

**Thermal Analysis Comparison between Three Random Glass Fibre Reinforced Thermoplastic Matrix Composites Bonded by Adhesives using Microwaves**

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**Abstract:** This paper compares the thermal analysis of three types of random glass fibre reinforced thermoplastic matrix composites joined by adhesives using microwave energy. Fixed frequency, 2.45 GHz, microwave facility is used to join thirty three percent by weight random glass fibre reinforced nylon 66 {Nylon 66/GF (33%)}, thirty three percent by weight random glass fibre reinforced low density polyethylene composite [LDPE/GF (33%)] and. thirty three percent by weight random glass fibre reinforced polystyrene composite [PS/GF (33%)]. The facility used is shown in Figure 1. With a given power level, the composites were exposed to various exposure times to microwave irradiation. The primer or coupling agent used was 5-minute two-part adhesive. The heat distribution of the samples of the three types of composites was analysed and compared. The relationship between the heat distribution and the lap shear strength of the samples was also compared and discussed.

*Keywords:* microwave irradiation, complex relative permittivity, loss tangent, glass fibre-reinforced thermoplastic composites, lap shear strength, Araldite and heat distribution.

## **Introduction**

This paper extends the applications horizon of microwaves in the area of reinforced thermoplastic composites joining, and places emphasis on the thermal analysis during joining process and its relationship with the lap shear strength of the joints. 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,  $\tan \delta = \varepsilon'' / \varepsilon'$  (Ku et al., 1997a; NRC, 1994). The real part of the permittivity,  $\varepsilon'$ , 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,  $\tan \delta$ , which predicts the ability of the material to convert the absorbed energy into heat. In this study nylon 66, low-density polyethylene and polystyrene are the thermoplastic matrices used. Nylon 66 was selected because its loss is high and the 33 percent by weight reinforced glass fibre Nylon 66 is readily available in the market; low density polyethylene (LDPE) was selected as the thermoplastic matrix for study because there was a successful case of joining a composite with high-density polyethylene (HDPE) as a matrix using microwave energy and it was believed that LDPE would couple better to microwaves as its crystallinity is lower than that of HDPE (NRC, 1994; Wu and Benatar, 1992). In addition, polyethylene is used more than any other thermoplastic polymers. In general the outstanding characteristics of polyethylene are toughness, ease of processing, chemical resistance, abrasion resistance, impact resistance, low coefficient of friction, near-zero moisture absorption and high electrical resistance. LDPE was the first of the polyethylene developed. It is a corrosion resistant, low-density extruded material that provides low moisture permeability (San Diego Plastics, undated). However, this composite is not readily available in the Australian market and it was manufactured specially for the project in the Plastic and Rubber Training and Education Centre (PARTEC) in Brisbane, Australia. A polystyrene (PS) matrix was also chosen; first because it is a common thermoplastic polymer matrix and second because its loss tangent is very near to that of LDPE and thus a comparison could be made later on (Shackelford, 1992; Michaeli, 1995). The composite was also manufactured by PARTEC.

## **Microwave Facilities Configuration**

The equipment is built around a modified commercial microwave oven. The two magnetrons were removed from the original locations and one of them (0.8 kW) is relocated onto the top of the oven cavity via a piece of WR340 waveguide. Another piece of waveguide with slits opened for positioning the test pieces is placed upright in the oven cavity so as to avoid hazardous radiation. The upper end was fitted with a flange connected to the magnetron mounted on top of the oven. The lower end is similarly attached to an additional length of waveguide containing a shorting plunger. With reference to Figure 1, the incident waves are generated by the magnetron. They travel downwards through three sections of WR340 waveguide and interact with the test pieces located in the second section before being reflected back by the top face of the adjustable plunger. The two mirror image test pieces were cut using a band saw from a standard tensile test piece for composite materials. The lapped area was made 20 mm x 10 mm. The lapped areas were first roughened by rubbing them against coarse, grade 80, emery paper. They were then cleaned by immersing them in methanol and allowed to dry in air before applying 1.5 to 2 cubic millimetres of Araldite onto both surfaces. After applying the filler, the two pieces were tightened by a dielectric band, which encircled the lapped areas four times as depicted in Figure 2. After tightening with a dielectric band, the two halves of the test pieces were positioned in the slot across the waveguide as illustrated in Figure 3. The test pieces were then exposed to two different power levels of 400W and 800W with varying time of microwave exposure. The test pieces were allowed to cool to

room temperature or below 60°C before being lap shear tested to obtain maximum bond strength (Selleys, undated).

