Lap Shear Strength Comparison between Two Types of Random Carbon Fibre Reinforced Thermoplastic Matrix Composites Bonded using Variable Frequency Microwaves (VFM) Irradiation

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Abstract: Fibre reinforced thermoplastic matrix composite materials have very strong development in the last 10-12 years because of their potential advantages and unique characteristics that cannot be found in their thermosett counterparts. This paper compares the lap shear bond strengths of 2 types of random carbon fibre reinforced thermoplastic matrix composites joined by microwave energy. Variable frequency microwave (VFM) (2 – 18 GHz) facilities are used to join thirty three percent by weight random carbon fibre reinforced low density polyethylene [LDPE/CF (33%)] and thirty three percent by weight random carbon fibre reinforced polystyrene [PS/GF (33%)]. With a given power level, the composites were exposed to various exposure times to microwave irradiation. The lap shear strengths of the joints were compared with those obtained using fixed frequency (2.45 GHz) microwave facility configuration. The VFMF was operated under software control, which provided automatic data logging facilities.

Keywords: variable frequency microwaves (vfm), complex relative permittivity, loss tangent, carbon fibre-reinforced thermoplastic composites and lap shear strength.

1. Introduction

Thermosetting resins have dominated the market in the last thirty years as the matrices for fibre reinforced composites in structural applications, aerospace industry, sporting goods and chemical engineering [1, 2]. Thermoplastics are almost exclusively used when no reinforcement is included and dominate also when short fibres are incorporated. However, in the last 10-12 years, thermoplastics have received increased attention in random as well as continuous fibre reinforced composite applications due to a number of attractive potential advantages. The advantages include ease of impregnation, faster and easier moulding cycle, no hazardous substances and better work environment. The most commonly used thermoplastics for matrix in continuous fibre reinforced composites are polypropylene (PP), nylon (PA), polyetherimide (PEI), polyphenylene sulphite (PPS), polyethersulphone (PES) and polyetheretherketone (PEEK). Traditionally, these fibre reinforced thermoplastic composites are joined by applying adhesives onto the surfaces to be joined and cured in ambient conditions. The curing process may take up to several days [1, 2]. At the same time, industrial microwave technology for processing polymers and polymer-based composites is currently in a state of considerable flux. This paper extends the applications horizon of microwaves in the area of reinforced thermoplastic composites joining, and places emphasis on the development of equipment and facilities aiming at maximising bond quality [3].

Factors that hinder the use of microwaves in materials processing are declining, so the prospects for the development of this technology seem to be very promising [4]. The mechanisms that govern the energy distribution process during microwave joining of materials include dipole friction, current loss and ion jump relaxation. This results in a relatively uniform heat distribution throughout the entire exposure to microwave irradiation, immediately in front of rectangular or circular waveguides [3, 5, 6]. The material properties of greatest importance to microwave processing of a dielectric are the complex relative permittivity $\varepsilon = \varepsilon' - j\varepsilon''$ and the loss tangent, $\tan \delta = \varepsilon''/ \varepsilon'$ [3, 7, 8]. The real part of the permittivity, ε', sometimes called the dielectric constant, mostly determines how much of the incident energy is reflected at the air-sample interface, and how much is coupled into the material. The most important property in microwave processing is the loss tangent, tan δ, which predicts the ability of the material to convert the absorbed electromagnetic energy into heat. For optimum microwave energy coupling, a moderate value of ε′ to enable adequate penetration, should be combined with high values of ε″ and tan δ, to convert microwave energy into thermal energy. If the material is very lossy, ie., high tan δ or ε″, then the microwave energy will attenuate rapidly with distance into the material. This can be an advantage, if one is trying to heat only a thin layer of material or a coating on a surface. This is the case in this research. However, if one is trying to uniformly heat a thick section of material, this may be a problem, and a lower loss in the material will permit more uniform heating. The more rapid heating possible with microwaves, as compared with conventional thermal sources, derives from the volumetric deposition of energy via microwaves, permitting much more rapid heating of materials without detrimental thermal gradients.

The fast heating rate encountered using microwave energy can thus lead to reduced processing time and consequent energy efficiency. These advantages have encouraged the development of facilities for joining a range of thermoplastic composites autogenously and heterogeneously. In the heterogeneous mode, at room temperature, radio frequency transparent materials, including a range of thermoplastic and thermosetting resins can be bonded using two part adhesives cured at fast rates when exposed to focused microwave irradiation [5, 7, 9].

2. Thermoplastics as matrices in composites

Issues that are of importance when selecting a polymer for use as a composite matrix are reinforcement-matrix compatibility in terms of bonding, mechanical properties, thermal properties, cost, etc., though perhaps the most important aspect may be its processability, ie. how easy it is to deal with it in manufacturing situations. Among the many issues that may be considered part of the processability are viscosity, processing temperature, processing time and health concerns. Low viscosity is vital in achieving reinforcement impregnation, where each reinforcing fibre should be surrounded by the matrix without voids.

Thermosets have the advantages of good infiltration through low viscosity monomers, low cost both in terms of monomers and in processing equipment, good mechanical properties with the exception of fracture toughness, and good chemical and thermal properties in terms of chemical inertness and high temperature stability. They suffer from some safety and health problems with toxic monomers, catalysts or reaction products during curing; long processing times and sometimes elevated temperatures; shrinkage and residual stresses from curing; disposal problems with materials and lack of recylability. Thermoplastics have advantages of rapid processing time, net shape processing, high fracture toughness, recylability, and generally lack of toxic chemical and products, but have disadvantages of requiring more expensive, high temperature and pressure processing facilities, high viscosity during infiltration, and high cost in materials. In general, a high-performance thermoplastic will outdo a standard-performance thermoset in most respects except cost and vice versa [1].

A thermoplastic is usually fully polymerised when delivered from the supplier, meaning that all chemical reactions are complete and the user can concentrate entirely on physical phenomena, such as heat transfer and flow. However, there are some rare exceptions to this rule. The user may choose to take care of part of the polymerisation starting off with low molecular weight prepolymer, thus avoiding the high viscosity disadvantage during reinforcement impregnation. Courtesy of the low molecular weight, the polymer fluid may have a viscosity comparable to that of a thermoset resin. After the reinforcement is impregnated, the final polymerisation process takes place and the molecular weight thus drastically increases.

