable susceptor. Samples have also been joined with the well known adhesive bonding technique for comparison purposes. Joint strength has been evaluated in each case as per standard procedures and results showed that microwave joining provides higher joint strength as compared to adhesive bonding. Microwave heating process has also been simulated with standard multiphysics finite element (FE) software to analyze the microwave heating mechanism. The results of the experimental study are in close agreement with the finite element investigation.

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1. Introduction

Nowadays, polymer based fiber composites (FRPs) are extensively used in many application areas like construction, aerospace, automobile industries etc. due to their inherent superior properties. Light to lighter weight requirements and strict environmental rules and regulations have led to the development of natural fiber based green composites. Now, many components of automobiles are fabricated using natural fiber based composites [1,2]. Polylactic acid (PLA), a corn derived fully biodegradable polymer based natural fiber green composites are substituting the existing areas of application of traditional composites especially in exterior and interior components of automobiles. The simple composite products are made to near-net shape using any of the primary processing techniques such as compression molding or putrusion. A certain degree of intricacy in the composite product design necessitates the joining of individually processed simpler parts into a complex composite product. These parts require some joining technique to be assembled together. There are basically three joining methods which are: mechanical fastening, adhesive bonding and welding (direct bonding). For joining polymer composites, mechanical fastening and adhesive bonding are well known techniques. But these techniques have several disadvantages [3–5] as explained in Table 1.

The joint strength is responsible for strength of the structure as joint strength is the failure criterion for any structure. Therefore, for composite structures, design of joint has become the prime area of research [6]. Microwave heating has already been applied in food processing, drying of textiles etc. Instead of these applications, microwave heating can also be used for processing of advanced materials [7,8]. Joining through microwave heating is a type of direct bonding technique and it has several advantages over traditional joining methods such as rapid processing, uniform temperature distribution, energy saving, no polluting gases, welding of complex geometries, high strength and improved microstructure of the joint. As this technique is relatively new, not much literature is available on joining of thermoplastic based composites using microwave energy.

Staicovici et al. [9] concluded that the tensile strength of the joints could reach that of the bulk material strength of high density polyethylene (HDPE) under the right conditions during the study of the welding and disassembly of HDPE butt joints with various polyaniline (PANI) concentrations at the weld line. Yarlagadda and Chai [10] investigated welding of engineering thermoplastics using focused microwave energy. Stoynov et al. [11] investigated the feasibility of utilizing concentrated solar beam radiation for joining engineering thermoplastics such as acrylobuta dinestyrene, poly carbonate and poly methyl methacrylate. Ku et al. [12,13] presented a state of the art review of microwave technologies, processing methods and industrial applications, using variable frequency microwave (VFM) facility and did the characterization of thermoplastic matrix composite (TMC) (glass fiber reinforced

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Table 1
Types and disadvantages of mechanical and adhesive joints [3–5].

Joining method	Types	Disadvantages
Mechanical fastening	Bolted joint, riveted joint, clamping, deformation, dowel, integral snaps	Loosening, stress concentration, delamination due to hole making, galvanic corrosion between dissimilar adherends, difference in thermal coefficients, weight gain, fiber discontinuity, load on the joint is concentrated on a single point rather than whole lap area, difficult to join irregular surfaces, water inclusion between adherend and fasteners
Adhesive joining	Organic adhesive (Epoxy, Polyurethanes, Cyanoacrylates), inorganic adhesive (Cement), solvent or water based adhesive (Accetone on PVC)	Extensive surface preparation, bond cannot be disassembled, some adhesives are toxic, hazardous and environment polluting, a long cure time with some adhesives, difficult to maintain uniformity in quality due to surface treatments

polystyrene (PS/GF (33%)), carbon fiber reinforced low density polyethylene (LDPE/CF (33%)) material using VFM. For green composites, Singh et al. [3] presented a feasibility study on microwave joining of natural fiber reinforced thermoplastic biopolymer green composite. Kathirgamanathan [14] used inherently conducting polymers as microwave absorbers to weld thermoplastic materials.

Literature shows that almost no work is done on microwave joining of green or partially biodegradable polymer composites. Therefore, in the present study, natural fiber reinforced PLA and PP based composites have been developed. Lap joint of composite samples has been prepared by microwave heating and adhesive bonding techniques and bond strength has been evaluated. Also, finite element modeling (FEM) of the microwave heating process has been done to predict optimal results.