### **Temperature Distribution**

After bonding, the temperatures at different locations, noted by  $E_{L4}$ ,  $E_{L3}$ ,  $E_{L2}$ ,  $E_{L1}$ ,  $E$ ,  $E_{R1}$ ,  $E_{R2}$ ,  $E_{R3}$ ,  $E_{R4}$  (Figure 4) were measured using infrared thermometer. Referring to Figure 4, microwaves travelled from the top of the test pieces but the hottest spots of the sample were expected on the lap area and along the points,  $E_{L4}$ ,  $E_{L3}$ , ...,  $E$ , ...,  $E_{R3}$  and  $E_{R4}$ , across the samples. This is because the lap area contained the Araldite, which absorbed the microwave energy and converted it into heat. Figure 5 shows the temperature distribution of samples exposed to different duration of microwave irradiation of 400 W. At an exposure time of 30 seconds, the recorded temperatures for points  $E_{L1}$ ,  $E$  and  $E_{R1}$  were 34 °C, 35 °C and 33 °C respectively. The ambient temperature was 19 °C. The oven cavity temperature after bonding for 30 seconds of microwave exposure was 24 °C. The mid-point of the sample, point  $E$ , was hottest and it was 14 °C higher than the room temperature. The longer the duration of exposure to microwave energy, the higher the temperatures of the points as depicted in Figure 5. The two points adjacent to the midpoint,  $E$ , ie,  $E_{L1}$ ,  $E_{R1}$  also recorded significant temperature rise. Furthermore, the longer the time of exposure of the sample to microwave energy, the greater the temperature difference between  $E$  and  $E_{L1}$ , and  $E$  and  $E_{R1}$  respectively. This is illustrated by the more acute angle  $E_{L1}EE_{R1}$ ; at shorter duration of microwave irradiation, the angle was obtuse, ie, there was not much temperature difference between  $E$  and  $E_{L1}$ , and  $E$  and  $E_{R1}$  respectively (see the 15 second-exposure in Figure 5) but the temperatures were much higher than the ambient temperature. The temperature of points outside the lapped

area, ie,  $E_{L4}$ ,  $E_{L3}$ ,  $E_{L2}$  on the left and  $E_{R2}$ ,  $E_{R3}$ ,  $E_{R4}$  on the right were also much higher than the ambient temperature.

Figure 6 shows the temperature distribution of samples exposed to different duration of microwave irradiation of 240 W. At an exposure time of 65 seconds, the recorded temperatures for points  $E_{L1}$ , E and  $E_{R1}$  were 28.5 °C, 30 °C and 28.5 °C respectively. The ambient temperature was 19 °C. The oven cavity temperature after bonding for an exposure time of 65 seconds was 24 °C. The mid-point of the sample, point E, was hottest and it was 11 °C higher than the room temperature. The temperature distribution along the points considered (see Figure 6) is similar to that of the 400 W microwave power exposure in Figure 6. The temperature of points outside the lapped area, ie,  $E_{L4}$ ,  $E_{L3}$ ,  $E_{L2}$  on the left and  $E_{R2}$ ,  $E_{R3}$ ,  $E_{R4}$  on the right were also much higher than the ambient temperature. This is expectable and the reason is the same as in the case of 400 W microwave irradiation mentioned above.

Figure 7 shows the temperature distribution of samples of LDPE/GF (33%) exposed to different duration of microwave irradiation of 800 W. At an exposure time of 70 seconds, the recorded temperatures for points  $E_{L1}$ , E and  $E_{R1}$  were 31.5 °C, 33.5 °C and 31.5 °C respectively. The ambient temperature was 21 °C. The oven cavity temperature after bonding for 70 seconds of microwave exposure was 27 °C. The mid-point of the sample, point E, was hottest and it was 12.5 °C higher than the room temperature. The two points adjacent to the midpoint, E, ie,  $E_{L1}$ ,  $E_{R1}$  also recorded significant temperature rise.