One of the main features of amorphous thermoplastics is that they are dissolvable in common industrial solvents. This means that the reinforcement can be impregnated with a low viscosity solution, thus avoiding the problem of high melt viscosity, but it also means that the solidified polymer is not solvent resistant. For solvent-impregnated reinforcement, the residue solvent that was not completely driven off after impregnation is a serious concern since it impairs the quality of the composite. Amorphous thermoplastics have very good surface finish since they do not shrink much when they solidify and there is no differential shrinkage from the presence of crystalline regions [1]. This is in fact a very important property of thermoplastics used as matrices of composites.

3. Fibres as reinforcement in composites

The reinforcement is the constituent that primarily carries the structural loads to which a composite is subjected. The reinforcement therefore to a significant degree determines stiffness and strength of the composites as well as several other properties. Composite reinforcement may be in the form of fibres, particles or whiskers. A fibre, or filament, has a length-to-diameter ratio that approaches infinity and a diameter typically of approximately 10 μm. The most common types of fibrous reinforcement used in composite applications are glass, carbon and aramid [1]. Glass fibres clearly dominate as reinforcement in all but high-performance composite applications due to an appealing combination of good properties and low cost. Property characteristics of a glass fibre are advantages such as high strength, very good tolerance to high temperatures and corrosive environments, radar transparency, and low price. Disadvantages include relatively low stiffness, moisture sensitivity and abrasiveness. Apart from S and R glass, which are used in some high-performance applications, glass reinforcement is mainly used where high stiffness is not required and where part cost is a critical factor [10, 11].

Carbon fibres have the highest strength and stiffness of any composite-reinforcement candidate and the development towards new carbon fibre types with improved stiffness, strength and ultimate strain is rapid. While carbon fibres have the highest strength and stiffness of any composite reinforcement candidate, high strength and high modulus cannot be normally obtained in the same fibre, and high modulus is also accompanied by fairly low strain to failure. Other advantages include tolerance to high temperatures and corrosive environments, as well as lack of moisture sensitivity. The major disadvantage is its high price, while others include brittleness and conductivity. Whereas the conductivity of carbon may be advantageous in some rare instances it is generally a nuisance in that carbon reinforcement may cause galvanic corrosion of metal inserts and loose carbon particles suspended in the air may easily short out electrical and electronic equipment. Carbon fibre reinforcement dominates in high performance applications due to its outstanding mechanical properties combined with low weight [1, 10].

Aramid fibres are the most commonly used organic fibres in composite reinforcement. Advantages of aramid fibres are very good mechanical properties, especially toughness and damage tolerance, and good electrical properties. Its major drawback includes that the strength of aramid fibre composites in longitudinal compression is only a fraction of that in tension, and that in nearly all of the fibre-matrix compatibility is generally poor. The outstanding toughness of aramid also creates a problem in that fibres are very difficult to cut and machining of aramid reinforced composites requires special tools and techniques. Other disadvantages of aramid fibres are moisture sensitivity and high price. The major advantage of aramid fibres lies in their outstanding toughness and damage tolerance which have given rise to energy-absorbing applications, such as in bullet-proof vests woven from aramid yarns Other fibres currently used in composite reinforcement include polyethylene fibres, α-aluminium oxide fibres and boron fibres [1, 10].

In this paper, only random carbon fibre reinforced thermoplastic matrix composite materials will be tested and discussed.

4. Materials / microwaves interactions

In conventional microwave processing, microwave energy is launched at a fixed frequency of either 915 MHz or 2.45 GHz or 5.8 GHz or 24.125 GHz into a waveguide or cavity, and this brings with it the inherent heating uniformity problems like hot spots and thermal runaway [8, 9, 12, 13]. Thermal runaway is the uncontrolled rise in temperature in some hotter parts of a material subject to microwave heating. This is because the hotter parts will absorb more microwave energy than any other part of the material and convert it into heat as a result of the increase of tan δ with temperature [8]. A US based company developed a new technique for microwave processing, known as variable frequency microwave (VFM) technique, to solve the problems brought about by fixed frequency microwave processing. The technique was geared towards advanced materials processing and chemical synthesis. It offered rapid, uniform and selective heating over a large volume at a high energy coupling efficiency. This was accomplished using a preselected bandwidth sweeping around a central frequency employing tunable sources such as travelling wave tubes as the microwave power amplifier. Selective heating of complex samples and industrial scale-up were now viable [13, 14]. Successful applications have been reported in the areas of curing advanced polymeric encapsulants, rapid processing of flip-chip underfills, materials characterisation, curing profiles for various adhesives, structural bonding of glass to plastic housing [14, 15].

5. VFM processing of materials

The VFMF are located at Industrial Research Institute Swinburne (IRIS), Swinburne University of Technology, Australia and consist of a Microcure 2100 Model 250 with a frequency sweep range of 2 - 8 GHz operating at a nominal power of 250W, and of a Wari-Wave VW1500 with a frequency range of 6.5 – 18 GHz at a nominal power of 125 W. The VFM facilities consist of a curing cavity and an oven control system, which is linked to a PC for programme input. The dimensions of the cavity for Wave-Vari VW 1500 are 250 mm x 250 mm x 300 mm. Two halves of lap shear test piece of the sample, as shown in Figure 1 were joined together using the VFM energy without primer. The lapped area for the joint was 10 mm x 20 mm. The bond surfaces were first roughened with coarse, grade 80 emery paper to increase the mechanical keying or interlocking [16]. The roughened surfaces were then cleaned and degreased by immersing them in methanol. The two test pieces were then brought together by a small G-clamp and the total pressure applied was about 20 N. Program with the required parameters was then written and input to control the VFMF via a PC. In one of the VFMF, Wari-Wave VW 1500, the input power level could be varied in steps of 10 W, starting from 50 W to 125 W. During cavity characterisation, the actual amount of power that passed through the test pieces with respect to time was measured using fibre optic; in addition, the power reflected back from the material could also be detected. By this way, the best frequency range to process a material by microwaves can be found.

