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Contrast Joints of Glass-fibre with Carbon-fibre Reinforced Polystyrene Composite Bonded by Microwave Irradiation

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Abstract: This paper contrasts the loss tangent, durability of reinforcement and the lap shear strengths of 33 percent by weight random glass fibre reinforced polystyrene matrix composite [PS/GF (33%)] with 33 percent by weight random carbon fibre reinforced polystyrene matrix composite [PS/CF (33%)] bonded using microwave irradiation. Fixed (2.45 GHz) and variable (2 – 18 GHz) frequency microwave (VFM) facilities are used to bond the two composites. With a given power level, the composites were exposed to various exposure times to microwave irradiation. The primer or coupling agent used for joining the glass-fibre-reinforced composite was 5-minute two-part adhesive, Araldite. No filler was used in joining the carbon-fibre-reinforced composite. The lap shear strengths of PS/GF (33%) obtained by FFM facility and VFMF are higher than those of PS/CF (33%). In all cases, the PS/CF (33%) absorbed too much microwave irradiation and this damaged the material (Ku et al., 2000c).

Keywords: variable frequency microwaves (vfm), loss tangent, lap shear strength and Araldite.

1. Introduction

Thermosetting resins have dominated the market in the last thirty years as the matrices for fibre reinforce composites in structural applications, aerospace industry, sporting goods and chemical engineering (Astrom, 1997; Hou, 1995). Thermoplastics are almost exclusively used when no reinforcement is included and dominate also when short fibres are incorporated. However, in the last 12 - 15 years, thermoplastics have received increased attention in random as well as continuos 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 continuos 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 (Astrom, 1997; Hou, 1995). 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, aiming at maximising bond quality.

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 (Sutton, 1989). 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 (Metaxas and Meredith, 1983, Siores, 1994; Ku, 1997a; 1999a, Illawarra Technology Corporation, 2001). 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, $\tan\delta = \frac{\varepsilon''}{\varepsilon'}{}'$ (NRC, 1994; Ku et al., 1997a). 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 absorbed. The most important property in microwave processing is the loss tangent, tan δ, which predicts the ability of the material to convert the absorbed 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. In a material with a very high loss tangent, the microwave energy density will reduce with distance of penetration into the material. This phenomenon is known as the skin effect. 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, 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 (Siores, 1994; Ku et al., 1997b; 1999a).

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. While thermoplastics only need to be melted, shaped, and then cooled to achieve dimensional stability in a matter of seconds at one extreme, thermosets may take several days to fully crosslink the polymer. In contrast, the molecular structure of thermoplastics makes them chemically inert if processed correctly, meaning that no hazardous substance need to be considered. On the other hand, the molten thermoplastic and the heated machinery may cause severe burns (Astrom, 1997).

While thermosets heavily dominate as matices in structural composite applications for reasons of good mechanical and thermal properties, low cost, and low viscosity to mention a few, the interest in thermoplastics is driven by several potential advantages. Among the prime reasons behind the increased interest in the usage of thermoplastic matrices are advantages in areas as toughness, processing time, recyclability, and work environment. In general, a high-performance thermoplastic will outdo a standard-performance thermoset in most respects except cost and vice versa.

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 (Astrom, 1997). This is in fact a very important property of thermoplastics used as matrices of composites.

In this research, polystyrene was chosen as the thermoplastic matrix for the composites because of its wide applications and acceptance. Polystyrene is found in your home, office, local grocery and in the cafeteria. It comes in many shapes and forms, from foam egg cartons and meat trays, to soup bowls and salad boxes, from coffee cups and utensils to CD "jewel boxes," and from produce trays to "peanuts" used in packing and the lightweight foam pieces that cushion new appliances. It guards against leaking and keeps its shape when holding your take-out meal. It keeps hot food hot and cold food cold, while you hold the package in comfort. It cradles your fruit, vegetables, eggs and meat to keep them fresh and intact. It is an excellent low-cost and sanitary choice for food service packaging. It protects valuable shipments without adding significant weight. Nothing else offers the combination of strength, lightness and durability to protect valuable objects from crystal to computers, from morning coffee to salad at lunch, from your children to you (Polystyrene Packaging Council, 2001).

3. 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 it brought with it the inherent heating uniformity problems like hot spots and thermal runaway (NRC, 1994; Ku et al., 1997b; Liu et al., 1996). 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 (Metaxas and Meredith, 1983). 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 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 (Lie et al., 1996; Wei et al., 1998). 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 (Wei et al., 1998; Fathi et al., undated).

When microwave energy of a fixed frequency, eg 2.45 GHz was launched into a waveguide eg WR340, as depicted in figure 1(a), containing a piece of material, some areas of the material would experience higher electric field strength than the others; the situation would even be more serious if the microwave energy was launched into a multimode cavity because many resonant modes will be established. Figure 1(b) shows the fixed electric field pattern across any cross section of the joint of the test pieces during fixed frequency heating. Those areas with higher electric field strength would be heated more, creating hot spots, which could even lead to thermal runaway. With variable frequency microwave heating, as shown in figure 2(a), more than one thousand frequencies were launched into the cavity sequentially (Wei et al., 1998). Each incident frequency set up its own electric field pattern across any cross section of the joint of the test pieces, and therefore resulted in hot spots at different locations at different time, as shown in figure 2 (b). Different areas were heated under different frequencies at different times. When a sufficient bandwidth was used, every element of the test piece would experience hot spots at one or more frequencies during sweeping. Therefore, time-averaged uniform heating could be achieved with proper adjustment of the frequency sweep rate and sweep range. Another advantage of the VFM heating is the capability of providing precise frequency tuning to optimise the coupling efficiency.

4. Fixed frequency microwave processing of materials

In the fixed frequency microwave facility configuration, a focus, high-energy rate, fixed frequency (2.45 GHz) equipment, as shown in Figure 3 is selected. Two halves of lap shear test piece of the sample as shown in Figure 4 were joined together using microwave energy with Araldite as primer for glass-fibre-reinforced composite. No primer is used in joining the carbon-fibre-reinforced composite. The primer used, which was microwave reactive, was two part adhesive containing 100% liquid epoxy and 8% amine (NRC, 1994). The lapped area for the joint was 10 mm x 20 mm. The bond surfaces were first roughened with coarse, grade 80 emery paper. The roughened surfaces were then cleaned and degreased by immersing them in methanol. After drying, five-minute two-part Araldite of around 1.0 to 1.5 cubic centimetres was applied to the two roughened surfaces to increase the mechanical keying or interlocking (Ku et al., 2000a). The two test pieces were then brought together and the total pressure applied was about 4 N/cm^2.