Figure 8 shows the temperature distribution of samples of LDPE/GF (33%) exposed to different duration of microwave irradiation of 400 W. At an exposure time of 240 seconds, the recorded temperatures for points  $E_{L1}$ , E and  $E_{R1}$  were 32 °C, 34 °C and 31.5 °C respectively. The ambient temperature was 21 °C. The oven cavity temperature after bonding for an exposure time of 240 seconds was 27 °C.

Figure 9 shows the temperature distribution of samples of PS/GF (33%) exposed to different duration of microwave irradiation of 800 W. At an exposure time of 60 seconds, the recorded temperatures for points  $E_{L1}$ , E and  $E_{R1}$  were 32 °C, 33 °C and 31.5 °C respectively. The ambient temperature was 21 °C. The oven cavity temperature after bonding for 60 seconds of microwave exposure was 27 °C. The mid-point of the sample, point E, was hottest and it was 12 °C higher than the room temperature.

Figure 10 shows the temperature distribution of samples of PS/GF (33%) exposed to different duration of microwave irradiation of 400 W. At an exposure time of 300 seconds, the recorded temperatures for points  $E_{L1}$ , E and  $E_{R1}$  were 32 °C, 36 °C and 31.5 °C respectively. The ambient temperature was 21 °C. The oven cavity temperature after bonding for an exposure time of 240 seconds was 27 °C. The temperature distribution along the points considered (see Figure 10) is similar to that of the 800 W microwave power exposure in Figure 9.

## Heat Flow and Temperature Gradient

Figure 11 shows heat flow lines, which spread out from the centre of the test pieces. The temperature did not change uniformly because the ends were not insulated. Bisect the test pieces along the point E and consider the right hand side of them, for two positions along the sample separated by distance  $dx$ , the average temperature gradient between the two positions is  $\frac{d\theta}{dx}$  where  $d\theta$  is the temperature difference between the two positions.

The heat flow along the sample depends on (Breithaupt, 1991):

- i) the temperature gradient  $\frac{\theta_1 - \theta_2}{L}$  along the sample;
- ii) the cross-sectional area of the sample and
- iii) the material of the test piece.

To measure heat flow, the heat energy  $Q$  conducted along the test piece in time  $t$  must be measured. The heat flow is given by  $\frac{Q}{t}$  and it is proportional to

- i) the temperature gradient and
- ii) the cross-sectional area of the test piece.

Therefore, by Fourier's law,  $\frac{Q}{t} = kA \frac{(\theta_1 - \theta_2)}{L}$  (Breithaupt, 1991).

where  $k$  = thermal conductivity of the material in  $\text{Wm}^{-1}\text{K}^{-1}$ ;

$Q$  = heat conducted in time  $t$  in seconds;

$(\theta_1 - \theta_2)$  = temperature difference between the centre to end of sample ( $\theta_1 > \theta_2$ ) in Kelvin,  $\text{K}$ ;

$A$  = cross-sectional area in  $\text{m}^2$ ;

$L$  = length of sample in  $\text{m}$ .



### Heat flow in Nylon 66/GF (33%) test pieces

Referring to Figure 4 and consider the case when the test pieces were exposed to microwave irradiation for 30 seconds at a power level of 400 W. Consider the flow of heat from point E to the end of the test piece on the right hand side and use Fourier's law:

$$\frac{Q}{t} = kA \frac{(\theta_1 - \theta_2)}{L}$$

The cross sectional area of the test piece, A, varied along the test piece from 10 x 3 mm<sup>2</sup> from points, E to E<sub>R4</sub>, to 20 x 3 mm<sup>2</sup> from points E<sub>R4</sub> to the end. The equivalent area has to be calculated as follow:

$$A = \frac{26(60) + 40(30)}{26 + 40} = 41.82 \text{ mm}^2.$$

The thermal conductivity of Nylon 66/GF (33%) was simulated from those of its constituents and was found to be 0.7210 Wm<sup>-1</sup>K<sup>-1</sup> (Callister, 2003)

Therefore, heat flow rate from centre point, E to the end

$$\frac{Q}{t} = kA \frac{(\theta_1 - \theta_2)}{L} = 0.721 \times 41.82 \times 10^{-6} \times \frac{(35 - 24)}{66 \times 10^{-3}} = 4.960 \times 10^{-3} \text{ W}$$

or energy flow = Q = 4.960 x 10<sup>-3</sup> x 30 = 0.419 J.