Two types of temperature monitoring systems were available for the VFM facilities. As standard, a single channel fibre optic measurement system was provided. This included a fibre optic probe within the cavity that had to be placed in contact with the surface at the location, which was monitored. An additional 3 (4 total) fibre optic channels were also installed. A second temperature device consisted of an infrared non-contact temperature measurement unit that provided specific surface temperature reading without making physical contacts with the parts being processed. The optical beam was targeted on parts being processed thus providing a temperature reading to the control system.

5.1 Program for LDPE/CF (33%)

In this study, Wari-Wave VW 1500 has to be used because of the frequency range chosen. The frequency range for this equipment is from 6.5 – 18 GHz and the best frequency to process LDPE/CF (33%) is 8.5 – 9.0 GHz and 10.7 – 12.0 GHz as shown in Table 1 based on previous work [17]. The parameters for joining this material are central frequency = 9 GHz, bandwidth = 1.5 GHz, power level = 100 W, set temperature = 95 ^{o}C and maximum temperature = 100 ^{o}C. Since the bandwidth of the sweep should be greater or equal to 1.1 GHz, the selected bandwidth was 1.5 GHz [18]. The actual start and stop frequencies would be centre frequency $\pm \frac{bandwidth}{2}$, ie the sweep would be from 8.25 GHz to 9.75 GHz. Because the sweep time could range from 0.1 second to 100 seconds, the chosen sweep time was 0.1 second. Since the material loss tangent was relatively high, a power level of 100 W was selected [19-21]. The processing temperature was set at 95^{O}C with a deadband (precision) of 1^{O}C and the total processing time was set at 90 seconds. The maximum permitted temperature was set at 100^{o}C, above that the machine was switched off automatically. The programme for joining LDPE/CF (33%) were as follows: central frequency = 9 GHz; bandwidth = 1.5 GHz; sweep time = 0.1 secs; power output = 100 Watts; set temperature = 95 ^{o}C; deadband = 1 ^{o}C; duration = 90 seconds; maximum temperature = 100 ^{o}C.

A maximum temperature of 100 ^{o}C was selected because it was very near to the melting point of one of the main constituents of the composite, the low density polyethylene (LDPE). The reason for setting this maximum temperature was to avoid excessive temperature rise, which forms hot spots and thermal runaway. Programs for other exposure duration were also similarly written. Results of the process will be given in the result section later on.

5.2 Program for PS/CF (33%)

Again, the best frequency to process PS/CF (33%) is from 8.0-9.3 GHz and 10.8 – 12.8 GHz as shown in Table 1 [17]. Because of frequency restriction, Wari-Wave VW 1500 VFMF has to be used. All parameters used in joining PS/CF (33%) were exactly the same to those for LDPE/GF (33%) except that the processing time was made 120 seconds. Programs for other exposure duration were also similarly written. Results of the experiments will be discussed later.

6. Fixed frequency microwave processing of materials

In the fixed frequency microwave facility configurations, one is a focused, high energy rate, fixed frequency equipment, as shown in Figure 2 and the other configuration is the variable frequency microwave (VFM) oven but a fixed frequency of 2.45 GHz is selected.

6.1 Fixed frequency equipment

This involves the use of a TE_{10} mode rectangular waveguide operating in a standing wave configuration. Slots were machined in the waveguide allowing the bondline on the specimens to pass through the microwave region. LDPE/CF (33%) specimens with the same lap area and surface treatment were placed in a standard rectangular waveguide as depicted in Figure 3 [13, 22]. To avoid microwave radiation leakage, the slotted waveguide was enclosed in a modified commercial microwave oven case (Figure 2). A short circuit was adjusted to ensure that the maximum of the standing wave coincided with the lapped area of the specimen [8, 13]. The input power to the system was in a step function and could only be 240W, 400W, 640W and 800W. The power was changed by altering the power of the source. The duration of exposure could be increased in steps of 1 second. The samples were exposed to 240 W and 400 W of power at different exposure times. The magnetron was operating at 2.45 GHz.

The other material, PS/CF (33%), was also joined with similar parameters. The power levels used are 240 W and 400 W. The bonds formed were lap shear tested and the results are outlined later.

6.2. Program for LDPE/CF (33%) using VFMF

A fixed frequency of 2.5 GHz was chosen and used with the VFMF. The power level of 100 W was also chosen. While the processing temperature was set at 95^{o}C and the processing time was set at 20 seconds. The maximum temperature was set at 100^{o}C to prevent overheating. Programs for other exposure duration were also written. Results will also be discussed later.

7. Results

7.1 Results of processing using VFMF

The results of processing the three composite materials using VFMF will be presented in 2 sections. They are as follows:

7.1.1 LDPE/CF (33%) processing results using VFMF

A Shimadzu tensile testing machine was used for the lap shear test. A load range of 2000 N and a load rate of 600 N per minute were used for the test [23]. With VFM, no bond was formed if the processing time was less than 30 seconds. Bonds started to form at an exposure time of 40 seconds or over. At an exposure time of 90 seconds or over, the parent material was weakened because when it was subjected to a tensile shear stress test, failure occurred at the parent material and the bond quality was poor and was discarded. Figure 4 shows that lap shear strengths obtained range from 180 N/cm^2 at an exposure time of 40 seconds to 230 N/cm^2 at an exposure time of 80 seconds. At an exposure time of 80 seconds, the test piece fails at the parent material. This means that the lap shear strength was more than 230 N/cm^2. This means that the parent material [LDPE/CF (33%)] was weakened by the excessive exposure to microwave irradiation. This behaviour is similar to that of LDPE/GF (33%) in another study when it was exposure to excessive microwave energy [24].

7.1.2 PS/CF (33%) processing results using VFMF

The results are summarised in Figure 5. The lap shear strength decreases from 256 N/cm^2 at an exposure time of 60 seconds to 168 N/cm^2 (lowest value) at an exposure time of 120 seconds. For all times of microwave exposure, the failures were at parent material. This means that the parent material [PS/CF (33%)] was weakened by the excessive exposure to microwave irradiation as in the case of LDPE/CF (33%). Figure 6 shows the lap shear strength of PS/CF (33%) versus different power levels at an exposure time of 100 seconds. The lap shear strength reducers from 237 N/cm^2 at an exposure time of 50 seconds to 209 N/cm^2 at an exposure time of 100 seconds. The failures were at parent material hence in all cases the parent material was weakened by excessive exposure to microwave energy.