The fixed frequency equipment involves the use of a TE_{10} mode rectangular waveguide operating in a standing wave configuration. Slots were machined in the waveguide allowing the adhesive layer on the specimens to pass through the microwave region. LDPE/GF (33%) or LDPE/CF (33%) composite specimens with the same lap area and surface treatment were placed in a standard rectangular waveguide as depicted in Figure 5 (Siores and Groombridge, 1997; Liu et al., 1996). To avoid microwave radiation leakage, the slotted waveguide was enclosed in a modified commercial microwave oven case (Figure 3). One to one and a half millilitre of Araldite were smeared on both surfaces of the lapped area. A short circuit was adjusted to ensure that the maximum of the standing wave coincided with the lapped area of the specimen (NRC, 1994; Liu, 1996). 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 apparatus used in the fixed frequency processing has been described in other papers and will not be discussed here (Ku et al., 1997a; 1997b). For LDPE/GF (33%), the samples were exposed to 400 W and 800 W of power at different exposure times. For PS/GF (33%), the samples were exposed to 150W, 400 W and 800 W of power at different exposure times. The 150W of power was achieved by setting the variable frequency microwave (VFM) facility to a fixed frequency of 2.5 (the machine can be set only to the nearest 0.1 GHz) GHz. The results will be discussed in the later section.

5. VFM processing of materials

The VFMF used 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 program input. The dimensions of the cavity for Microcure 2100 Model 2500 are 300 mm x 275 mm x 375 mm. Program with the required parameters was then written and input to control the VFMF via a PC. In one of the VFMF, Microcure 2100 Model 250, the input power level could be varied in steps of 10 W, starting from 50 W to 250W. 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.

5.1 Program for PS/GF (33%)

In order to have enough power to process PS/GF (33%) at 200 W, Microcure 2100 Model 250 VFM oven has to be used. The frequency range for this equipment is from 2 to 8 GHz but the best frequency range to process PS/GF (33%) is 8.5 – 9 GHz (Table 1). It is therefore necessary to make a compromise and a central frequency of 7.45 GHz has been selected in accordance with the 'compromised' best frequency to process PS/GF (33%). Since the bandwidth of the sweep should be greater or equal to 1.1 GHz, the selected bandwidth was 1.1 GHz (Bow, 1999). The actual start and stop frequencies would be centre frequency $\pm \frac{bandwidth}{2}$, ie the sweep would be from 6.9 GHz to 8 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 low, a power level of 200 W was selected (Ku et al., 1999a; 1999b). The processing temperature was set at 95$^{\mathrm{O}}$C with a deadband (precision) of 1$^{\mathrm{O}}$C and the longest processing time was set at 8 minutes. The maximum permitted temperature was set at 100$^{\mathrm{O}}$C, above that the machine was switched off automatically. The program for joining PS/GF (33%) were as follows: central frequency = 7.45 GHz; bandwidth = 1.1 GHz; sweep time = 0.1 secs; power output =

200 Watts; set temperature = 95 ^{o}C; deadband = 1 ^{o}C; duration = 8 minutes; maximum temperature = 100 ^{o}C.

The centre sweep frequency, 7.45 GHz, and its sweep bandwidth, 1.1 GHz, were found to be very close to that required for processing the epoxy resin primer, Araldite at optimum conditions (Ku et al., 2002).

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 polystyrene (PS). The reason for setting this maximum temperature was to avoid excessive temperature rise, which forms hot spots and thermal runaway. Programs for other exposure times are also written. Results of the process will be given in the result section later on.

5.2 Program for PS/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 range process PS/CF (33%) is 8.0 – 9.3 GHz and 10.8 – 12.8 GHz as shown in Table 1 (Ku et al., 2000b). The parameters for joining this material are central frequency = 11.8 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 (Bow, 1999). The actual start and stop frequencies would be centre frequency $\pm \frac{bandwidth}{2}$, ie the sweep would be from 11.1 (the machine can be set only to the nearest 0.1 GHz) GHz to 12.6

GHz. The chosen sweep time was 0.1 second. Since the material loss tangent was relatively high, a power level of 100 W was selected (Ku et al., 1999b; 2001).

6. Results

6.1 Results by using fixed frequency facility

6.1.1 Fixed frequency results for PS/GF (33%)

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 (Bolton, 1996). With reference to Figure 6, it was found that with 400 W power level, peak lap shear strength was achieved by exposing the test pieces to microwaves for 2 minutes; the lap shear strength (326 N/cm^2) at this exposure duration exceeded that obtained by ambient conditions (conventional) curing by 17% but the time required was a mere of 3 % of its counterpart. For exposure times of one and a half to four and a half minutes, the lap shear strength obtained at microwave cured filler were higher than those obtained by allowing the adhesive to set under ambient conditions. With a power level of 800 W (Figure 7), maximum lap shear strength (331 N/cm^2) was achieved when the exposure time was 45 seconds and it exceeded the ambient conditions cured lap shear strength by 19 % but the time required was only 1.25 % of its counterpart. The lower lap shear strength obtained, for test pieces exposed to microwaves for over 2 minutes and 45 seconds for power levels of 400 W and 800 W respectively, may be due to over-curing of the adhesive (1997b). With some exposure durations, the bond strengths might be higher than those cured conventionally because the parent material may have melted and diffused into the primer or interface and this was reflected in the softening of the lapped area after it was just removed from the applicator and examined using low power microscopy (1997b). Lap shear tests revealed that sixty percent of the failures were due to failure of the adhesive and took place at the joint interface. The remaining failures took place at the parent material [PS/GF (33%)]. With a power level of 400 W and exposure time of 2 minutes, the highest lap shear strength achieved was 326 N/cm^2; while with a power level of 800 W and exposure time of 45 seconds, the peak lap shear strength obtained was 331 N/cm^2. It can therefore be argued that the higher the power level used the shorter the exposure time required to achieve higher lap shear strength. These were up to 29 % and 62 % respectively stronger than the conventionally cured test pieces.

With a VFMF a fixed frequency of 2.5 GHz was chosen. The same primer was also used and the power level of 150 W was chosen. Figure 8 shows the 'apparent' lap shear strength of PS/GF (33%) bonded with two-part five-minute Araldite as primer, using VFMF. 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 tensile strength of the parent material (tensile strength = 47.43 N/cm^2). It was found that the apparent peak lap shear strength of 266N/cm^2 (tensile strength = $\frac{force}{area} = \frac{532N}{10mmx3mm} = 17.73N/mm^2$) was observed at an exposure time of 480 seconds. Values for other exposure times were just above 250 N/cm^2 (tensile strength = $\frac{force}{area} = \frac{500N}{10mmx3mm} = 16.67N/mm^2$).

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

Figure 9 shows the lap shear strength of PS/CF (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.

Figure 10 shows the lap shear strength of PS/CF (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.