Similarly, the heat flow rate,  $\frac{Q}{t}$  from points, E to E<sub>R3</sub> and E to E<sub>R1</sub> are 3.780 x 10<sup>-3</sup> W

and 4.530 x 10<sup>-3</sup> W respectively. Furthermore, energy flow, Q from points, E to E<sub>R3</sub> and

E to E<sub>R1</sub> is 0.113 J and 0.136 J respectively. The values for  $\frac{Q}{t}$  and Q are very small and are due to the small value of thermal conductivity of Nylon 66/GF (33%).

The specific heat capacity of Nylon 66/GF (33%) was simulated from those of its constituents and was found to be 1394 Jkg<sup>-1</sup>K<sup>-1</sup> (Callister, 2003). By referring to Figure 4, the total energy, Q, absorbed by the test pieces during their exposure to microwave irradiation can be estimated by dividing the test pieces into sections of different temperatures. Consider the section of E and E<sub>R1</sub> of Nylon 66/GF (33%), the temperature of E and E<sub>R1</sub> after exposing to microwaves of 400 W for 30 seconds were 35 °C and 33 °C respectively.

Their average temperature was  $\frac{35^{\circ}C + 33^{\circ}C}{2} = 34^{\circ}C$ . The volume of the section = 10 mm x 10 mm x 3 mm x 2 (lapped area) = 600 mm<sup>3</sup>. The volumes and average temperatures of the other sections of the test pieces were similarly calculated and were tabled in Table 1. The mass of the test pieces was 10.75 g. Since the total volume of the test pieces was 6200 mm<sup>3</sup> or 6.2 cm<sup>3</sup>, the density of LDPE/GF (33%) =  $\frac{mass}{volume} = \frac{10.75g}{6.2cm^3} = 1.73 \text{ g/cm}^3$ . The mass of section E and E<sub>R1</sub> = volume x density = 0.6 cm<sup>3</sup> x 1.73 g/cm<sup>3</sup> = 1.04 g.

The microwave power absorbed = (mass) x (specific heat capacity) x (rise in temperature)

$$= 1.04g \times 1394 \text{ Jkg}^{-1}\text{K}^{-1} \times [(34 + 273) \text{ K} - (19 + 273) \text{ K}] = 21.746 \text{ J}$$

The mass and energy absorbed of other sections can be similarly calculated and are shown in Table 2. The total energy absorbed by the test pieces was the sum of energy absorbed by each section and was 62.796 J.

The heat energy stored in the section  $E_{R4}$  and the end of the test piece on the right hand side was 22.203 J, it was found that this is much larger than the heat energy flow from E to the same end of the test piece (0.149 J). It can be argued that the heat energy in section  $E_{R4}$  and the end of the sample came mainly from the absorption of microwave and then conversion of the radiation into heat by that part of the test piece. Only very small amount, probably, 0.2 % came from heat flow from the centre of the sample, E. Despite the low to medium loss of the composite material, Nylon 66/GF (33%), the heat generated in the test pieces came overwhelmingly from the microwave absorption and then conversion of the irradiation into heat by the samples.

### **Heat flow in LDPE/GF (33%) test pieces**

Referring to Figure 4, the cross sectional area of the test piece, A, varied along the test piece from  $10 \times 3 \text{ mm}^2$  from points, E to  $E_{R4}$ , to  $20 \times 3 \text{ mm}^2$  from points  $E_{R4}$  to the end. The equivalent area is the same as above and equals  $41.82 \text{ mm}^2$ . The thermal conductivity of LDPE/GF (33%) was simulated from those of its constituents and was found to be  $0.8692 \text{ Wm}^{-1}\text{K}^{-1}$  (Callister, 2003).