7.2 Fixed frequency results using slotted waveguide

In this case, the results will also be presented in two sections. They are as follows:

7.2.1 Fixed frequency results for LDPE/CF (33%)

Figure 7 shows the lap shear strength of LDPE/CF (33%) joined by a fixed frequency microwave facility in a slotted rectangular waveguide, at a fixed frequency of 2.45 GHz and a power level of 400 W. The microwave exposure times ranges from 4 to 8 seconds and the lap shear strength increases from 36 N/cm^2 to 127 N/cm^2. The joints at exposure times of 4, 5, 6 and 7 seconds were good but that at 8 seconds was poor and should be discarded. The peak lap shear strength (127 N/cm^2) was when the exposure time was 7 seconds. Figure 8 shows the lap shear strength of LDPE/CF (33%) joined by a fixed frequency microwave facility in a slotted rectangular waveguide, at a fixed frequency of 2.45 GHz and a power level of 240 W. The microwave exposure times ranges from 6 to 20 seconds, the lap shear strength increases from 95 to 150 N/cm^2. The joints at exposure times of 6 to 15 seconds were good but that at 20 seconds was poor and should be discarded. The peak lap shear strength (150 N/cm^2) was when the exposure time was 10 seconds.

7.2.2 Fixed frequency results for PS/CF (33%)

Figure 9 shows the lap shear strength of PC/GF (33%) joined by a fixed frequency microwave facility in a slotted rectangular waveguide. It was found that with 400 W power level, the lap shear strength ranged from 163 N/cm^2 at an exposure time of 4 seconds to 214 N/cm^2 at an exposure time of 9 seconds. At an exposure of 10 seconds, the bond quality obtained was poor and should be discarded. The peak lap shear strength was 222 N/cm^2 at an exposure time of 6 seconds.

Figure 10 shows the lap shear strength of PC/GF (33%) joined by a fixed frequency microwave facility in a slotted rectangular waveguide. It was found that with 240 W power level, the lap shear strength ranged from 138 N/cm^2 at an exposure time of 4 seconds to 171 N/cm^2 (peak value) at an exposure time of 15 seconds. At an exposure of 20 seconds, the bond quality obtained was poor and should be discarded.

7.3 Fixed frequency results using VFMF

In this case, only one material, LDPE/CF (33%), was studied. The result is as follows:

7.3.1 Fixed frequency results for LDPE/CF (33%)

Using VFMF, LDPE/CF (33%) was joined at a fixed frequency of 2.5 GHz. The power level was 100 W and the maximum time of exposure was 20 seconds. Figure 11 shows the ‘apparent’ lap shear strength of LDPE/CF (33%) versus time of exposure. The word apparent was used because all test pieces failed at the parent material and not at the bondline. This meant that the bondline was stronger than the parent material. It was found that the lap shear strength ranged from 114 N/cm^2 at an exposure time of 12 seconds to 216 N/cm^2 (peak value) at an exposure time of 18 seconds. At an exposure of 20 seconds, the bond quality obtained was poor and should be discarded.

8. Discussion

The first thing worth discussing will be the lap shear strengths of the two materials obtained by processing them with VFMF. All other parameters used for processing for the two materials are the same except the exposure time to microwave irradiation. Referring to Figures 4, 5 and Table 3, the average lap shear strengths for LDPE/CF (33%) and PS/CF (33%) are 195 N/cm^2 and 219 N/cm^2 respectively. The average lap shear strength of PS/CF (33%) is higher than its counterpart because the dielectric properties, particularly the loss tangent, of polystyrene is higher than that of low density polyethylene as shown in Table 2 [25]. From Table 2, it is found that the loss tangent for polystyrene is 5.3 x 10^{-4} or 1.5 times higher than that for LDPE (3.6 x 10^{-4}). The carbon fibre in the composites are not taken into consideration while comparing the dielectric properties because each composite has the same percentage by weight of carbon fibre and its effect is neutralised. It is therefore expected that PS/CF (33%) will absorb more microwave energy and will take shorter time to reach peak lap shear strength.

Comparing Figures 4 and 11, the average lap shear strength of LDPE/CF (33%) joined by VFMF is 195 N/cm^2 and that bonded by VFMF at a fixed frequency of 2.5 GHz is 165 N/cm^2. The former is more superior in strength as well as in bond quality. Joining LDPE/CF (33%) by VFMF is therefore recommended. It can be argued that within limits the lower the power level of VFMF used, the higher will be the average lap shear strength. With reference to Figure 6, it was found that the lower the power level used by VFMF, the higher the average lap shear strength of PS/CF (33%). This is in line with the case of LDPE/CF (33%).

Referring to Figures 7, 8 and Table 3, it was found that the average lap shear strength of LDPE/CF (33%) joined by fixed frequency facility at a power level of 400 W was 99 N/cm^2 and that at a power level of 240 W was 119 N/cm^2. It can therefore be argued that the lower the power level used, the higher the lap shear strength will be, and this is in line with the case using VFMF.

Again, by comparing the average lap shear strengths of LDPE/CF (33%) (Figure 7, 99 N/cm^2) and PS/CF (33%) (Figure 9, 204 N/cm^2) obtained by exposing test samples to a power level of 400 W, at different exposure times, it is found that the results matched with the loss tangent values of the two thermoplastic matrices. The PS has a higher loss tangent value than LDPE and the lap shear strength of PS/CF (33%) improves more than its counterpart. Again, by comparing the average lap shear strengths of LDPE/CF (33%) (Figure 8, 119 N/cm^2) and PS/CF (33%) (Figure 10, 159 N/cm^2) obtained by exposing test samples to a power level of 240 W, at different exposure times, it is found that the results matched again with the loss tangent values of the two thermoplastic matrices. The PS has a higher loss tangent value than LDPE and the lap shear strength of PS/CF (33%) improves more than its counterpart.