6.2 Results of processing using VFMF

6.2.1 PS/GF (33%) processing results using VFMF

For obtaining lap shear test results, several sets of test pieces were joined at different duration. The results are summarised in Figure 11. The lap shear strength increases from 380 N/cm^2 at an exposure time of 180 seconds to 430 N/cm^2 (peak value) at an exposure time of 420 seconds. Up to these times of microwave exposure, the failures were at bond line. At exposure times of 450 and 480 seconds, the lap shear strengths were 405 N/cm^2

and 370 N/cm^2 respectively. The quality of the bonds was not good. The failures were at the parent material. This means that the parent material [PS/GF (33%)] is weakened by the excessive exposure to microwave irradiation. This behaviour is similar to that of LDPE/GF (33%) (thirty three percent by weight random glass fibre reinforced low-density polyethylene) when it is exposure to excessive microwave energy (Ku et al., 2000c). At an exposure time of 420 seconds, the peak lap shear strength is 430 N/cm^2, which is 55% higher than the average lap shear bond strength obtained by curing the Araldite under ambient conditions. For all intervals of exposure to VFM, the lap shear strengths are stronger than the average lap shear strength procured under ambient environment.

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

The results are summarised in Figure 12. The lap shear strengths decrease 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%) (Ku et al., 2000c). Figure 13 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. Discussion

Referring to Figures 6 through 12 the average lap shear strengths of the two composites at different powel levels, using fixed and variable frequency microwave facilities are summarised in Table 2. Comparing the lap shear strengths of the two types of materials, procured by exposing the test pieces to a power level of 400 W at fixed frequency of 2.45 GHz, at different times, it was found that the average lap shear strengths of PS/GF (33%) and PS/CF (33%) were –6% and –33% respectively lower than those cured in ambient conditions. It is found that microwave energy will only be beneficial if the exposure times for joining PS/GF (33%) at 400 W range from 100 to 260 seconds as shown Figure 6. With a power level of 800 W, PS/GF (33%) will benefit only from microwave processing if the times range from 40 to 50 seconds. While for PS/CF, at all power levels of microwave energy, they will not help in the bonding process because the composite was damaged by excessive microwave dosage (Ku et al., 2000c). Shorter exposure times may improve this.

The next thing worth discussing will be the lap shear strengths of the two materials obtained by processing them with variable frequency microwave facilities (VFMF). Both materials were bonded at a frequency range most suitable to process them (see Table 2). The power used for PS/GF (33%) was 200 W because its loss tangent is relatively low. On the other hand, the power used for PS/CF (33%) was 100 W. Referring to Figures 10 and 11, the average lap shear strengths for PS/GF (33%) and PS/CF (33%) are 402 N/cm^2, and 218 N/cm^2 respectively. They are 32% and -29% higher (or lower) than the average lap shear strengths cured under ambient conditions respectively. From Table 2, it is found that PS/GF (33%) is best joined by VFMF and the best time range to process it is from 180 to 420 seconds. Araldite must also be used as the binding agent to absorb the microwave energy, otherwise no bond will form. This is due to its relatively low loss tangent of the material. The microwave energy is then converted to heat and melt the parent material. On the other hand, PS/CF (33%) is best bonded by gluing it with Araldite and leave it to cure in ambient conditions. With reference to Figures 11 and 12 and if VFM facility is to be used for bonding PS/CF (33%), it seems that the power level used should be less than 100 W and the duration of exposure should be less than 60 seconds. Further study will be required to make final conclusion about it. It is found that the improvement in lap shear strength for PS/GF (33%) joined by using VFMF was significant but that of PS/CF (33%) was negative.

The average lap shear strengths for bonding PS/GF (33%) using VFM facility (200 W) and fixed frequency microwave facility (FFMF) (400W) were 402 N/cm^2 and 304 N/cm^2 respectively. The difference was significant. On the other hand, as far as the duration of exposure is concerned, it is found that the exposure times required for VFMF range from 180 to 420 seconds, while those for FFMF range from 100 to 260 seconds. The duration of exposure to microwaves for the latter is shorter and hence the energy required to bring the two materials to their average lap shear strengths is significantly different. The saving in power was $\frac{400W}{200W}$ = 2 times; the saving in time was $\frac{(100+260)\sec onds \div 2}{(180+420)\sec onds \div 2} = 0.77$ times. Therefore the energy saving is 2 x 0.77 x 100% = 153 %. This is entirely due to the multimode characteristics of the VFMF. By and large, the VFMF are more superior than their fixed frequency counterpart in joining and processing materials.

The single lap joint is easy to carry out as is therefore widely used, but it generates peel or cleavage sources at the ends of the bond, and is thus a stringent measure of bond strength. Adhesive joints represent discontinuity in the materials and should be carefully analysed. The high shear and normal stresses at the ends of the joint are due to stress concentrations from materials discontinuity and to bending. The bending effects can be reduced by using double lap shear joint. The stress concentrations can be reduced by using scarf joints. Pertinent details of the lap shear test are given by ASTM D-1002 (Schneberger, 1983; Gutowski, 1997).

It will be noticed that the exposure time for fixed frequency processing of PS/CF (33%) (Figures 9 and 10) was significantly shorter than other cases. This is due to the fact that in fixed frequency processing the interaction of random carbon fibre in the composite with the microwaves energy will result in arcing and this will damage the material.

8. Conclusion

The lap shear strengths of PS/GF (33%) obtained by FFM facility and VFMF are higher than those of PS/CF (33%). In all cases, the PS/CF (33%) absorbed too much microwave irradiation and this damaged the material (Ku et al., 2000c). This phenomenon will not happen in PS/GF (33%). By and large, the VFMF are more superior than their fixed frequency counterpart in joining and processing materials because the quality of bonds obtained by the former facility are much better than those of the latter. In addition, the processing time using VFMF can also be reduced by employing larger power but more expensive ovens.