Therefore, heat flow rate from centre point, E to the end

$$\frac{Q}{t} = kA \frac{(\theta_1 - \theta_2)}{L} = 0.8692 \times 41.82 \times 10^{-3} \times \frac{(33.5 - 27)}{66 \times 10^{-3}} = 3.580 \times 10^{-3} \text{ W}$$

$$\text{or energy flow} = Q = 3.580 \times 10^{-3} \times 70 = 0.251 \text{ J}$$

The specific heat capacity of LDPE/GF (33%) was simulated from its constituents and was found to be  $1510 \text{ J kg}^{-1} \text{ K}^{-1}$  (Callister, 2003). By referring to Figure 4, the total energy,  $Q$ , absorbed by the test pieces during their exposure to microwave irradiation can be estimated by dividing the test pieces into sections of different temperatures.

The volumes and average temperatures of the all other sections of the test pieces were similarly calculated and were tabled in Table 1. The mass of section E and  $E_{R1}$  = volume x density =  $0.6 \text{ cm}^3 \times 1.2 \text{ g/ cm}^3 = 0.72 \text{ g}$ . The microwave power absorbed = (mass) x (specific heat capacity) x (rise in temperature) =  $0.72 \text{ g} \times 1510 \text{ J kg}^{-1} \text{ K}^{-1} \times [(32.5 + 273) \text{ K} - (21 + 273) \text{ K}] = 12.503 \text{ J}$

The mass and energy absorbed of other sections can be similarly calculated and are shown in Table 2. The total energy absorbed by the test pieces was the sum of energy absorbed by each section and was 94.06 J. The heat energy stored in the section  $E_{R4}$  and the end of the test piece on the right hand side was 19.572 J, it was found that this is much larger than the heat energy flow from E to the same end of the test piece (0.251 J). It can be argued that the heat energy in section  $E_{R4}$  and the end of the sample came mainly from the absorption of microwave and then conversion of the radiation into heat by that part of the test piece.

### Heat flow in PS/GF (33%) test pieces

The thermal conductivity of PS/GF (33%) was simulated from its constituents and was found to be  $0.648 \text{ Wm}^{-1}\text{K}^{-1}$  (Callister, 2003).

Therefore, heat flow rate from centre point, E to the end

$$\frac{Q}{t} = kA \frac{(\theta_1 - \theta_2)}{L} = 0.648 \times 41.82 \times 10^{-6} \times \frac{(33 - 27)}{66 \times 10^{-3}} = 2.464 \times 10^{-3} \text{ W}$$

or energy flow =  $Q = 2.464 \times 10^{-3} \times 60 = 0.148 \text{ J}$ .

Similarly, the heat flow rate,  $\frac{Q}{t}$  from points, E to  $E_{R3}$  and E to  $E_{R2}$  are  $3.239 \times 10^{-3} \text{ W}$

and  $3.399 \times 10^{-3} \text{ W}$  respectively. Furthermore, energy flow,  $Q$  from points, E to  $E_{R3}$  and

E to  $E_{R1}$  are  $0.194 \text{ J}$  and  $0.204 \text{ J}$  respectively. The values for  $\frac{Q}{t}$  and  $Q$  are very small and

are due to the small value of thermal conductivity of PS/GF (33%).

The volumes and average temperatures of the all other sections of the test pieces were similarly calculated and were tabled in Table 1. The mass of section E and  $E_{R1}$  = volume

x density =  $0.6 \text{ cm}^3 \times 1.58 \text{ g/cm}^3 = 0.95 \text{ g}$ . The microwave power absorbed

= (mass) x (specific heat capacity) x (rise in temperature)

$$= 0.95 \text{ g} \times 1061 \text{ Jkg}^{-1}\text{K}^{-1} \times [(32.5 + 273) \text{ K} - (21 + 273) \text{ K}] = 11.340 \text{ J}$$

The mass and energy absorbed of other sections can be similarly calculated and are shown in Table 2. The total energy absorbed by the test pieces was the sum of energy absorbed by each section and was  $63.92 \text{ J}$ . The heat energy stored in the section  $E_{R4}$  and

the end of the test piece on the right hand side was 13.241 J, it was found that this is much larger than the heat energy flow from E to the same end of the test piece (0.148 J). It can be argued that the heat energy in section  $E_{R4}$  and the end of the sample came mainly from the absorption of microwave and then conversion of the radiation into heat by that part of the test piece.