9. Conclusion

It is beneficial to use VFMF to join LDPE/CF (33%) and PS/CF (33%) the lap shear strengths obtained, at all exposure times, are higher than those acquired by using fixed frequency facility. As from the above discussion, the power level used in VFMF should be reduced to less than 50 W to get higher lap shear strength. This, however, should be complimented by increasing the time of exposure to microwave irradiation. The carbon fibres, as compared to the glass fibres, are vital in enhancing the ability of the materials to absorb microwave energy.

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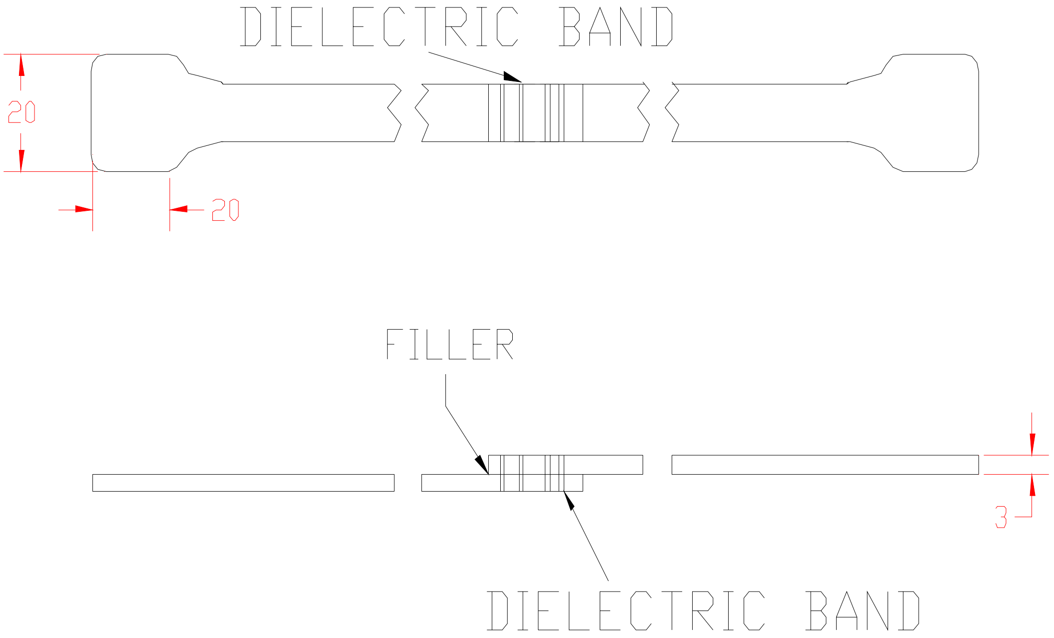

Figure 1: Two Mirror Image Test Pieces of LDPE/GF (33%)

Figure 2: Slotted Rectangular Waveguide Microwave Configuration

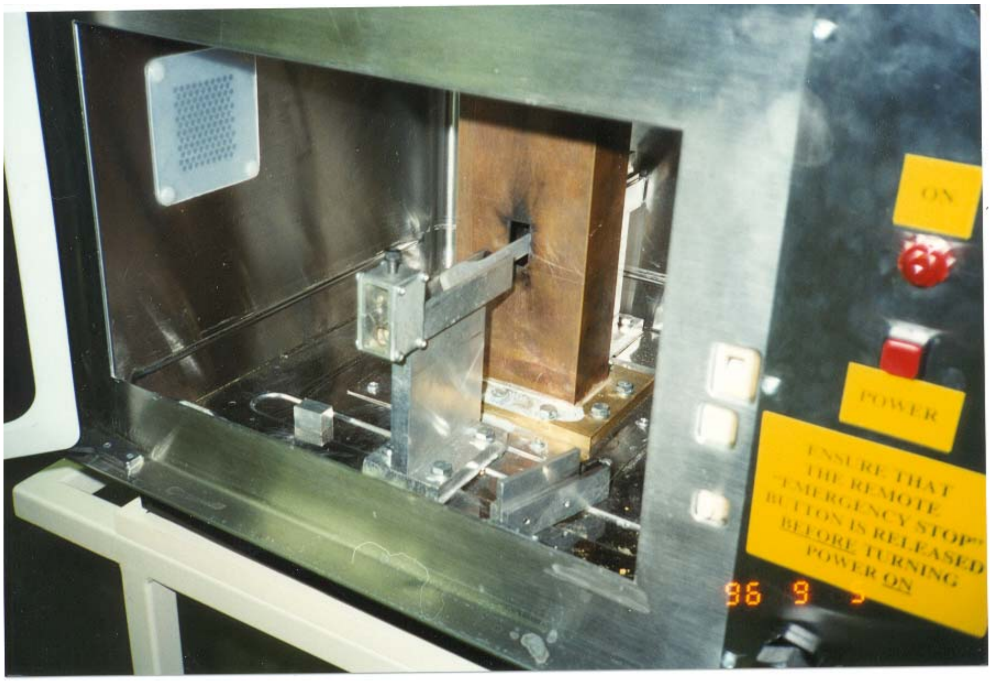

Figure 3: Slotted Rectangular Waveguide Used for Joining LDPE/CF (33%) with Araldite Using Fixed Frequency Equipment