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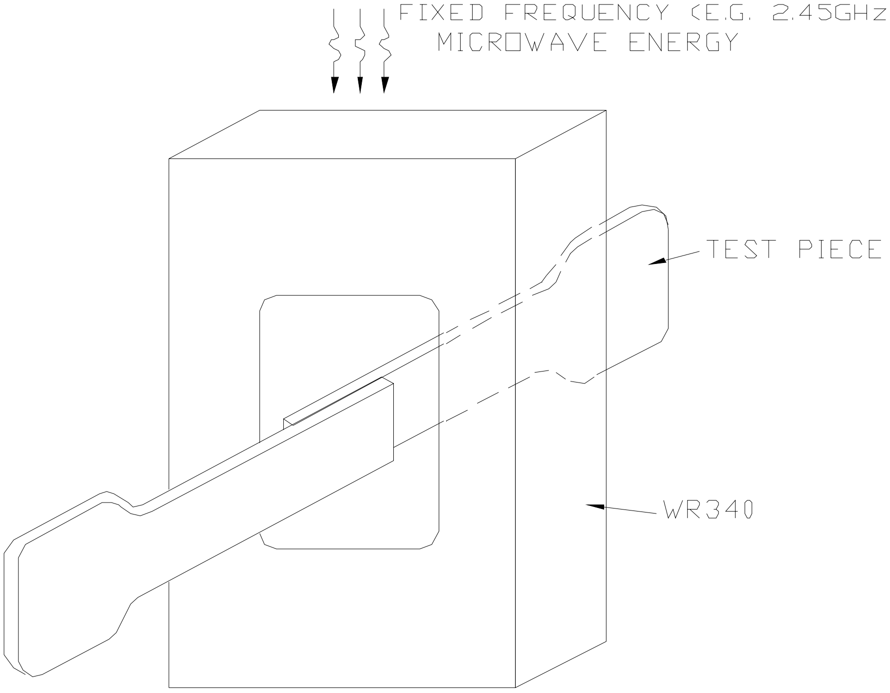
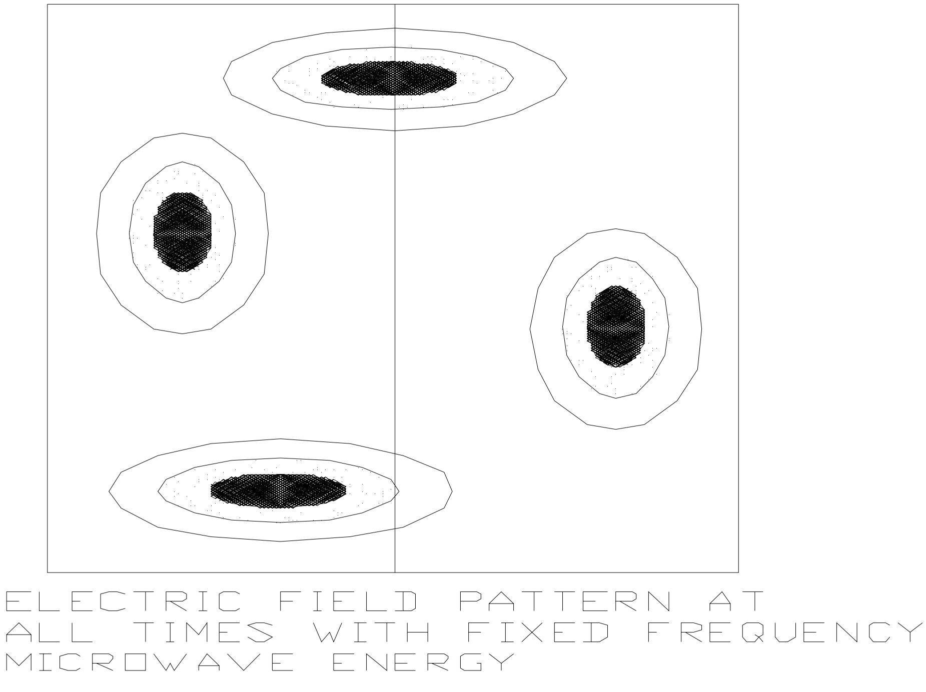
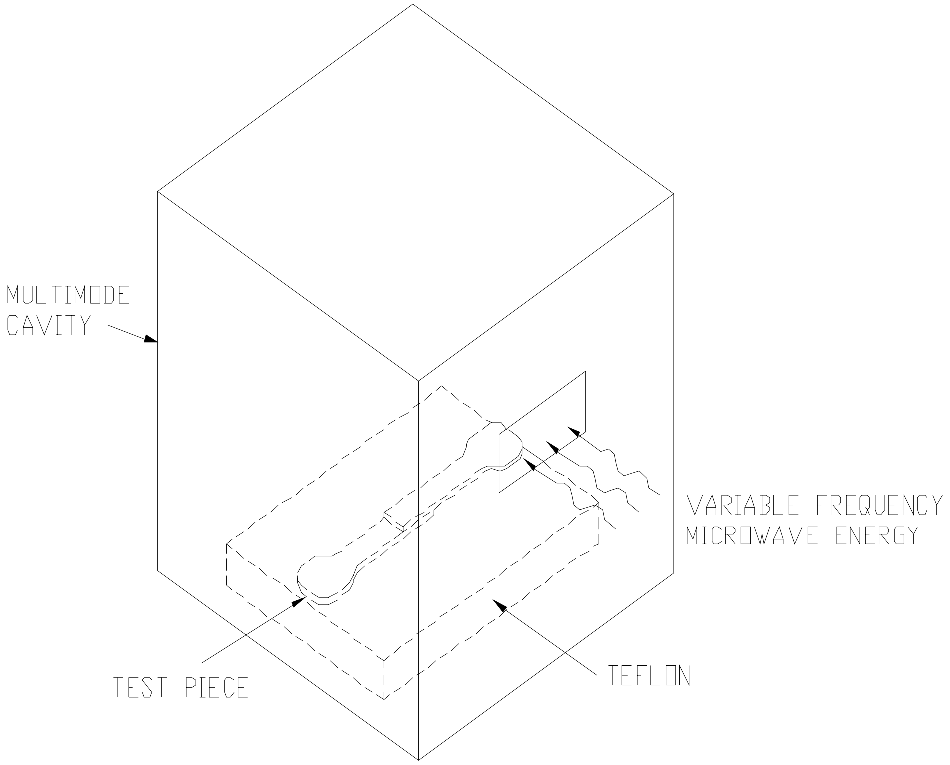