Referring to Table 1, the temperature difference to ambient temperature at different sections of the test pieces were generally higher in Nylon 66/GF (33%) sample than in LDPE/GF (33%) and PS/GF (33%) samples. This is particularly obvious in the sections of  $E_{L1}$  and E, and E and  $E_{R1}$ . This is because Nylon 66/GF (33%) had a higher loss tangent than LDPE/GF (33%) and PS/GF (33%) and absorbed more of the supplied microwave energy and converted it into heat. The loss tangent at 2.45 GHz for Nylon 66/GF (33%), LDPE/GF (33%) and PS/GF (33%) are  $71.9 \times 10^{-4}$ ,  $3.6 \times 10^{-4}$  and  $2.6 \times 10^{-4}$  respectively (Metaxas and Meredith, 1983). Referring to Table 2, the thermal energy absorbed by the sections of  $E_{L1}$  and E, and E and  $E_{R1}$  of the test pieces were higher in Nylon 66/GF (33%) sample than in LDPE/GF (33%) and PS/GF (33%) samples. The reason is the same as above.

### **Lap shear strength for Nylon 66/GF (33%)**

The joints were also lap shear tested. 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 selected for the test (Bolton, 1996). Figure 12 shows the lap shear strength of Nylon

66/GF (33%) joined by a fixed frequency microwave facility in a slotted rectangular waveguide. With glass fibre reinforced Nylon 66, the peak lap shear strengths obtained at exposure times of 35 and 55 seconds for the power levels of 400 W and 240 W respectively are depicted in Figure 12. They were 32% and 28% respectively higher than those obtained by curing the adhesive at room temperature conditions but the times required were only 1.0 % and 1.53 % of their counterparts. Any excess Araldite that spilled over the sides and opposite faces of the interfaces of the test pieces had to be totally removed as the primer facing the microwave energy directly could bring about thermal runaway and the parent material could burn, depending on the degree of spill-over of the adhesive (Ku et al., 1997a: 1997b).

With reference to Figure 12 and at a power level of 400 W, an exposure time to microwaves of over 42 seconds burned the test pieces even without spilling of the filler over the sides and the lapped area could also be easily bent with an exposure time of 30 seconds or over. For a power level of 240 W, burning of test pieces occurred at an exposure time of over 62 seconds and the lapped area was also bent with ease when exposed to microwave energy of 55 seconds or over. When exposed to 65 seconds, the test pieces burned mildly and diffusion of parent material into the filler became more prominent (Ku et al., 1997a: 1997b). This brought about higher bond strength than the 62 seconds of exposure to microwave irradiation. However, the quality of the bond was not too good. The lap shear strength at an exposure time of 70 seconds was similar to those exposed to 65 seconds. However, the test pieces were more seriously burnt which weakened the parent material and the bond quality was much poorer.

### **Lap shear strength for LDPE/GF (33%)**

Figure 13 shows the lap shear of LDPE/GF (33%) joined by a fixed frequency microwave facility in a slotted rectangular waveguide. At the fixed frequency of 2.45 GHz and a power level of 800 W, and at microwave exposure times ranging from 25 to 40 seconds, the cluster of bond strengths was best represented by their average value of 151 N/cm<sup>2</sup> (line 800PE1 in Figure 13); while those resulting from microwave energy exposure in the range of 45 to 65 seconds were represented by their average value of 219 N/cm<sup>2</sup> (line 800PE2 in Figure 13) (Schwartz, 1992; 1995; Varadan and Varadan, 1991). In both cases, the results obtained were similar to the work of another researcher using high-density polyethylene (Siores and Groombridge, 1997).

### **Lap shear strength for PS/GF (33%)**

The joints were also lap shear tested. 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 selected for the test (Metaxas and Meredith, 1983). Figure 14 shows the lap shear strength of PS/GF (33%) joined by a fixed frequency microwave facility in a slotted rectangular waveguide. The primer used for joining this material was also five minute two part adhesive. It was found that with 400 W power level, peak bond strength was achieved by exposing the test pieces to microwaves for 2 minutes; the lap shear strength, 326 N/cm<sup>2</sup>, at this exposure duration exceeded that obtained by ambient conditions curing by 17%, but the time required was a mere of 3.3 % of its counterpart (Ku et al.,



1997b; Schwartz, 1992). For exposure times of one and a half to four and a half minutes, the lap shear strengths obtained using microwave-cured filler were higher than those obtained by allowing the adhesive to set under ambient conditions. With a power level of 800 W, the maximum lap shear strength was 331 N/cm<sup>2</sup> and 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 rival (Ku et al., 1997b; Schwartz, 1995). The lower bond 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, might be due to over-curing of the adhesive (Schwartz, 1992).