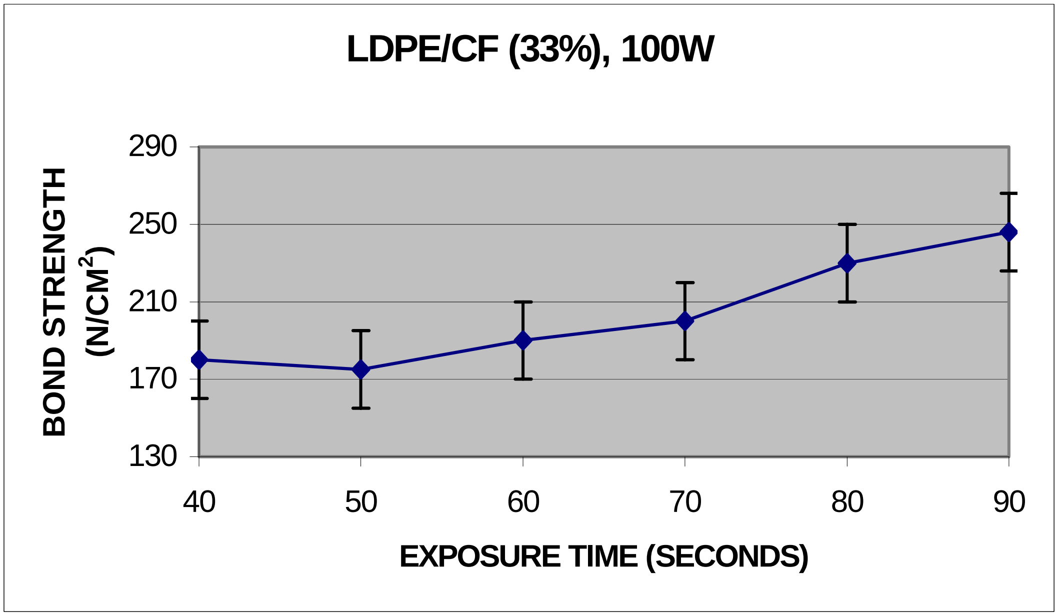

Figure 4: Lap Shear Strength of LDPE/CF (33%) Bonds Joined by VFM

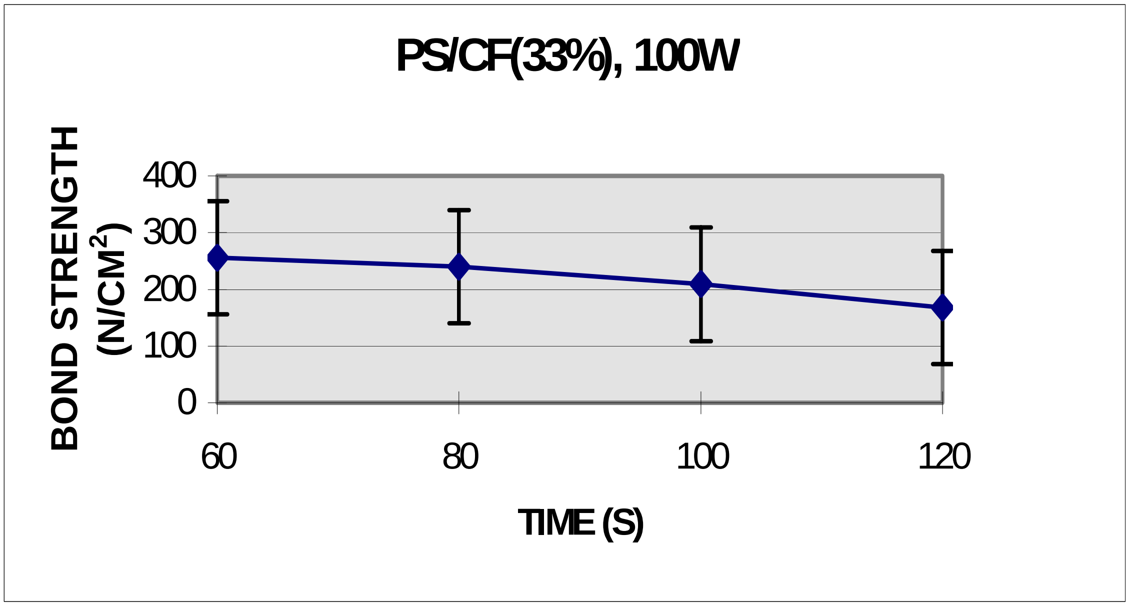

Figure 5: Lap Shear Strength of PS/CF (33%) Bonds Joined by VFM

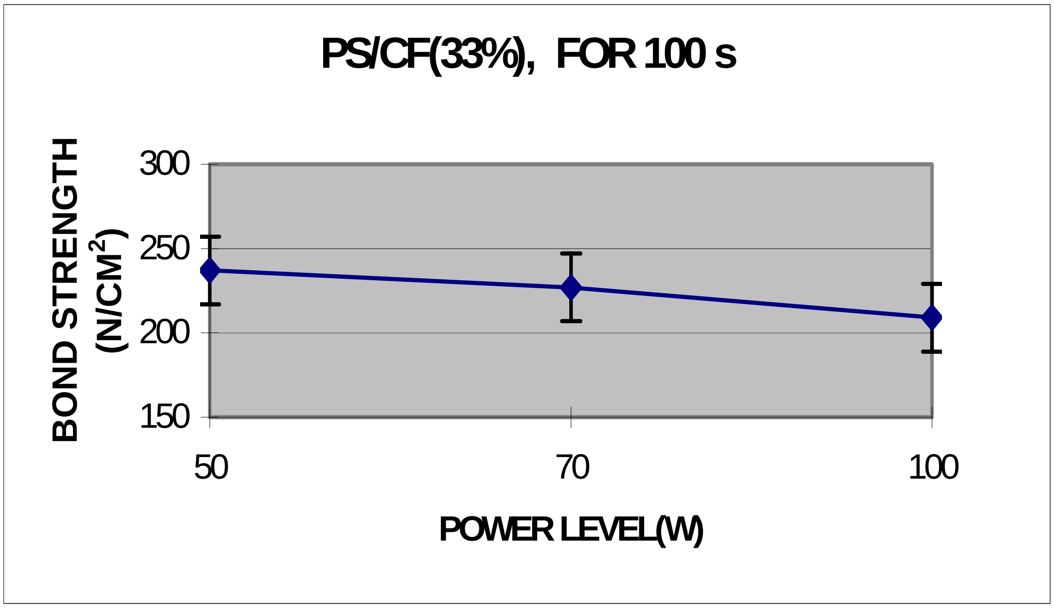

Figure 6: Lap Shear Strengths of PS/CF (33%) Joined by VFM at Different Power Levels