a) 2.45 GHz Microwave Energy Launched into a Single Mode Applicator

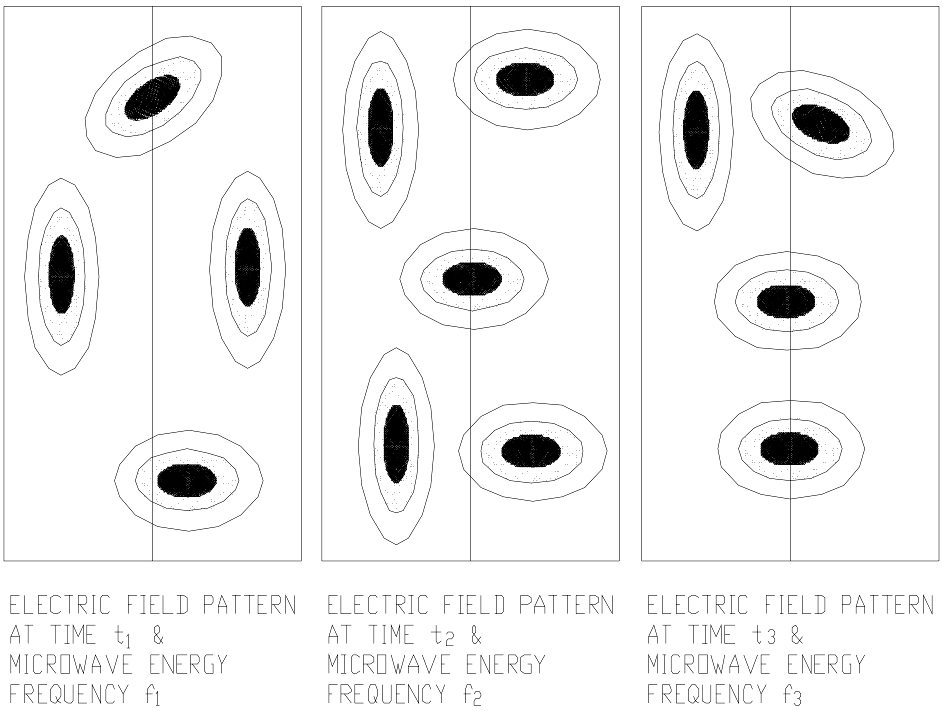


b) Electric Field Pattern for (a)

Figure 1: Fixed Frequency Microwave Heating – Nonuniform Heating



a) Variable Frequency Microwave Energy Launched into Multi Mode Cavity



b) Electric Field Pattern at Different Times in (a)

Figure 2: Variable Frequency Microwave Heating – Time-Averaged Uniform Heating

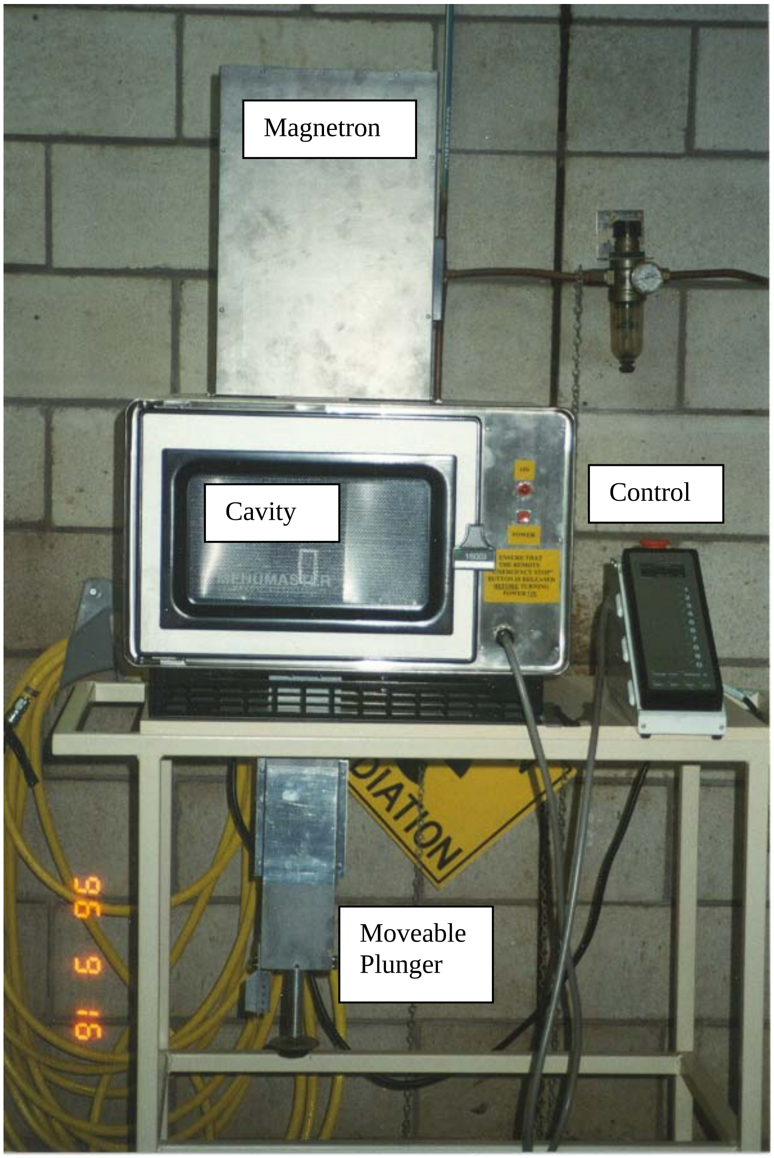


Figure 3: Fixed Frequency Microwave Facilities Configuration

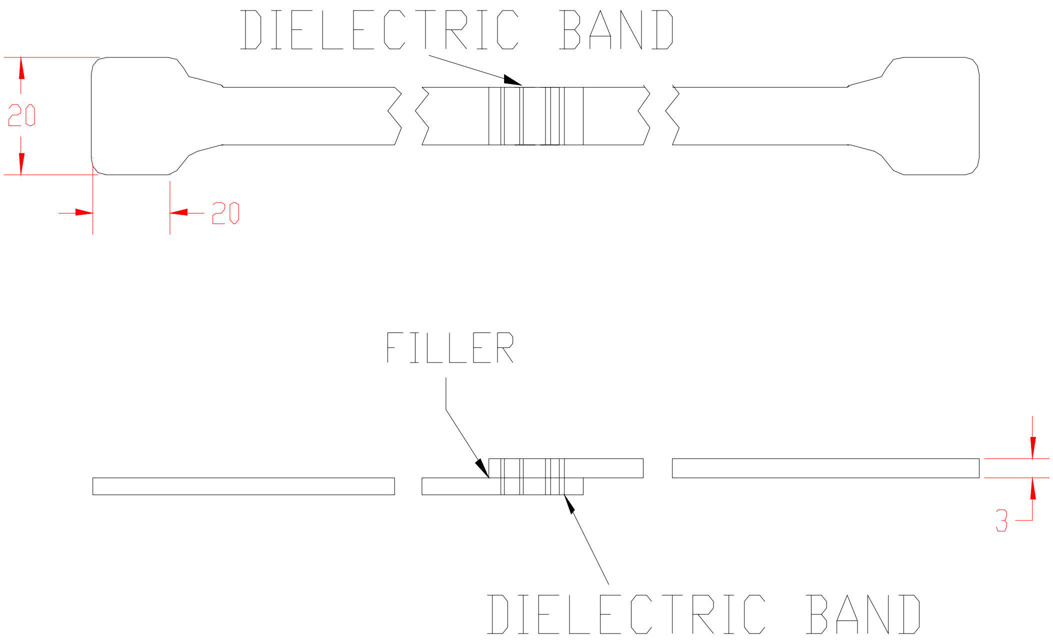


Figure 4: Two Mirror Image Test Pieces of PS/GF (33%)