### **Temperature Distribution and Lap Shear Strength in Nylon 66/GF (33%)**

Figure 15 shows the relationship of lap shear bond strengths and temperatures of the centre points of the test pieces with respect to the duration of exposure to 400 W microwave irradiation. The temperatures of the centre points of the test pieces increased steadily with the increase in time of microwave exposure but the lap shear strength of them did show the same trend and the lap shear strength peaked at 495 N/cm<sup>2</sup> with an exposure time of 35 seconds. It can be argued that the rise in temperature was significant enough to initiate the rapid curing of the primer. At longer duration of exposure, ie, from 35 seconds onwards, the temperatures of the centres of the samples increased steadily but the Araldite was overcured. The lap shear strength dropped and the quality of the bonds was very bad (Ku et al, 1997a; 1997b). When compared with the ambient cured samples, the increase in lap shear strength was 32 % (Ku et al., 1997b; 2000a; 2000b). This means

that the amount of microwave energy absorbed and converted into heat by the Araldite was enough to cure it fully in a much shorter time.

Figure 16 shows the relationship of lap shear bond strengths and temperatures of the centre points of the test pieces with respect to the duration of exposure to 240 W microwave irradiation. The temperatures of the centre points of the test pieces increased steadily with increase in microwave exposure but the lap shear strength did not show the same trend. The lap shear strength initially increased with the rise in temperature of the test pieces and it peaked at  $482 \text{ N/cm}^2$  with 55 seconds of exposure time and then declined. It can be argued that the rise in temperatures in the test pieces cured the Araldite rapidly (Ku et al., 1997b; 2000a; 2000b). The primer became overcured when exposed to microwaves for more than 55 seconds.

### **Temperature Distribution and Lap Shear Strength in LDPE/GF (33%)**

Figure 17 shows the relationship of lap shear bond strengths and temperatures of the centre points of the test pieces with respect to the duration of exposure to 800 W microwave irradiation. At short duration of exposure to microwaves, ie, from 20 to 40 seconds, the temperatures of the centre points of the test pieces increased steadily with the increase in time of microwave exposure but the lap shear strength of them did not showed the same trend and could be represented by the average value line, 800PE1 ( $151 \text{ N/cm}^2$ ). Line 800PE1 is only 97 % of the average lap shear strength value of test pieces cured under ambient conditions; it can be argued that the rise in temperature was not significant enough to initiate the rapid curing of the primer. At longer duration of

exposure, ie, from 45 to 70 seconds, the temperatures of the centres of the samples increased steadily with the time of exposure, while at the same time the values of the lap shear strength, which were much higher, did increased steadily. They could be represented by the line 800PE2 (219 N/cm<sup>2</sup>). When compared with the ambient cured samples, the increase in lap shear strength was 45 % (Ku et al., 2000a). This means that the amount of microwave energy absorbed and converted into heat by the Araldite was enough to cure it fully in a much shorter time.

Figure 18 shows the relationship of lap shear bond strengths and temperatures of the centre points of the test pieces with respect to the duration of exposure to 400 W microwave irradiation. The temperatures of the centre points of the test pieces increased steadily with increase in microwave exposure and the lap shear strength showed the same trend. However, the difference in maximum and minimum values of the lap shear strength was only 8% and they could be represented by the average value line, 400PE1(185 N/cm<sup>2</sup>) (Figure 13). It can be argued that values of the lap shear strength were not high, but the rise in temperatures in the test pieces was significant enough to cure the Araldite rapidly (Ku et al., 2000a). Exposure times of over 240 seconds will deform the samples.

### **Temperature Distribution and Lap Shear Strength in PS/GF (33%)**

Figure 19 shows the relationship of lap shear strengths and temperatures of the centre points of the test pieces with respect to the duration of exposure to 800 W microwave irradiation. At all duration of exposure to microwaves, the temperatures of the centre points of the test pieces increased steadily with the increase in time of microwave exposure; the lap shear strength of them showed the same trend initially but when the duration of exposure was over 50 seconds, the values of the lap shear strength fell and this was due to over-cured of the Araldite.