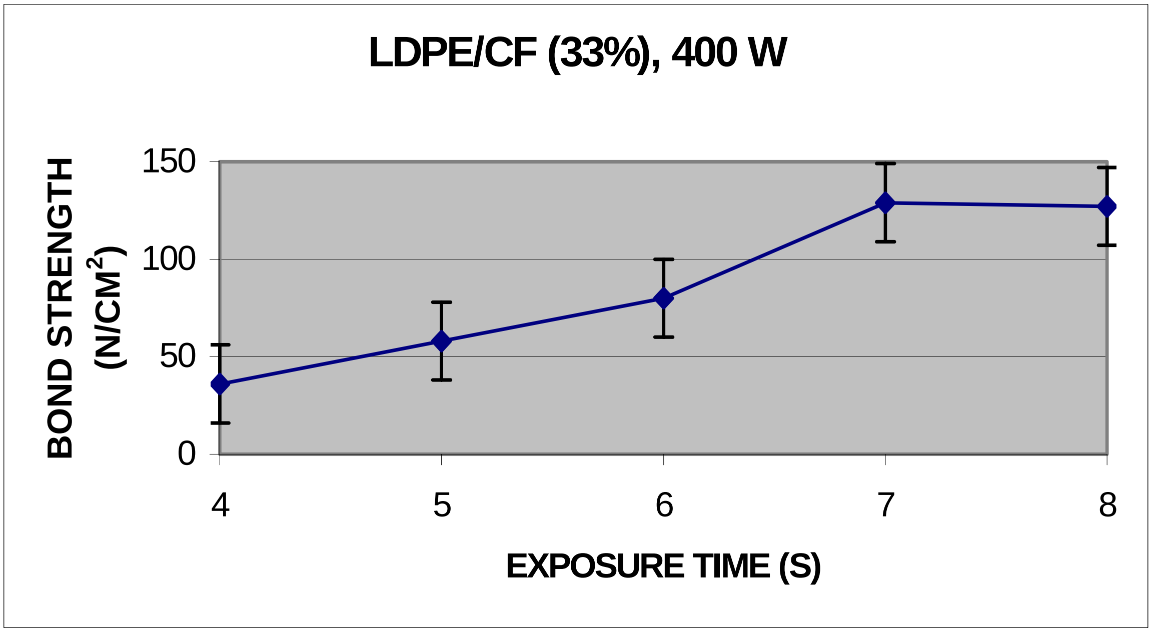

Figure 7: Lap Shear Strength of LDPE/CF (33%) Joined by Fixed Frequency Microwave (2.45 GHz) in a Slotted Rectangular Waveguide at a Power Level of 400 W

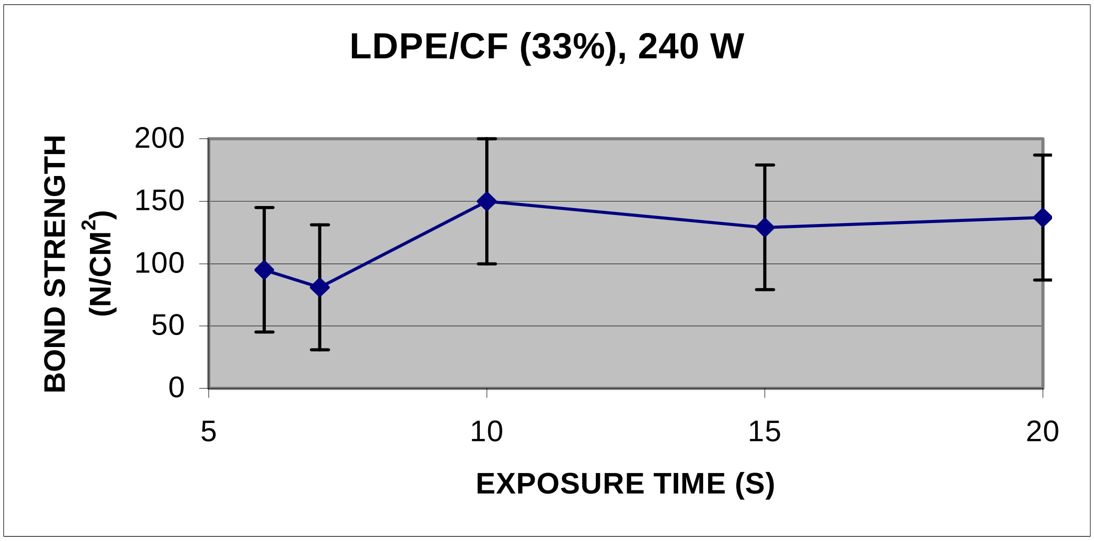

Figure 8: Lap Shear Strength of LDPE/CF (33%) Joined by Fixed Frequency Microwave (2.45 GHz) in a Slotted Rectangular Waveguide at a Power Level of 240 W

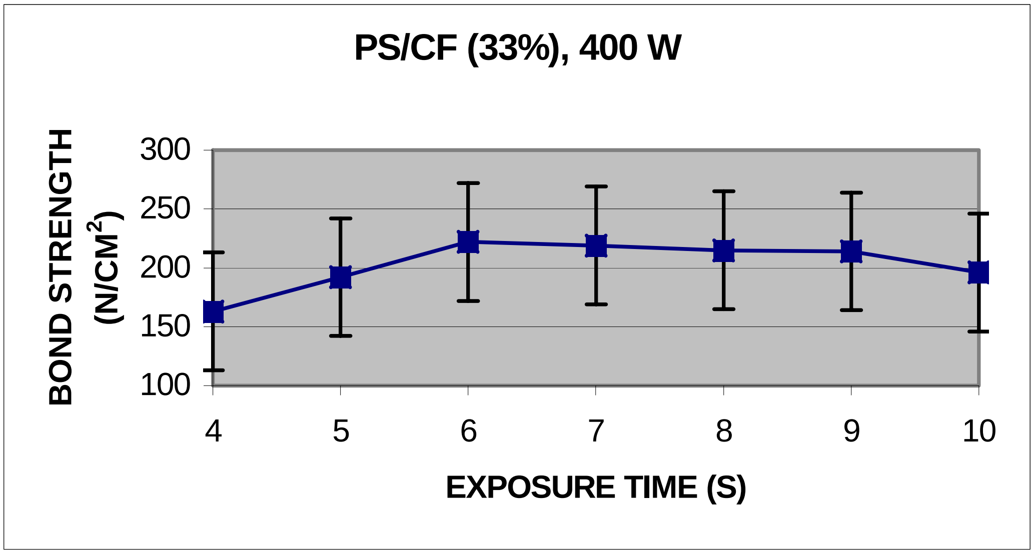

Figure 9: Lap Shear Strength of PS/CF (33%) Joined by Fixed Frequency Microwave (2.45 GHz) in a Slotted Rectangular Waveguide at a Power Level of 400 W