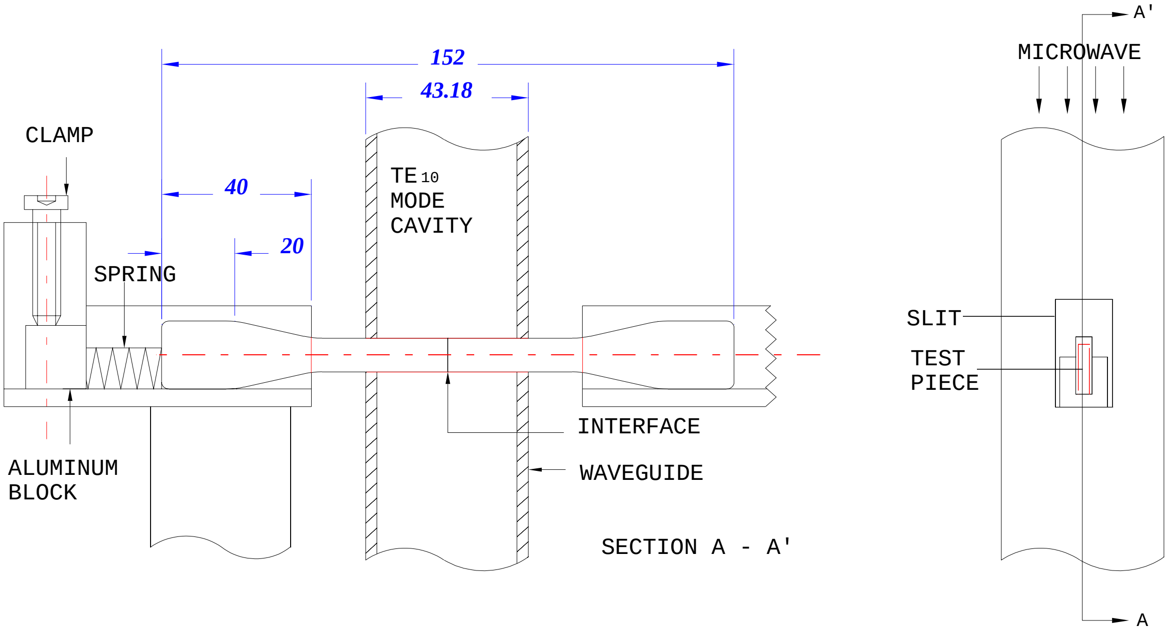


Figure 5: Slotted Rectangular Waveguide Used for Joining LDPE/GF (33%) with Araldite using Fixed Frequency Equipment

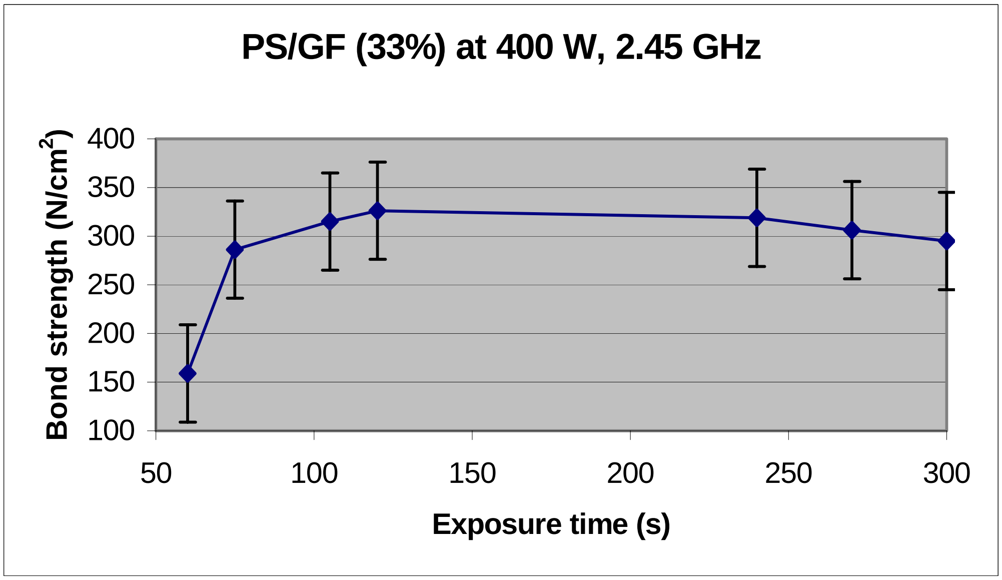


Figure 6: Lap Shear Strengths of PS/GF (33%) Joined by Fixed Frequency Microwave (2.45 GHz) of 400 W in a Slotted Rectangular Waveguide using Rapid Araldite

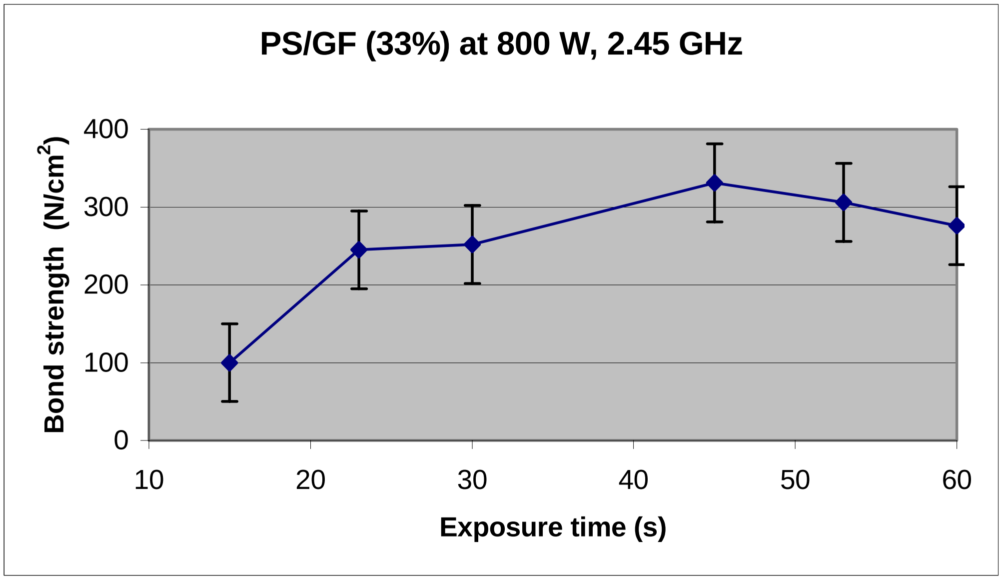


Figure 7: Lap Shear Strengths of PS/GF (33%) Joined by Fixed Frequency Microwave (2.45 GHz) of 800 W in a Slotted Rectangular Waveguide using Rapid Araldite