Figure 20 shows the relationship of lap shear strengths and temperatures of the centre points of the test pieces with respect to the duration of exposure to 400 W microwave irradiation. The temperatures of the centre points of the test pieces increased steadily with increase in microwave exposure and the lap shear strength showed the same trend but flattened and declined slightly when the exposure time was over 120 seconds. Exposure times of over 300 seconds will deform the samples.

### **Conclusion**

By comparing the heat distribution and lap shear strength of three random glass fibre reinforced thermoplastic matrix composite materials, Nylon 66/GF (33%), LDPE/GF (33%) and PS/GF (33%), and it can be argued that the loss tangent of the material plays a vital role in the absorption of microwave irradiation. It will determine the

characteristics of heat distribution in the samples. The heat flow from the hottest parts (lapped areas) of the samples towards the other parts of the test pieces was negligible in both composite materials because their thermal conductivities were low.

If the loss of a material is low, the longer exposure time to microwaves may not necessarily result in the desired heat distribution and lap shear strength. If the material is very lossy, 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 gradient.

## **References**

Bolton, W. (1996). *Materials and Their Uses*, Butterworth and Heinemann, 128.

Breithaupt, J. (1992). *Understanding Physics for Advanced Level*, 2<sup>nd</sup> ed., U.K., 111-112, 116-118.

Callister, W D (2003). *Materials Science and Engineering: An Introduction*, 6<sup>th</sup> Ed., John Wiley and Sons, Inc., p. 660.

Ku, H.S., Siores, E. and Ball, J.A.R (1997a). Welding of Thermoplastic Composites Using Microwave Energy, Proceedings of CIPR International Symposium, Hong Kong, 2:612-619.

Ku, H. S., Siores, E. and Ball, J.A.R. (1997b). Welding of Thermoplastic Composite Using Microwave Energy, Proceedings of CIRP International Symposium - Advanced Design and Manufacturing in the Global Manufacturing Era, 2: 612--618.

Ku, H S, Siores, E and Ball, J.A.R. (2000a). Relationship between Microwave Irradiation and Constituents of Composites during Joining Process, Transactions, The Hong Kong Institution of Engineers, 7:3: 41-49.

Ku, H.S., MacRobert, M., Siores, E. and Ball, J.A.R. (2000b). Variable Frequency Microwave Processing of Thermoplastic Matrix Composites, Plastics, Rubber and Composites, 29:6:278-284.

Meataxes, A.C. and Meredith, R.J. (1983). *Industrial Microwave Heating*, Peter Peregrinus Ltd. 6-7, 43, 278.

Michaeli, W. (1995). *Plastic Processing*, Carl Hanser Verlag, Munich Vienna New York, 189-190.

NRC (National Research Centre) (1994). *Microwave Processing of Materials*, National Advisory Board Commission on Engineering and Technical Systems, National Research Council, USA, 7, 11-12, 100, 105.

Wu, C.Y. and Benatar, A.(1992). Microwave Joining of HDPE Using Conductive Polyaniline Composites, Proceedings of Society of Plastic Engineers, 50<sup>th</sup> Annual Technical Conference, 1771-1774.

San Diego Plastics, Inc. (undated). Polyethylene, [www.sdplastics.com/polyet.html](http://www.sdplastics.com/polyet.html), 1-4.

Schwartz, M. M. (1992). *Composite Materials Handbook*, 2nd edition, McGraw-Hill, USA, 6.55-56.

Schwartz, M. M. (1995). *Joining of Composite-matrix Materials*, ASM International, USA, 64.

Selleys Araldite (undated). Five Minute Epoxy Adhesive User Instructions, Selleys Chemical,

Shackelford, J.F. (Ed.) (1992). *The CRC Materials Science and Engineering Handbook*, CRC Press, 486, 731-739,

Siores, E., and Groombridge, P. (1997). Preliminary Investigations into the use of Microwave Energy for Fast Curing of Adhesively Bonded Joints Formed Using Engineering Thermoplastics, American Ceramic Society Bulletin, 8:437- 44.

Varadan, V. K. and Varadan V.V. (1991). Microwave Joining and Repair of Composite Materials, Polymer Engineering and Science, 31:7: 470- 486.