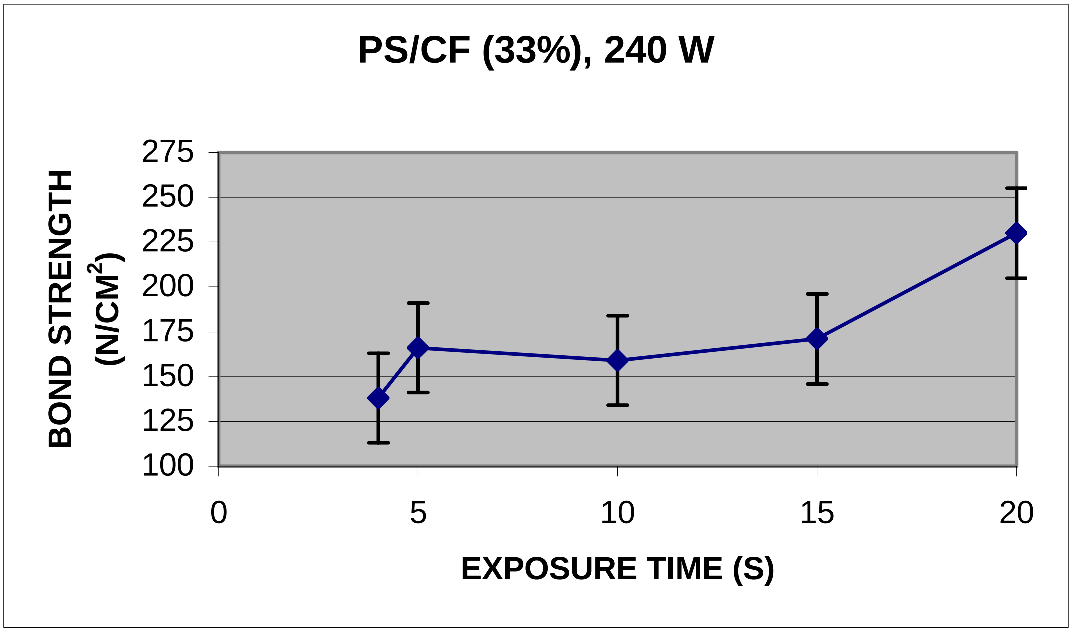

Figure 10: Lap Shear Strength of PS/CF (33%) Joined by Fixed Frequency Microwave (2.45 GHz) in a Slotted Rectangular Waveguide at a Power Level of 240 W

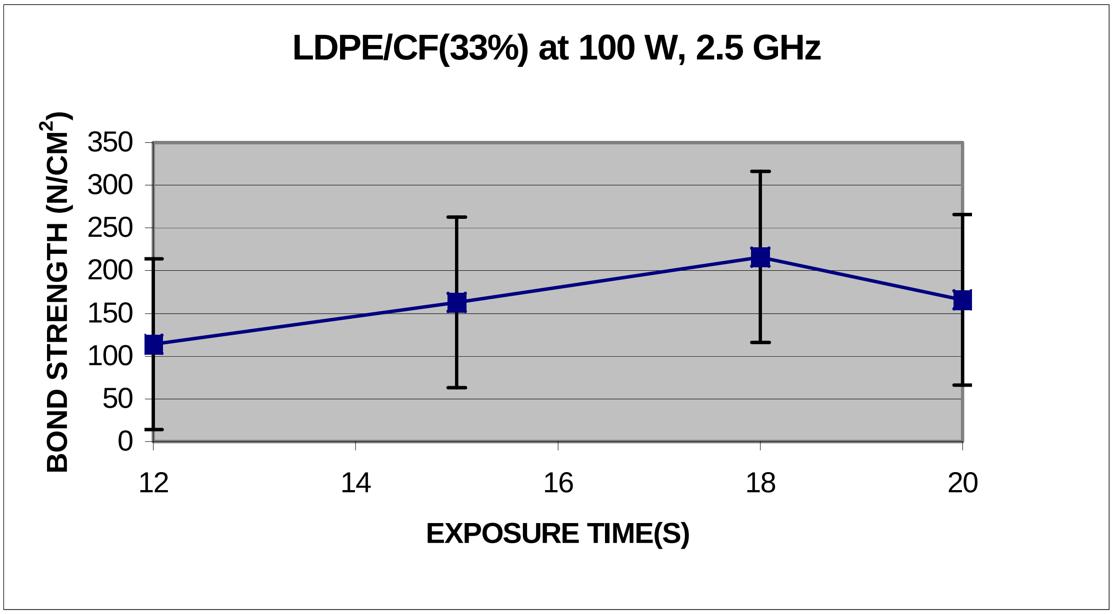

Figure 11: Lap Shear Strength of LDPE/CF (33%) using VFMF at Fixed Frequency of 2.5 GHz

Table 1: Optimum Frequency Bands to Process the 2Thermoplastic Matrix Composite Materials in the Frequency Range of 2 GHz to 18 GHz.

Materials	Optimum Frequency Band (GHz)
LDPE/CF (33%)	8.5 - 9.0 and 10.7 - 12.0
PS/CF (33%)	8.0 - 9.3 and 10.8 - 12.8

Table 2: The Dielectric Constant and Loss Tangent of the Two Matrix Materials of the Composites at 25^{o}C and 10 GHz.

Matrix Materials	Dielectric Constant	Loss Tangent (1 x 10^{-4})
Low density polyethylene	2.26	3.6
Polystyrene	2.53	5.3

Table 3: Lap Shear Strengths of Joints of 2 Different Composite Materials at Different Input Parameters.

Composite Materials	Power Level	Lap Shear Strength (N/cm^2)
LDPE/CF (33%)	100, VFMF 400 240	195 99 119
PS/CF (33%)	100, VFM 400 240	219 204 159