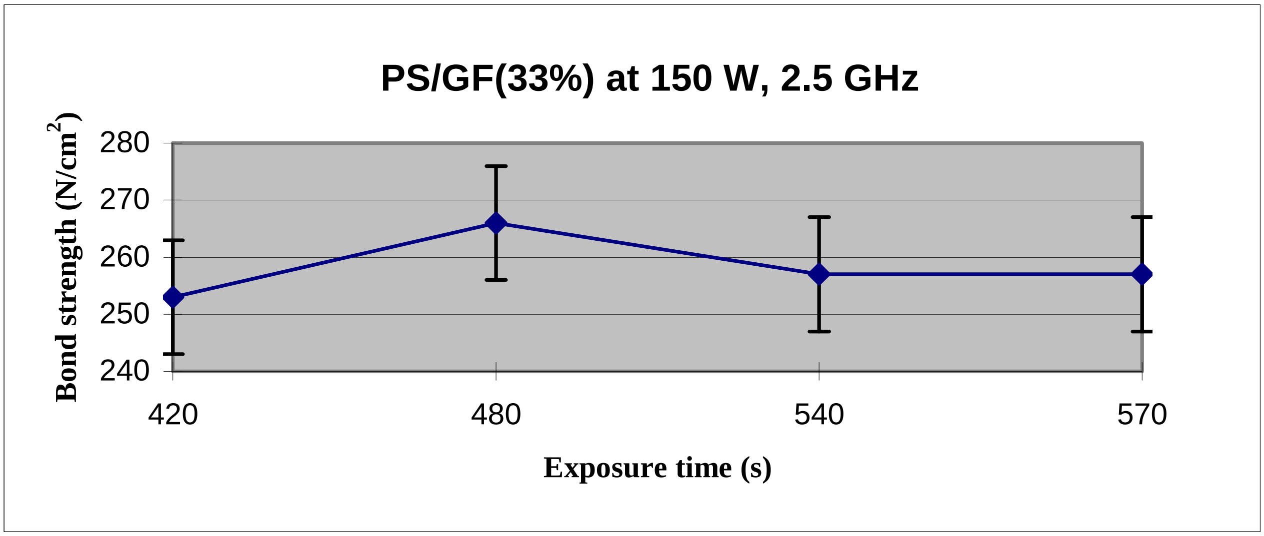


Figure 8: Lap Shear Strengths of PS/GF (33%) using VFM facility with Primer and at 2.5 GHz

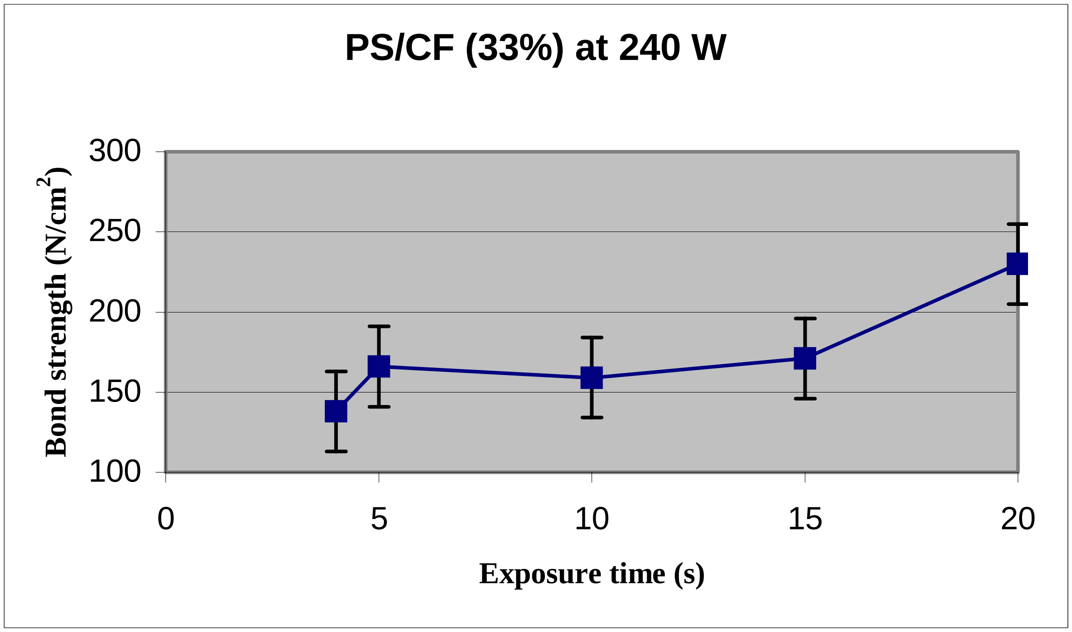


Figure 9: Lap Shear Strengths of PS/CF (33%) Joined by Fixed Frequency Microwave (2.45 GHz) in a Slotted Rectangular Waveguide at a Power Level of 240 W

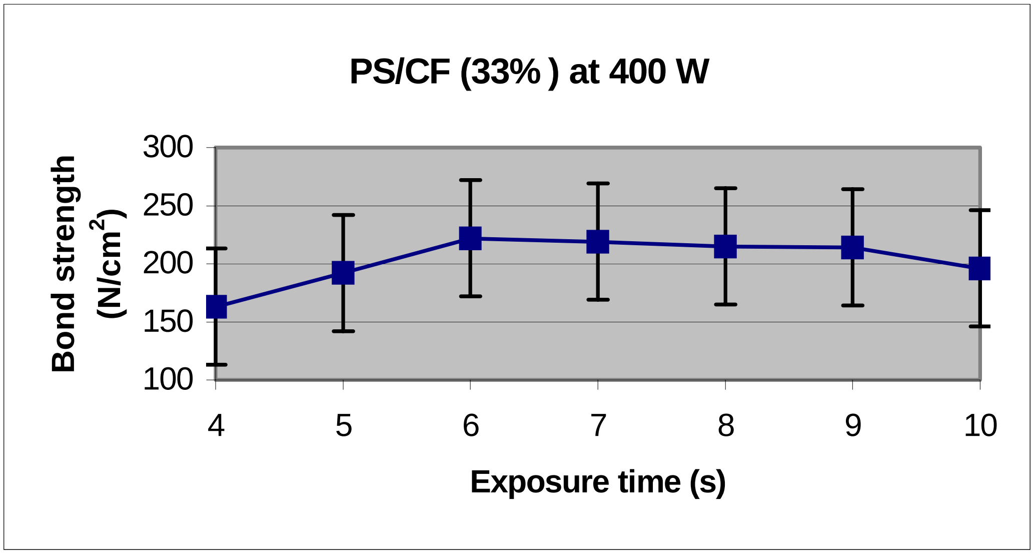


Figure 10: Lap Shear Strengths of PS/CF (33%) Joined by Fixed Frequency Microwave (2.45 GHz) in a Slotted Rectangular Waveguide at a Power Level of 400 W