1.1. Microwave heating mechanism

A material can be heated with microwave radiations which are high frequency electromagnetic waves. In conventional heating, heat is supplied externally to the surface of the material whereas in microwave heating, microwave irradiation penetrates and simultaneously heats the bulk of the material [15]. It is volumetric heating as microwaves can supply energy throughout the material and provides uniform and rapid heating of thick materials. The thermal gradient in microwave processed materials is reverse of that conventional heating. The generation of microwaves and its analysis is based on Maxwell equations [16] which are:

$$\nabla \times \mathbf{E} = \frac{\partial B}{\partial t}, \nabla \cdot \mathbf{B} = 0, \nabla \times \mathbf{H} = \frac{\partial D}{\partial t} + \mathbf{I} \text{ and } \nabla \cdot \mathbf{D} = \boldsymbol{\rho} \quad (1)$$

where **E** is the electric field vector, **H** is the magnetic field vector, **D** is the electric flux density vector, **B** is the magnetic flux density vector, **I** is the current density vector and **ρ** is the charge density. The electric field component of microwaves exerts a force on the charged particles found in the compound. If the charged particles are bound and have restricted movements in the compound, they merely reorient (oscillate) themselves with the electric field. This is termed as dielectric polarization. But at higher frequencies, it becomes difficult for the charged particles to follow the electric field reversal i.e. to maintain the phase with the electric field and thus bounded particles lag the electric field reversal and this leads to the dielectric heating inside the compound. Dielectric polarization is combined effect of four components based on the different types of the charged particles in matter which is given as [17]:

$$\alpha_t - \alpha_e + \alpha_a + \alpha_d + \alpha_i \quad (2)$$

where α_t = total dielectric polarization, α_e = electronic polarization due to polarization of electrons surrounding the nuclei, α_a = atomic polarization due to the relative motion of the atoms, α_d = dipolar polarization due to polarization of permanent dipoles in the material and α_i = interfacial polarization due to polarization of charges at interfaces. The friction associated with oscillation of dipoles causes localized heating and this forms the basis of dielectric heating mechanism in polymers [10]. All materials are not suitable for microwave processing due to specific characteristics of the process. Blind application of microwave energy in material processing may lead to disappointment. Complex relative permittivity and loss tangent (dielectric loss) are two main properties which play important role in microwave processing of a dielectric material. These are given as follows:

$$\left.\begin{array}{l}\text{Complex relative permittivity, } \varepsilon = \varepsilon' - i\varepsilon'' \\ \text{Loss tangent, } \tan\delta = \varepsilon''/\varepsilon'\end{array}\right\} \quad (3)$$

where ε': dielectric constant, ε'': loss factor.

Dielectric constant determines how much of the incident energy is rejected and how much enters the sample. Loss tangent determines the ability of a material to convert the incoming energy into heat [12]. Many thermoplastics have similar dielectric behavior as that of ceramics.

2. Materials and methods

2.1. Materials and composite fabrication

Grewia optiva fiber mat (GOF) and Nettle fiber mat (NF) were obtained from Uttarakhand Bamboo and Fiber Development Board, Dehradun, India. GOF and NF are abundantly available plant fibers. Polylactic acid (PLA) was supplied by Dow Cargill in pellets form. The biopolymer has a density of 1.24 g/cm^3. The glass transition temperature (T_g) and melting temperature (T_m) of PLA are 54 °C and 160 °C respectively. Polypropylene (PP) was supplied by Atma Autotech Engineers Pvt. Ltd. (Unit-4), Gurgaon, India. The glass transition temperature (T_g) and melting temperature (T_m) of PP are 100 °C and 170 °C respectively. Charcoal was purchased from Ran Baxy, Fine Chemicals Ltd.

Firstly, both types of fiber mat and polymer pellets were dried in an oven at 80 °C for 4 h to remove all absorbed moisture (if it was present there). PLA and PP pellets were converted into PLA and PP films of 1 mm thickness by compression process at a temperature of 170 °C for a contact time of 8 min followed by cooling under pressure and finally, films were removed at 80 °C. Fiber mat and polymer films were stacked alternatively in picture frame type mold. At top and bottom, Teflon sheets were used to avoid sticking of films to the steel plates. The whole assembly was hot pressed at a temperature of 170 °C at a high pressure for 10 min and cooling was performed under pressure. Composite laminates were removed from the mold when temperature was 80 °C. The thickness of composite laminate obtained was 4 mm.

2.2. Sample preparation for bond strength investigation

The samples were cut as per ASTM-D3039 [18] for the tensile testing of parent material (fabricated composites). For lap joints,

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