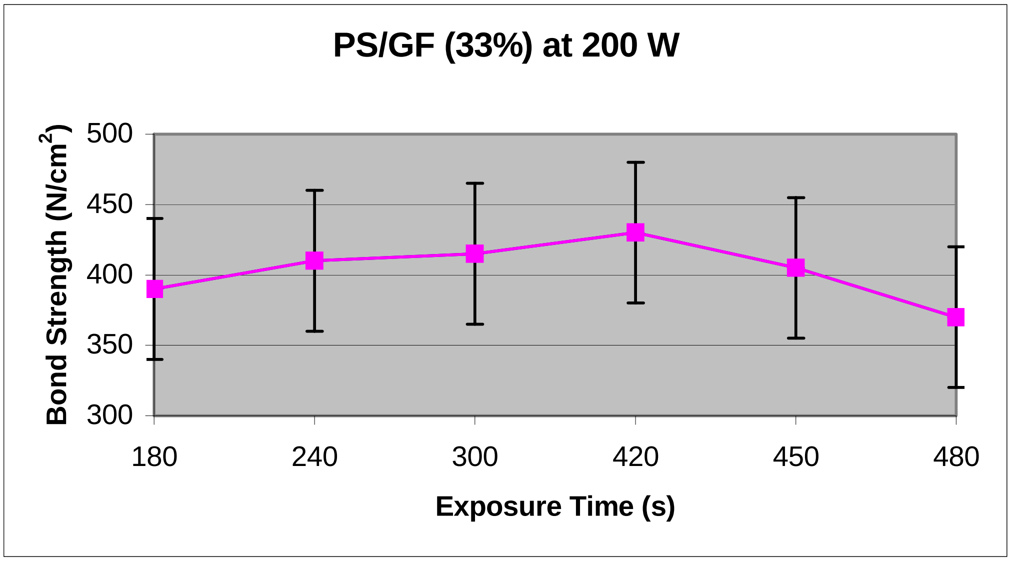


Figure 11: Lap Shear Strengths of PS/GF (33%) Bonds Joined by VFMF

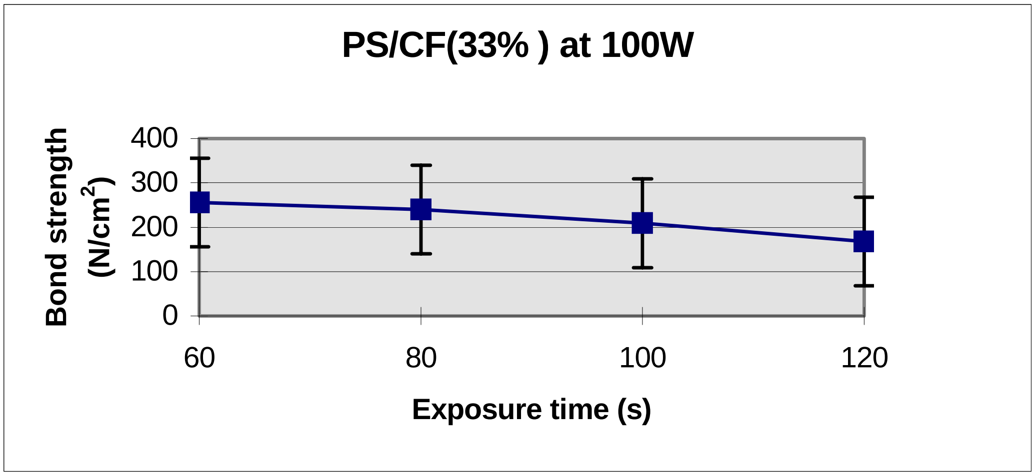


Figure 12: Lap Shear Strengths of PS/CF (33%) Bonded by VFMF

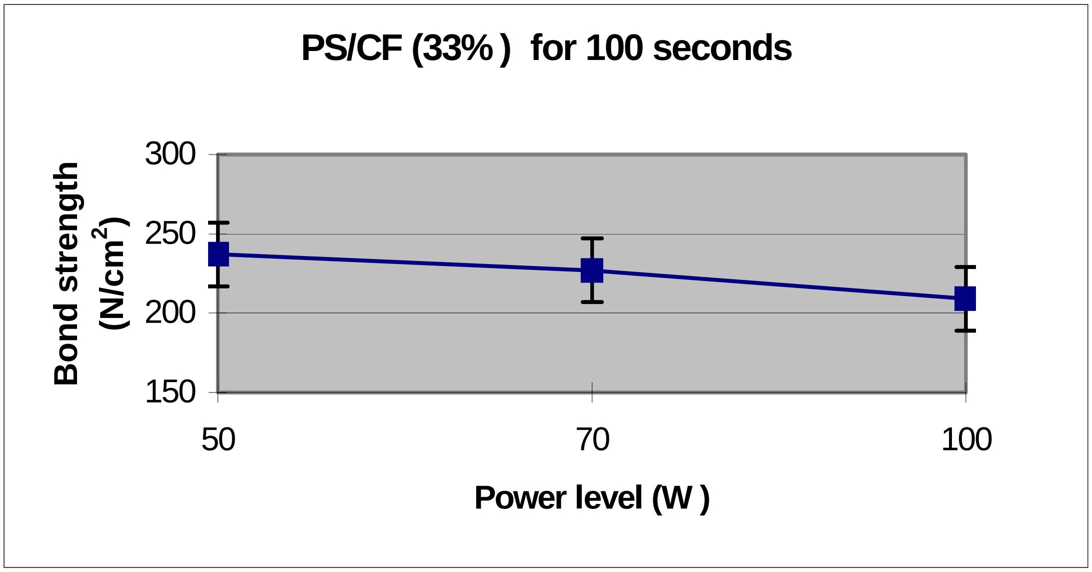


Figure 13: Lap Shear Strengths of PS/CF (33%) Joined by VFMF at Different Power Levels

Table 1: Optimum Frequency Bands to Process the 3 Thermoplastic Matrix Composite Materials in the Frequency Range of 2 GHz to 18 GHz.

Materials	Optimum Frequency Band (GHz)
PS/GF(33%)	8.5 -9.0 and 10.0 - 12.0
PS/CF (33%)	8.0 - 9.3 and 10.8 - 12.8

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

Composite Materials	Power Level (W)	Lap Shear Strength (N/cm^2)
PS/GF (33%)	Ambient cured	304
	150	258
	400	286
	800	251
	VFM, 200	402
PS/CF (33%)	Ambient cured	306
	240	159
	400	204
	VFM, 100	218